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Evaluating and Assessing the Relative Effectiveness of Acoustic Deterrent Devices and other Non-Lethal Measures on Marine Mammals

marine scotland

Evaluating and Assessing the Relative Effectiveness of Acoustic Deterrent Devices and other Non-Lethal Measures on Marine Mammals

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Executive Summary

Acoustic Deterrent Devices (ADDs) have long been used to try to keep animals away from human activities. They have been developed in the marine environment particularly to keep marine mammals away from fishing operations, aquaculture sites and more recently to keep marine mammals away from industrial operations that might be harmful to the animals themselves. This review attempts to synthesise the costs and benefits of the acoustic deterrent approach, drawing on a wide range of examples and types of deterrent device, but the primary focus is on the use of ADDs in aquaculture.

The aquaculture industry is probably still the main market for ADDs. The levels of damage caused by pinnipeds are poorly documented but such damage is generally thought to be a significant operating cost in Scotland at least. Damage caused by pinnipeds includes torn nets, direct damage to or removal of fish or indirect damage through reduced growth. The exact mechanisms involved in depredation are not known. ADDs are a widely used method of trying to minimise such damage. Solutions other than the use of ADDs include the use of anti-predator nets, more robust netting material, frequent removal of dead fish, ‘blinds’ that conceal dead or moribund fish at the bottom of cages and better tensioning of the net pens, as well as translocation and lethal removals. Electric fields and conditioned taste aversion have also been suggested but have not yet to our knowledge been tested on sites. None of these methods, including the use of ADDs, has been shown to be fully effective in the long term. Many authors suggest that a suite of anti-predator methods is necessary in most situations.

At least five different types of ADD are used in Scotland, but many more devices are available and may be marketed for other purposes. We have tabulated all devices that we are aware of as of 2013 within this review.

About half of all fish farm sites appear to use ADDs, but there is no register of which sites are using what devices, and little information on their effectiveness. Source levels, signal characteristics, duty cycles and modes of operation are all likely to have significant bearings on how effective they are and also on the extent to which they have an impact on non-target species such as cetaceans. Harbour porpoises are known to avoid areas where Airmar and Lofitech ADDs are being used, but the maximum range that cetaceans are likely to be impacted by these or other ADDs is not currently known.

ADDs have been used to deter some cetaceans and pinnipeds in capture fisheries, but with mixed success. Better success has been achieved with the use of low powered devices (pingers) to minimise the accidental entanglement of certain cetacean species, but these are typically neophobic species that are easily deterred, are not necessarily using the nets as a source of food and therefore lack motivation to stay near the sound source.

The use of ADDs to move animals away from pile driving and other potentially damaging industrial activities is also being developed. We discuss the acoustic characteristics of, and behavioural responses to, such sounds from a theoretical perspective, and summarise published trials of such mitigation activities. We note that some seals seem to have become habituated to ADDs used at fish farm sites, and point out that the use of the same devices at industrial developments therefore runs a risk of being counterproductive. We judge the potential for the success of aversive signals for mitigation to be high, but many details still need to be explored.

One specific industrial innovation that poses a potential risk of injury (collision) to marine mammals is the development of tidal turbine devices. There are several questions which need to be addressed in order to make a more informed assessment of the severity of animal-turbine collision risk. Specifically we need to know more about how regularly marine mammals use such sites, but also at what range they are likely to detect the noises made by tidal turbines. If acoustic deterrent devices are to be used in such situations, over the lifetime of the turbine, then more information will also be required on the responses elicited by the deterrent devices, how these may vary between species and contexts, and how such responses may change over time.

Ship strikes are a significant threat to some whale populations and are a concern for many others. It has been hypothesised that whales at the surface of the sea do not react to approaching ships because there may be an acoustic shadow directly in front of a ship which would conceal its approach. It has been suggested that forward projected aversive sounds could help minimise the risk of ship strikes. Some initial trials of such a device to protect manatees from approaching speedboats have shown some promise. Elsewhere there has been little enthusiasm for using acoustic deterrence to minimise whale – ship interactions, largely because it is unclear that such an approach would elicit the correct response from the animals concerned.

A number of concerns about the use of acoustic deterrent devices are also discussed. Several authors have noted a decrease in the responsiveness of animals to acoustic deterrence over time. This may be due to habituation, to hearing damage, or could represent learned strategies to avoid responding to the signals, or to reduce their effects.

Hearing damage has been widely speculated upon for animals that are frequently exposed to acoustic deterrent signals. It is thought that the cumulative exposure to sound energy (sound exposure level) is the appropriate measure of concern. Concerns over how sound exposure level thresholds might be set are discussed. It is important to know the target species' hearing sensitivity over the full spectrum of audible frequencies, but reliable audiogram data are not available for several key species. Temporary and Permanent Threshold Shifts in hearing are discussed and it is noted that one recent study suggests that porpoises may be most vulnerable to TTS at frequencies well below their peak hearing sensitivity.

The fact that ADDs deter animals from areas that they would otherwise use, suggests that habitat exclusion may also be a concern, though so far the exact extent of habitat exclusion has not been well defined for any species, nor are the impacts on individual foraging success understood, still less the population level consequences.

Throughout the report knowledge gaps are identified and these are summarised at the end of the report. From these knowledge gaps, ten general research recommendations are made; most of these are focused on concerns around aquaculture.

- Work is required to improve transparency and adequacy of data that are collected for statutory and other purposes in relation to fish farms, acoustic deterrence, seal depredation and shooting.
- The efficacy of fish farm management and husbandry techniques in minimising seal depredation should be investigated by comparing depredation rates between and among sites, taking into consideration differences in environmental conditions, proximity to seal haul out sites and site specific differences in cage structure and husbandry methods.
- Interactions between seals and fish farms need to be further explored to ensure that any lethal management is as efficient and effective as possible in reducing predation.
- The extent to which different types of ADD are effective in minimising both seal damage and consequent lethal removal needs to be demonstrated clearly.
- The nature, deployment techniques and success or otherwise of anti-predator nets used in other countries should be investigated.
- The risks of hearing damage to marine mammals needs to be investigated by exploring cumulative sound exposure levels for animals frequenting farm sites and potentially by examining hearing in ADD-habituated animals.
- The impacts of ADDs on non-target species (porpoises in particular) need to be explored for the full range of devices used in Scotland.
- Further work is needed to investigate the ecological consequences of habitat restrictions on small cetaceans.
- New management options to limit depredation need to be explored to minimise the need for lethal removals.
- More broadly, for a wider range of applications, research is needed to show how animals move in response to different sound types and how such signals could be used to provide practical and predictable mitigation for a variety of industrial processes in the marine environment.

1 General Introduction

1.1 Project Overview

There is a long history of using sound to keep animals away from human interests (Bomford and O'Brien, 1990), usually to protect those assets from unwelcome attention but sometimes also to protect the animals themselves from harm. For marine mammals, which have acute hearing, spend most of their time below the surface of the water, and which inhabit a medium (water) through which sound propagation is highly efficient, acoustic methods of deterrence represent an attractive means of behavioural manipulation.

Marine acoustic deterrents were initially developed to keep marine mammals away from fishing gear, but have since found use in other sectors of marine industry. They are now widely used in a variety of applications to keep marine mammals away from specific installations or activities where their presence may result in damage to human interests or to the mammals themselves.

The aquaculture industry in particular makes use of high-powered acoustic deterrents to dissuade seals from damaging fish pens, attacking fish through the meshes or making holes through which fish can escape. In Scotland this principally applies to salmon farming, one of rural Scotland’s most important industries.

Much the same principle is also now being applied to wild salmon fisheries, where Acoustic Deterrent Devices (ADDs) have been used in attempts to reduce seal damage to rod and line fisheries and to salmon bag-net fisheries. A different suite of acoustic deterrent devices is also being used in certain long-line and other fisheries to deter cetacean depredations.

Offshore marine engineering projects have increased greatly in past decades; some associated activities, particularly pile driving at offshore construction sites, have the ability to cause severe hearing damage to marine mammals. Acoustic deterrent devices have the potential to exclude animals from areas where they might be at risk of damage.

Smaller and less powerful devices are used to keep some species of small cetacean away from static net fisheries (gillnets) where there is a danger of them becoming entangled. These devices have been shown to reduce the unintentional entanglement of small cetaceans like harbour porpoises by more than 90% in some situations (Dawson *et al*., 2013; Kingston and Northridge, 2011; Kraus *et al*., 1997; Northridge *et al*., 2011).

There is now a wide range of commercially available devices, each generally marketed toward a specific application of the types described above. These devices are known to differ substantially in their acoustic characteristics (frequency and amplitude) as well as practical aspects such as power supply and cost. In many cases, however, the efficacy of specific devices in their respective applications remains largely untested and poorly understood.

Reducing the risk of entanglement in nets, of hearing damage at construction sites, or reducing the chance of being shot at a fish farm site, are all potential benefits to individual animals. The use of acoustic devices in these cases may therefore have conservation or welfare benefits to animal groups or species. However, excluding animals from parts of their natural habitat, as well as potentially causing reductions in hearing sensitivity due to long term exposure to ADD sounds, are costs that need to be balanced against these potential benefits.

A number of studies have investigated the effects of various noises on marine mammals, both behaviourally and physiologically. Conservation and economic benefits have also been addressed in many of the areas described above. This study attempts to provide an overview of this large body of work, and to identify current uncertainties and directions for future research. It is also intended to provide a comprehensive assessment of the capabilities of current and developing non-lethal measures which are used to alter the behaviour of marine mammals in different scenarios with the purpose of answering several management oriented questions.

The main objective of this research project is to review the literature and data on current and developing acoustic deterrent devices which are used for deterring marine mammals in different scenarios, with the purpose of answering questions regarding design, effectiveness, best practice and impacts of these devices on marine mammals in Scotland. More specifically, through this review we also address the following management related questions:

- What types of ADD are currently employed, or are in development, which are used to deter marine mammals in different scenarios, for example at fish farms, netting stations, rivers, and in/around areas of development (e.g., oil and gas, renewables)?
- Are these devices fit for purpose and appropriate for deterring marine mammals in a range of scenarios and often at a very local scale? For example, are some commercial devices more applicable for deterring seals in more constrained salmon rivers, while others are more appropriate for deployment in coastal or offshore waters? Will some devices be more appropriate for long-term deployment as opposed to short-term?
- Are certain devices more appropriate to a particular species? Are there different requirements for seals, toothed cetaceans, and baleen whales (dependent on the purpose of deterrence)?
- What is the relative effectiveness of existing ADDs on marine mammals (considering seals and cetaceans separately)? For example, at what range do

they exclude mammals? Do certain devices exclude seals and not cetaceans, and vice versa?

- Are there efficiency improvements which could be made by best practice in using existing ADDs? For example, targeted activation of devices when marine mammals are located in the vicinity of the devices (as opposed to continuous use).
- What are the ecological consequences of ADD's in terms of underwater noise? Are some devices more 'noisy' (ecologically disruptive) than others?
- Beyond ADDs, are there any other current or developing technologies for deterring marine mammals? When answering this question, consideration should be given to the reasons for deterrence (e.g., aquaculture, fisheries, mitigation for renewable development).
- Can baseline information be improved which would benefit developing marine industries?

Many of these remain open questions, and we conclude our review by addressing them in turn and in the light of the information reviewed below.

1.2 Acoustic Deterrence

The mechanisms by which aversive sounds or alerting signals achieve their effect have rarely been elucidated. However, there are a number of models that are likely to apply for different species in different circumstances. An important distinction can be drawn between those signals for which animals have a learned association and those for which they do not. Many responses to sounds can be understood in terms of predator-prey behaviour; most marine mammals are on one hand predators that will use acoustics cues to locate prey and on the other potential prey themselves for which acoustic cues may be important for detecting the presence of predators. Interactions with conspecific competitors and other competitor species may also be harmful, for example harbour porpoises (*Phocoena phocoena*) are often harassed and even killed by bottlenose dolphins (*Tursiops truncatus*) (Ross and Wilson, 1996) and acoustic cues will also have relevance to these scenarios.

Acoustic signals which have no particular relevance may induce avoidance in neophobic species, or those that tend to show fear of novel stimuli. Dawson *et al*. (2013) suggested that acoustic devices will be most effective in reducing bycatch of neophobic species, such as porpoises, which are well known for being extremely timid. The degree of neophobia an animal exhibits probably reflects its anti-predatory behaviour, being an important component of strategies that involve simple avoidance of potential predators. The behavioural response may be mediated by other factors such as the likelihood of predators being locally present and the proximity of refuges. By contrast, for opportunistic foragers, novel signals may elicit curiosity and attraction. This might be the case for seals, especially in situations where predation risk is perceived as being low. Marine mammals, with the exception of killer whales (*Orcinus orca*), are both predators and prey so we might expect their responses to novel sounds to be complex and sometimes contradictory.

In humans, some signal characteristics seem to be inherently unpleasant due to the way they interact with the auditory system. For example, research summarised by Zwicker and Fastl (2004) showed that acoustical properties such as loudness, fluctuation strength and sharpness correlated well with a sound's perceived 'annoyance'. In addition, consonant sounds, which involve the combination of tones whose frequency ratios are small integers, are perceived as being more pleasant than dissonant sounds. However, experiments indicate these characteristics which make sounds pleasant or unpleasant to humans may not transfer to other primates (McDermott and Hauser, 2004).

Götz (2008) and Götz and Janik (2010) attempted to measure whether signals designed to be aversive based on the characteristics summarised by Zwicker and Fastl (2004), termed Psycho-Physical Model Sounds (PPM), were in fact more aversive to seals than signals from existing ADDs or control signals (such as white noise). Their results were equivocal. In captive studies, seals were provided with motivation by a feeding station. Initially, animals avoided the feeding station on first exposure to all sound types, but in subsequent trials then largely ignored all sound playbacks equally. However, when playbacks were made at real haulout sites, where motivation for animals to remain in the area was lower, observation of the distances at which seals surfaced from the sound source indicated a stronger avoidance for PPM signals. Thus, this work suggests that a psycho-physical model might be used to generate sounds that are more aversive, but also indicates that this degree of aversion is mediated by motivational state and may be insufficient to overcome a feeding motivation.

A sound received at a very high level becomes unpleasant as it begins to exceed the dynamic range of the auditory system eventually causing physical discomfort and then pain. Some ADD manufacturers claim that their devices operate in this manner; they are simply too powerful for animals to be able to approach. Götz (2008) has stressed that devices that work in this way are inherently flawed because the sound levels that are necessary to cause discomfort are likely to lead to permanent threshold shifts after moderate exposure durations, while those that induce pain are operating very close to levels that would cause immediate damage.

Acoustic signals are likely to induce avoidance if they are similar to signals for which the subject has made a negative association. The most obvious example will be noises associated with predators or predation. Such learned associations will become stronger if they are repeatedly reinforced, if for example predators are often encountered, and weaken if animals are repeatedly exposed to signals without reinforcement. This waning in responsiveness with repeated unreinforced exposure is termed habituation. In a review of the use of aversive sound to exclude terrestrial pests, Bomford and O'Brien (1990) concluded that biologically significant signals showed most promise, especially if measures were taken to minimise habituation. In terrestrial species alarm signals are often used, but such calls are not known to be commonly used by marine mammals. A concern with the routine use of predator sounds is that it could interfere with the target animal's ability to respond appropriately to genuine predators – they may, for example, become habituated to predator calls and thus not show avoidance of actual predators. Effects on the predatory species themselves should also be considered before the widespread use of such signals.

Other than its acoustic characteristics, the behavioural response to an acoustic signal is known to depend upon a variety of psychophysical parameters relating to the way the sound is perceived, such as the animal's motivational state and basic learning processes which may have already occurred (e.g. habituation or conditioning)(Götz and Janik, 2010). The potential for using stimuli that elicit a startle response as aversive signals was investigated by Götz (2008), as part of a Scottish Government funded project to investigate more effective and discriminatory acoustic deterrent devices for use as salmon farms. The acoustic startle response is one of a suite of autonomous reflexes hypothesised to mediate a rapid flight response. To be capable of doing this a sound must be sufficiently loud (received at 92 dB above sensation level in humans) and also have a fast rise time during onset. This principle was studied in further detail by Götz and Janik (2011) who conducted captive trials with seven grey seals (*Halichoerus grypus*). By broadcasting high-intensity bursts of sound with very short rise time of 5 ms (the time between the signal onset and maximum amplitude) they found that five of the test subjects exhibited a startle response, while two did not. Rather than the response diminishing over time, as is often observed as animals habituate, they found increasing responses from all of the startled animals, indicating sensitisation, or increased responsiveness to the signal. After six trials the sensitisation effect was marked, with retrieval of the food source prevented and a flight response reliably induced. They also investigated the potential for behavioural conditioning of seals (as discussed by Pryor in Mate and Harvey, 1986). By pairing the startle stimulus with an originally neutral 'conditioned stimulus', played 2 seconds prior to the startle signal, they were able to show that the pre-sound could be used to induce a conditioned response (avoidance behaviour). Results from farm trials are expected soon and commercial trials are underway.

1.3 History of Development

The idea of using acoustic devices to deter marine mammals has existed for many decades, with one of the earliest reported attempts by Fish and Vania (1971) who used broadcasts of killer whale calls in attempts to keep beluga whales (*Delphinapterus leucas*) away from salmon nets. Since this time, several research groups and private companies have sought to utilise aversive underwater sounds for a variety of applications, with mixed results.

Anderson and Hawkins (1978) authored the first publication describing attempts to deter pinnipeds acoustically. During a feasibility trial they broadcast pure tones and killer whale calls at salmon netting stations at the mouth of the river Tweed. However, they were unable to achieve any consistently useful deterrent effects. Elsewhere, a programme to develop a high powered acoustic deterrent to reduce pinniped depredation was undertaken in the 1980s by Bruce Mate and colleagues of Oregon State University. Their early reports (Mate *et al*., 1986b; Mate and Harvey, 1986) describe the development and testing of a device with peak frequencies of 12 and 17 kHz, around the peak of seal hearing sensitivity. They developed a device called the ‘sealchaser’, which had a source level of 188 dB (re 1 µPa RMS) and an upsweeping frequency from 11.5-15 kHz (Mate and Harvey, 1986). A separate system, developed by Coastline Environmental Systems in Vancouver, Canada was described by an article in ‘Canadian Aquaculture’ in 1988 (Smith, 1994). This device used recorded and synthesised tones, including killer whale vocalisations. Shortly after this, two similar acoustic deterrents were first tested in Tasmania (reported by Pemberton and Shaughnessy, 1993), one with peak energy at 10 kHz, the other at 27 kHz. The report of a workshop which focused on the use of acoustics to deter marine mammals (Reeves *et al.*, 1996) stated that recent advances in underwater technology had allowed the development of very high-amplitude devices (such as a device from Airmar), and which appeared to have overcome past problems of declining effectiveness.

Acoustic devices were first introduced to the Scottish salmon aquaculture industry in the mid-1980s, after trials made by the Department of Agriculture and Fisheries for Scotland (DAFS) and shortly afterwards an Orcadian company began to market a similar device. Since then, several different companies have produced models of acoustic deterrent in attempts to control pinniped depredation.

Some early work attempted to scare seals using the vocalisations of mammal-eating killer whales. Attempts were generally unsuccessful in this context and these devices no longer appear to be in use. The use of killer whale vocalisations is discussed in detail below (section 4.4.1).

More recently, the work of Thomas Götz and Vincent Janik at St Andrews University has pursued an alternative, more discriminatory, approach to the problem based on the use of the acoustic startle reflex. While earlier devices had aimed to maximise acoustic output within pinnipeds’ most sensitive frequency band (around 15 kHz), Götz and Janik aimed to reduce unintended impacts on odontocetes by producing sound at lower frequencies, where odontocete hearing is less sensitive than that of pinnipeds. This device emits high intensity sound (180 dB re 1 µPa peak to peak) with very short rise time and a peak frequency of 950 Hz (much lower than other devices)(Götz, 2008). The device was tested at a fish-farm site in Scotland by Götz (2008) who found that seals were excluded from within 50m of the device and that sighting rate was reduced up to 250m. In contrast to these results, the behaviour of harbour porpoises in the vicinity of the farm appeared to be unaffected. The concept of their device and the investigations they have conducted are discussed throughout this review where appropriate.

The concept of using acoustic deterrence to minimise cetacean entanglement in fishing gear was pioneered by Jon Lien, working in Newfoundland, during the 1980s. Lien and colleagues, after several prototype trials, developed a portable, low power acoustic device (4 kHz fundamental frequency, with a source level of 135 dB re 1 µPa @ 1m) which was successful in reducing whale entanglements (Lien *et al*., 1992). In the early 1990s, fishermen in the US Gulf of Maine persuaded Jon Lien to deploy some of his 'pingers' in a demersal gillnet fishery, with the aim of reducing porpoise bycatch. Initial trials seemed at least partially successful, but were dogged by poor experimental design. Subsequently a consortium of New England research scientists and fishermen working with the Dukane corporation, used a modified 'pinger' originally designed as an underwater location aid, to demonstrate the effectiveness of such devices in minimising the bycatch of porpoises (Kraus, 1999; Kraus *et al*., 1997). Porpoise bycatch rates were reduced by more than 90%, and numerous other experiments with these and other low powered devices have demonstrated their effectiveness in minimising the bycatch of porpoises and a few other small cetacean species (Dawson *et al*., 2013).

Although at one stage there was a marked divergence of marketed devices into high powered seal deterrents, primarily used in the Aquaculture industry, on the one hand and lower powered 'pingers' primarily used to minimise porpoise bycatch in gillnets, several companies have subsequently produced devices that bridge the 'gap' between these two archetypes. Quieter seal scarers and louder cetacean deterrent devices have entered the market. So although it has been suggested that acoustic deterrent devices can be grouped into low amplitude and high amplitude devices (sometimes termed acoustic deterrent devices (ADDs) and acoustic harassment devices (AHDs) respectively – see Reeves *et al*. (2001)), we do not use this distinction as it may imply an unwarranted attribution of intent in the use of higher amplitude devices. In general, all such devices are intended to deter animals and it is the mechanism by which they evoke an aversive response which is important. This will depend on many factors of which source level is just one. The distinction is considered unhelpful given the broad range of source levels employed by the different acoustic devices which has blurred a previously clear cut distinction between two groups of device. Here we refer to all devices as ADDs, while also including the widely used term 'pinger' to describe the subset of small alkaline or lithium-ion cell devices predominantly used to reduce small cetacean bycatch in gillnet fisheries.

1.4 Current Uses

A large number of acoustic devices are now available for commercial use, most of which are marketed toward the mitigation of interactions with a specific species or industrial practice (e.g. gillnetting, aquaculture, etc.). In the majority of cases the acoustic characteristics of these devices are poorly described, if at all. Table 1 lists all known devices, past and present, and shows the usage and species for which the device was designed, or has subsequently been used. This table is adapted and expanded from Dawson *et al*. (2013), and more details on some devices are available there, including acoustic characteristics where available.

Table 1 Acoustic devices, their manufacturers and intended use/species. Adapted and expanded from Dawson *et al*. (2013).

Manufacturer	**Device**	**Use/Species**
Mustad	Orcasaver	Longline depredation – *Orcinus orca*[1]
Ixtrawl	Cetasaver	Pair trawl bycatch – *Delphinus delphis* (Morizur *et al*., 2008)
STM	DDD	Set net bycatch – Odontoceti (Northridge *et al*., 2011) Longline depredation – Odontoceti (Nishida and McPherson, 2011)
	DDD-03H	Pair trawl bycatch – Delphinidae (Northridge *et al*., 2011)
	DiD	Longline depredation – Odontoceti (Nishida and McPherson, 2011)
Fishtek	Banana Pinger	Set net bycatch - *Phocoena phocoena*[2]
Dukane	Netmark	Set net bycatch - *Phocoena phocoena* (e.g. Kraus *et al*., 1997) plus various small cetacean species (e.g. Pro Delphinus, 2010)
Aquatec	Aquamark models: 100,200,210,300, and 848	Set net bycatch - *Phocoena phocoena*, *Stenella* (e.g. Sea Fish Industry Authority, 2005) and gill net depredation - *Tursiops truncatus* (e.g. Brotons *et al*., 2008)
Airmar Technology Corp.	Gillnet Pinger 10 kHz	Set net bycatch - *Phocoena phocoena* (e.g. Sea Fish Industry Authority, 2005)
	Gillnet Pinger 70 kHz	Gillnets & Handlines – *Pontoporia blainvillei* (Bordino *et al*., 2004)
Fumunda Marine/Future Oceans	3 kHz Whale Pinger	Fishing gear entanglement – Baleen whales[3]
	10 kHz Porpoise Pinger	Set net bycatch - *Phocoena phocoena* (e.g. Sea Fish Industry Authority, 2005) *Tursiops truncatus*
	70 kHz Dolphin Pinger	Set net depredation – *Tursiops truncatus* (Read and Waples, 2010)
Marexi Marine Technology	Pinger V02	Set net bycatch - *Phocoena phocoena* (e.g. Morizur *et al*., 2009)

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[1] http://mustad-autoline.com/products/orcas_saver/

[2] http://www.fishtekmarine.com/acousticPinger.php

[3] http://www.futureoceans.com/products/future-oceans-3-khz-whale-pinger

	Orca-Stop	*Orcinus orca*[4]
Seamaster Fishing Supplies	Seamaster Fish Protector	Aquaculture, gill nets, purse seine, squid & fish trawl industries – *Tursiops truncatus, Delphinus delphis*[5]
Ingenieria y Ciencia Ambiental (ICA)		Aquaculture interactions – *Tursiops truncatus* (López and Mariño, 2011)
SaveWave	SaveWave ADD	Gill net depredation – *Tursiops truncatus* (Waples *et al*., 2013)
Jon Lien *et al*.		Static gear entanglement – *Megaptera novaeangliae* and later set net bycatch – *Phocoena phocoena* (e.g. Gearin *et al*., 1996)
Loughborough University	PICE	Set net bycatch – *Phocoena phocoena* (e.g. Culik *et al*., 2001)
Ferranti-Thomson	Mk2 Seal Scrammer and '4x – 24V'	Aquaculture depredation – Phocidae (Gordon and Northridge, 2002)
Ace Aquatec	Silent Scrammer and Universal Scrammer 3	Aquaculture depredation – Phocidae [6]
	Marine Mammal Deterrent (MMD)	Mitigation of pile-driving and natural disasters[7]
Terecos Limited	DSMS-4	Aquaculture depredation – Phocidae (Gordon and Northridge, 2002)
Airmar	dB Plus II	Aquaculture depredation – Phocidae & Otariidae (e.g. Vilata *et al*., 2010)
Lofitech	Fishguard/Seal Scarer/Universal Scarer	Aquaculture depredation – Phocidae[8] Capture fisheries - Odontoceti[9]
Poseidon	T88	Aquaculture depredation – Otariidae (Stewardson and Cawthorn, 2004)
Kemers Maskin AB	MkII	Capture fisheries depredation – Otariidae (Stewardson and Cawthorn, 2004)
Northern Gulf Natural Resource Management (NGNRM)	Dugong/Dolphin Acoustic Alarm	Set net bycatch – *Dugong dugon* (McPherson, 2011)
Edmund Gerstein *et al*.	Parametric Alarm	Vessel collision - *Trichechus manatus* (Gerstein *et al*., 2008)

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[4] http://www.marexi.com/PDF/marexi_english.pdf
[5] http://www.commercial-fishing.net/product/seamaster-australia-fish-protector/
[6] http://www.aceaquatec.com/scarer.htm
[7] http://www.aceaquatec.com/scareroffshoretest.htm
[8] http://www.lofitech.no/seal.htm
[9] http://www.lofitech.no/universal.htm

2 Seals and Salmon Farms

2.1 Introduction

The most common application for marine acoustic deterrent devices in Scotland is the aquaculture industry. Furthermore, much of the relevant research on the effects of acoustic deterrent devices has been conducted in the context of marine aquaculture. This is a reflection of the economic losses sustained by aquaculture as a result of seal depredation of caged fish. Much of this report is therefore focused on acoustic deterrents used on fish farms, and other methods that might be useful in minimising seal damage.

2.1.1 Size and Nature of the Problem

Salmon aquaculture is one of Scotland's most important rural industries, producing more than 158,000 tonnes of salmon at 254 sites in 2011, with a farm gate value of more than £400 million. The industry directly employed 1,064 people in 2010, with a further 850 in directly related onshore jobs and an estimated 4,500 jobs in downstream processing (Marine Scotland Science, 2011). The industry now accounts for about half of all Scottish food exports by value. Scotland's National Marine Plan pre-consultation draft (2011) aims for sustainable production of marine finfish to increase to 210,000 tonnes by 2020. Predator control is highlighted as a potential environmental impact within this plan, which recognises a need for high standards of environmental protection at every stage of fish farm planning, operation and regulation. The Scottish Government's renewed strategic framework for Scottish aquaculture, 'A Fresh Start' (Marine Scotland, 2009), also highlights the need for the growth of the aquaculture industry to be sustainable, within the carrying capacity of the environment and balanced against the needs of others.

Hawkins (1985) was the first to review the problem of seal depredation in Scotland, and found predation by seals at 41 of 63 farms (65%). This was shortly followed by Ross (1988) who found predation at 92 of 96 farms (96%). Work in this area has since been intermittent in Scotland. The Fisheries Research Service (2001) found that, of the 195 sites that responded to a questionnaire, 81% reported predation from seals (both grey and harbour), and Northridge *et al.* (2010) reported seal predation at 61 of 83 sites (73%). The problem has also been recognised in other parts of the world, probably existing wherever there is overlap between the aquaculture industry and pinniped populations. Literature discussing pinniped depredation, and at fish farms more generally, relates to industries in Australia/Tasmania (e.g. Pemberton and Shaughnessy, 1993), British Columbia (e.g. Olesiuk *et al*., 2010), Maine (Anon., 1996), Bay of Fundy (Jacobs and Terhune, 2002), New Zealand (Kemper *et al*., 2003), Turkish Aegean (Guclusoy and Savas, 2003) and in Chile (Sepulveda and Oliva, 2005). This range of studies shows that the problem is of global concern to the aquaculture industry, and reveals that a certain amount of disparate research effort has been invested in attempts to find and develop potential solutions.

The total financial impact of seal depredation is not straight-forward to estimate and consequently few reliable figures are available. Even a direct count of reported mortality may not provide a true estimate of the real economic impact. Some of the depredated fish may have been sickly and less likely to survive due to a predatory preference for ‘easy targets’ while, conversely, the effects of seal depredation may extend beyond direct loss of fish by impacting on fish growth and feeding rate (see below).

Hawkins (1985) found that while most sites experienced relatively low level predation (<£1000 per annum at 20 of 41 sites), 5 sites reported losses of more than £10,000, and one site estimated loss at over £100,000. Ross (1988) found slightly higher figures; the annual loss across 45 sites where interviews were conducted averaged £31,000 per site, with the highest reported loss per site at £280,000 per annum. Northridge *et al*. (2013) examined industry data from 87 sites over a 129 month period and found that almost 1.4 million fish were reported lost to seals. If these fish had made it to harvest size of 5kg with a market value of £3.5 per kg; they would have been worth almost £25 million, a loss of roughly £26,000 per site per annum. The highest reported monthly predation loss was 70,000 fish - assumed to be associated with a major containment breach or other catastrophic incident.

KG No.	**Knowledge Gap**
1	The extent and monetary cost of seal depredation at Scottish fish farms is unknown.

In New Zealand, one salmon farming company estimated losses of NZ $3500 - 5700 per day (~£1500 - 2500) during August 1997 (Stewardson and Cawthorn, 2004). Rueggeberg and Booth (1989) estimated that predation by seals and sea lions in British Columbia accounted for the loss of around 1% of total production. In the Pacific Northwest the problem was estimated to be as much as 10% of production cost (Moore and Wieting, 1999). The annual value of depredated fish in the Tasmanian Atlantic salmon aquaculture industry was estimated at AUS $11.5 million in 2000 (Anon., 2002a). Losses of salmon from farm sites in Maine, USA, attributed to seals between 2001 and 2003, ranged from 0 to 27,629 individual fish per site (Nelson *et al.*, 2006), and in Los Lagos, Chile, Sepulveda and Oliva (2005) found that 90% of salmon farms had reported attacks by South American sea lions (*Otaria flavescens*). Clearly then, the problem can be considered as financially significant to the industry worldwide.

2.1.2 Types of Damage

2.1.2.1 Equipment Damage

In general, damage by seals to fish farm equipment involves holes being made in the main, or growth, net. The base of the net is usually considered most vulnerable to seal attack. However, Thistle Environmental Partnership (2010) found that holes are found in all parts of nets, including side panels, and are more common on the base and in areas of increased wear such as near the water-line.

Damage to netting attributed to predators was the second largest cause of escapes from Scottish farms over the period from 2009 to 2012 (Northridge *et al*., 2013). While this form of damage is by no means insignificant – facilitating the release of at least 21,000 farmed salmon in 2011 (Northridge *et al*., 2013) – it is clear from previous reports that a far greater number of fish are bitten through the meshes of nets without causing escapes. In other parts of the world, particularly where Otariid species are the main cause of depredation, damage to nets may be a more serious concern. For example, Pemberton and Shaughnessy (1993) observed 150 holes which had been created in one net over a single night at a Tasmanian farm. These authors compared the different materials used to construct nets and found that two types (e.g. 5mm diameter braided polyethylene and steel mesh), were not damaged during the course of the study. We understand that certain new types of netting material have been deployed and tested in Scotland, including high modulus polyethylene (HMPE) – such as Dyneema ^{TM}, PVC coatings (such as Aquagrid^{TM}) and steel or copper cores, and that many of these new materials are marketed as having ‘predator resistant’ properties. While some of the trials have been reported on manufacturers and fish farm company websites, no detailed or independent assessment of their efficacy has been published.

KG No.	Knowledge Gap
2	What effect do different netting materials have upon seal depredation of salmon?

2.1.2.2 Physical Damage to Fish

The most obvious form of damage caused by seals is the direct injury of fish which can take several different forms. Northridge *et al*. (2013) defined four separate categories of damage inflicted by the predatory behaviour of seals at fish farms. These could be summarised as:

1) Heads – only the head of the salmon is left, where the seal has chewed and eaten the rest of the carcass.
2) Halves – half of the fish has been bitten off, leaving the anterior half intact. At one site at least these fish appeared to have been ‘sucked’, tail-first, through the net.
3) Gashes – multiple rake-marks or gashes with irregular spacing which does not seem to be consistent with being caused by a seal’s teeth.
4) Abdominal bite – the most readily recognisable form of damage, typically found on larger fish (>1.5kg), a pair of parallel teeth marks on either side of the abdomen, just behind the gills.

It is likely that other categories of damage could be distinguished.

By categorising damage types in this way it is possible to compare and contrast their characteristics, and learn more about the mechanism of attack. For example, category 4 damage appeared to always be inflicted from below the fish, suggesting that these attacks occur through the netting at the base of the net. Category 2 damage however, was, in one instance at least, reported to have occurred through the side netting, with fish being observed by divers still stuck through the mesh. Category 3 damage seems to be caused by the seal's flippers rather than its teeth and could therefore represent a very different predatory strategy.

Different types of damage and different sizes of fish may have different likelihood of being classified and reported as seal or predator damage. Small fish for example tend to decay more quickly than large fish, which could lead to an artificially reduced rate of damage reported among fish early in the cycle. The Code of Good Practice for Scottish Finfish Aquaculture (2010 section 5.3.5.5) states that likely cause of death should be determined by a competent person, and we understand that certain companies provide training in order to meet this criteria, but there is no industry-wide standard for classification of fish mortality (known as 'morts').

KG No.	Knowledge Gap
3	Exactly what has been - and what should be - classified as seal predation mortality?

2.1.2.3 Growth Reduction

In addition to the direct loss of fish due to predation mortality, reduced growth rates due to the presence and aggressive behaviour of seals are believed to further reduce profitability (Schotte and Pemberton, 2002). This relationship is difficult to quantify and although this is a widely held perception within the industry, we are not aware of any studies which have investigated the effect directly. Schotte and Pemberton (2002) point out, however, that Atlantic salmon are thought to 'habituate' to the presence of divers, and the same process may occur if seals could be effectively prevented from causing direct damage to fish (e.g. by anti-predator netting) or at sites where seals are present but do not regularly attack nets. During a trial of the efficacy of ADDs by one of the manufacturers at a Scottish fish-farm site, the 'Specific Feed Rate' was recorded and used as a proxy for growth rate (Ace-Hopkins, 2002a). This parameter was compared with the number of 'seal detections' measured by the trigger devices of the *Ace-Aquatec Silent Scrammer* acoustic deterrent device. The industry report claims that predation by seals significantly reduced the 'Specific Feed Rate' and they hypothesised that this would result in reduced growth rate. One concern with this study is that triggers do not measure seal depredation directly, instead they are triggered when they are agitated by the movement of the fish. Seal depredation can cause fish to panic and knock the triggers, however, farm managers have reported that the triggers can also be activated by other forms of fish movement and indeed by poor weather. It is possible that both of these causes could be correlated with changes in feeding rate. Modern fish farms control and regulate food delivery by monitoring feeding rate. It should therefore be quite straightforward to look for a correlation between food delivery, feeding rate and direct measures of seal presence at cages and depredation using data the industry has already collected.

KG No.	Knowledge Gap
4	How are salmon growth rates affected by seal presence and depredation?

There are also anecdotal reports from the Scottish industry that increased stress levels caused by depredation, or attempted depredation, make fish more susceptible to disease (Northridge *et al*., 2010). Nash *et al*. (2000) refer to outbreaks of Hitra, a bacterial disease, starting in and having greatest impact on pens which were already being attacked by seals. It is known that individual seals sometimes travel between fish-farm sites in Scotland (Northridge *et al*., 2013), and there is therefore a possibility that seals may act as a vector for disease (Ross, 1988). This possibility has not to our knowledge been investigated and the suggestion is speculative only.

KG No.	Knowledge Gap
5	Is there a relationship between seal depredation and disease among farmed salmon?

2.1.2.4 Stress/Welfare Concerns

In addition to the possibility of illness from elevated levels of stress, there are more direct welfare issues in cases where farmed fish are injured but not killed by seals. Farmers clearly have a duty of care to protect their stock and minimise suffering in this situation. The recent licensing system for predator removal in Scotland regulates applicants who have a need to protect the health and welfare of stock. There were 39 applications for licences to shoot seals on the basis of fish welfare concerns in 2011, of which 32 were granted.

Again, to our knowledge this type of damage is unquantified, but the number of fish injured in this way could feasibly be assessed by farm managers or by observations from fish farm video monitors.

KG No.	Knowledge Gap
6	Quantification of welfare concerns – to what extent do seals injure without killing fish?

2.1.3 Mechanism of Attacks

In order to manage seal depredation and design techniques and protocols to reduce it, it is important to understand seal behaviour during depredation events. There is remarkably little literature documenting the methods of seal predation on farmed fish. There is however anecdotal evidence available from fish farmers, some of which have been reported previously. Here we describe some accounts most relevant to the subject of this report.

Tillapaugh (1991) [as described in Ace-Hopkins (2002b)] reported an attack by a harbour seal (*Phoca vitulina*) in Canada as witnessed by a diver, "*The seal circled the netpen until the fish were frightened enough to charge the opposite side of the pen. The seal then dove under the pen and attacked the fish pushing against the* *side of the netpen. This procedure was repeated several times*." Ross (1988) also described seals 'charging' at the net, causing fish to panic and the seal was then able to grasp the fish inside a fold of net.

Ace-Hopkins (2002b) described harbour seal attacks, as witnessed by farm workers, in greater detail, "*Common seals rarely damage the growing net but grab a fish between their front paws, bite the abdomen of the fish and suck the guts through the mesh*" and, "*When nets are loosely tensioned farm workers have also reported that common seals can manipulate the growing net into a pocket directly, so entrapping a fish that swam too close*". There is further evidence to suggest seals may take advantage of pockets of slack by manipulating netting. Iwama *et al*. (1997) described harbour seals, again in Canada, creating a pocket in the netting and thus entrapping a fish.

On the attack methods of grey seals, Ace-Hopkins (2002b) described two further methods of attack; "*Apparently one grey seal was able to "climb" the 3 feet to the handrail and squeeze between the two nets and thus swim with the fish. No one witnessed his entry but did witness his exit (on three occasions). The animal was seen to swim at speed to the exit point, use his impetus to leap from the water, rotate and arch its back in the manner of a human high jumper (the Frisbee flop* [sic.]*) and landing in the sea in one fluid movement.*" And, "*In strong tides the growing nets become distorted and the fish inevitably swim closer to the nets than they would otherwise do. The grey seal hooks itself onto the upstream side of the net and waits for a salmon to come too close. When the seal judges the fish is within range he increases his drag by letting go with his back flippers (becoming more upright) and using this impetus coupled with his strength to make the growing net into a pocket to entrap the fish.*"

Where predator nets (a secondary net positioned outside of the main net) are used and the gap between the two nets is insufficient, Iwama *et al*. (1997) stated that seals can manipulate both nets simultaneously. A video available online[10] shows a sea lion at an unknown location pushing an outer anti-predator net in order to reach dead fish in the bottom of the main net.

Iwama *et al*. (1997) also suggested that harbour seals looked for small openings in anti-predator net systems where these were being used. This mechanism has been observed by previous work in Scotland (Northridge *et al*., 2013) where footage was captured of grey seals in between the growth net and the anti-predator net. In this way the seal only needs to manipulate one layer of netting in order to grasp the fish, but clearly there is an increased risk of the seal becoming entrapped between the two layers of netting.

Anecdotal evidence from Schotte and Pemberton (2002) described several methods of attack employed by fur seals, including: corkscrewing through anti-predator netting

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[10] www.youtube.com/watch?v=ILlqTNrdk5c (last accessed May 2013)

side panels, pushing the base of anti-predator netting upward into the growth net and gaining access between growth and anti-predator netting at the surface. Predation here was thought to be more pronounced at times of high tidal flow, and fur seals were thought to seek the easiest opportunity to access fish (which may be the next pen, or the next farm site). These behaviours seem to broadly correspond with those reported from phocid seals elsewhere.

In some locations at least, pinniped depredation is known to involve groups of animals. Pemberton and Shaughnessy (1993), for example, recorded 12 attacks (of 106 in total) where more than five fur seals were recorded. Tillapaugh *et al*. (1993) also observed predators working in groups. In other locations, however, this appears to be uncommon; Northridge *et al*. (2010) found that single 'rogue' animals were reported to be the cause of the majority of predation (61 of 83 sites responding to a questionnaire), and Guclusoy and Savas (2003) reported that in 38 of 40 monk seal (*Monachus monachus*) attacks recorded at fish farms in the Turkish Aegean only a single animal was involved.

KG No.	**Knowledge Gap**
7	What specific mechanisms do pinnipeds use to damage fish within nets?

2.1.4 Potential Solutions Overview

Several research groups have considered potential solutions to the issue of pinniped depredation on marine aquaculture sites worldwide. In the main, their publications have taken the form of review articles, often written for the audience of their respective regulatory body. Specific points of interest from these reviews will be presented in more detail at relevant points in this report; here we provide a brief overview of each of these reviews to illustrate the extent of previous work in this area. We have included research relating to species not found in Scotland because to exclude this work would be to reduce the available information significantly, and in many cases the findings are directly comparable with the Scottish situation.

Ross (1988) discussed various methods for predation control in Scotland. The main mitigation techniques considered were the use of anti-predator nets, ADDs and shooting, reflecting industry practice at the time. The negative impact of anti-predator nets, as perceived by the industry, was found to vary significantly between locations. Fouling, reduction of water flow and entanglement of predators were the main problems cited. Entanglement and drowning of animals was considered unacceptable at some sites, but at others it was considered justifiable or even desirable.

Arnold (1992) reported to Greenpeace on attempts to improve the predator exclusion measures to protect aquaculture sites in Shetland. The author discussed the use of various deterrence and exclusion methods including anti-predator netting, lethal removal and acoustic deterrents, but the emphasis of the report is on improved techniques for weighting and net tensioning systems, particularly the benefits of the use of 'sinker tubes' which were relatively new to the industry at the time. The continued development of these to improve predator exclusion, along with other net tensioning methods, was considered to merit serious investigation.

Pemberton and Shaughnessy (1993) reviewed and assessed the methods of deterrence used for Australian fur seals (*Arctocephalus pusillus doriferus*) in Tasmania, including ADDs, lethal removal, pursuit with boats, floodlights activated to scare seals and emetics. The authors concluded that physical exclusion was the ‘best’ solution and that shooting was ineffective.

Smith (1994) provided a useful literature review for the Canadian Department of Fisheries and Oceans, summarising much of the very early work, including that on acoustic deterrence. He noted agreement among several authors that current acoustic deterrents were expensive and often ineffective. He recommended an emphasis on the prevention of predation and the use of properly designed and maintained anti-predator nets was seen as the most effective way of doing this. The use of emetics (discussed further in section 2.3.3) was described as worthy of further research having shown some effectiveness in limited trials. Harassment techniques, such as pursuit of problem animals, and the use of lights, explosives and warning shots were not found to have lasting effectiveness.

The report of the Gulf of Maine Aquaculture-Pinniped Interactions Taskforce (NMFS, 1996) described efforts made to mitigate perceived problems with pinniped conflicts in the Maine aquaculture industry. The taskforce was partly established to address recent changes to the US Marine Mammal Protection Act (MMPA) which came into force in 1995 and prohibited the use of lethal force to control predators. The use of explosives (seal bombs and cracker shells) was considered to have some benefit to the industry, when used responsibly. Concerns over the use of acoustic deterrents were the expense (US $10000 - 12000 per system) and the likely effects on non-target species. They were, however, considered to be a useful tool for growers, and authors recommend that they should be available for use. Deployment of predator models and playback of vocalisations (killer whales) were described as having very short-term effects only, but it was suggested that these could be useful in some scenarios. The use of live marine predators (killer whales and sharks) was dismissed as impractical. Aversive conditioning, including shock-collars and emetics administered through dart-injection or food bait, was deemed to be worthy of further study. Translocation of problem individuals was also discussed, but was thought to be prohibited under deterrence regulations, and was not considered further. The use of boats to harass nearby animals was described as potentially useful, as was the presence of humans on the pen-site. The use of dogs on sites was mentioned but not considered to be useful. Anti-predator nets in their different forms (e.g. ‘curtain’ – one sheet of netting surrounding a net without a base, ‘box’ – a box of netting which encloses a growth net and ‘perimeter’ – a large net surrounding the entire site) were found to be of some use, but limited by the technical challenge of achieving adequate weighting and maintaining a useful distance between the predator and growth net. Good husbandry practice in the removal and disposal of fish mortalities was also highlighted as a potentially important factor.

A workshop was held in Seattle, USA, in 1996 to consider the problems and uncertainties surrounding the use of acoustic deterrents in commercial and conservation practices. The proceedings (Reeves *et al*., 1996) included a discussion of the use of ADDs to mitigate salmonid predation by pinnipeds. Consistent aversive effects were only reported at very high sound intensities. It was suggested that resistant individuals might have had impaired hearing and/or have learned avoidance behaviour or habituation.

Iwama *et al.* (1997) reviewed some previous research surrounding the use of ADDs at commercial net-cage salmon farming in British Columbia, Canada, as well as alternative methods of deterrence/exclusion. The authors recommended the prohibition of ADDs because there was so little evidence that they were effective and made several recommendations regarding physical changes to cage systems such as pen shape, mesh size and net flexibility.

Moore and Wieting (1999) reported on a US National Oceanographic and Atmospheric Administration (NOAA) workshop addressing interactions of aquaculture with marine mammals and turtles, including a discussion of acoustic deterrence and the likelihood of habituation. The principle concern of the report was the improvement of industrial practice in response to rapid growth of marine mammal populations. The main areas highlighted were: engineering improvements to cage-design and anti-predator nets, development of more effective acoustic deterrents, relocation of sites offshore, relocation or elimination of ‘rogue’ animals and reduction of local populations through reintroduction of pinniped harvest programs. They made many recommendations for further research including the need for characterisation of marine mammal interactions and behaviour around aquaculture sites and the investigations of new net technologies.

Nash *et al*. (2000) discussed the extent of pinniped depredation at aquaculture sites in the Pacific NW and potential solutions, including relocation of problem animals and the use of ADDs, both of which they dismissed as being valuable as short-term strategies only. The only long-term solution suggested by this report was the relocation of fish-farm complexes away from haulout sites.

An analysis of the predator control techniques used in British Columbia by Jamieson and Olesiuk (2001) described all harassment techniques (explosives, acoustic deterrents, ‘tactile harassment’ and chasing by vessels) to be ineffective in the long-term. Anti-predator netting was described, but no details of efficacy were given. The risk of entanglement and drowning, as described elsewhere, was noted. Bio-fouling of nets was thought to reduce the incidence of predation, possibly due to the net having reduced pliability or by reducing the predator’s view of the fish. Translocation of problem animals was thought to be ineffective because the animals often returned to the capture site. The authors noted that the existing government guidelines discouraging the location of sites closer than 1km to a seal haulout had no scientific basis, and the authors note that harbour seal telemetry data indicated daily foraging movements in the range of 10km.

Würsig and Gailey (2002) reviewed various aspects of marine mammal interactions with shell-fish and fin-fish aquaculture worldwide. They categorise deterrent techniques into six major categories; (i) harassment; (ii) aversive conditioning; (iii) exclusion; (iv) non-lethal removal; (v) lethal removal; and (vi) population control, and provided a short review of each. They concluded that predator interactions need to be considered from the start of an aquaculture site installation so that effective solutions can be factored into the cost of the facility, rather than hoping for quick fixes later on. The methods most likely to provide functional long-term solutions were; exclusion of predators through physical barriers, non-lethal removal of problem individuals and aquaculture facilities being located further from known haulouts.

A 2002 report by the Tasmanian Marine and Marine Industries Council (Anon., 2002a), summarised the anti-predator techniques from aquaculture industries worldwide and provided a comprehensive review of methods employed in Tasmania. Mitigation methods considered were acoustic deterrents (including explosives), capture and relocation of problem individuals, improved exclusion techniques such as anti-predator netting, tactile harassment (rubber bullets and cattle prods), chasing of animals by vessels, taste aversion, electric fencing (to prevent seals climbing across walkways), lethal removal, population control (culling) and the use of a device which emits an electric field to repel sharks (not considered worthy of further investigation). Their discussion of tensioning methods for anti-predator netting suggests that this is an important mitigation technique for Tasmanian farms. Specific methods for tensioning Australian aquaculture nets are described in detail in another review by Schotte and Pemberton (2002) (see section 2.3.1 for more details). Acoustic deterrent devices were characterised as having ‘limited effect’. Airmar devices have been trialled at Australian tuna farms and were reported to have ‘mixed success’, with farmers believing that any apparent effect disappeared after a year, after which a ‘dinner bell’ effect was reported. Capture and relocation was not thought to be an effective long-term strategy due to the cost, risk of disease transmission, and ethical issues associated. The authors of both reviews concluded that no easy or fool-proof method for mitigating interactions was available, stressing the need to more effectively manage inevitable interactions, rather than trying to ‘solve’ the problem.

Petras (2003) reviewed potential deterrence measures for reducing killer whale predation on Steller sea lions (*Eumetopias jubatus*) near the Western Aleutian Islands. The author focused on acoustic deterrents, and discussed both pingers and seal scarers in detail. The use of existing devices in this context was concluded to be speculative at best, and the need for behavioural research was stressed.

Guclusoy and Savas (2003) discussed and compared techniques used for deterring Mediterranean monk seals from predating on gilthead sea bream (*Sparus auratus*) and European sea bass (*Dicentrarchus labrax*) at fish farms in the Turkish Aegean. Farmers tried flashing lights at seals, feeding them with pesticide-injected fish, underwater noise (banging the walkway or tin cans) and both warning and direct gunshots, all of which were reported to be unsuccessful. Anti-predator netting was used at 6 of 25 sites, but all reported difficulties in creating an effective barrier. Seals found gaps in between curtains of netting, or in the case where the net extended to the seabed, they found gaps where insufficient sinkers had been installed on the ground rope. Authors later supervised the adjustment of anti-predator netting, after which no more losses were reported (unfortunately there are no details reported as to the changes effected).

Baird (2004) and Stewardson and Cawthorn (2004) reviewed the use of deterrents including ADDs, Pulsed Power Devices (PPD – which generates an underwater shockwave), predator noises, gunshots, pyrotechnics, taste/scent deterrents, tactile deterrents and vessel chasing against fur seals in New Zealand aquaculture and fisheries. None of the acoustic deterrents reviewed were found to have sustained effectiveness, but further research was recommended into the potential of ADDs and taste deterrents (see section 2.3.3).

Nelson *et al*. (2006) used a modelling approach to analyse the influence of farm siting and ADD use on seal depredation rates at fish farms in Maine, USA, between 2001 and 2003. Siting apparently had a significant effect on depredation rate, with farms further from haulouts being less affected. They found no evidence that ADD use reduced seal depredation.

Robinson *et al*. (2008a) and Robinson *et al*. (2008b) reviewed the practice of fur seal relocation from around Tasmanian fish farms in detail. The methodology appeared to be well developed and frequently used, but despite this the authors concluded that it only provided short-term relief from depredation (see section 2.3.5).

The results of questionnaire surveys of fish farm managers on seal depredation and management at fish farms in Scotland and their apparent relative efficacy, are provided by Quick *et al*. (2002), Quick *et al.* (2004) and, more recently, by Northridge *et al*. (2010) and Northridge *et al*. (2013). Generally, these reports showed that net tensioning was believed to be the key factor in minimising depredation events. Northridge *et al*. (2013) also examined industry data, and found that farm sites located in closer proximity to seal haul out sites did not experience higher seal damage levels.

A report from ‘Hydroacoustics Incorporated’ (De La Croix, 2010) compared several different varieties of acoustic deterrent devices, including explosives, ADDs and ‘pulsed power’ devices. It also provides some consideration of their relative merits, with explosives and ADDs being found to have limited short-term effects only. An impulsive airgun device which the company (HAI inc.) was marketing for use at fish farms was described but this was yet to be tested in a real-world scenario.

The extent of conflicts between aquaculture and marine mammals in the Southern hemisphere is reviewed in Kemper *et al*. (2003), particularly addressing finfish aquaculture in South America, Australia and New Zealand. This article addressed the methods of deterrence used at various aquaculture operations and their varying degrees of success. They summarised other reports on anti-predator methods in the Southern hemisphere, and found no empirical evidence for the efficacy of ADDs. Anti-predator netting was reported to be effective at some locations; however, lethal entanglements were also reported. The characteristics of anti-predator nets which lead to entanglements were: too large a mesh size, unrepaired holes, nets not enclosed at the bottom, loose and baggy nets and inappropriate feeding practices which encouraged marine mammal interactions. At Marlborough Sounds, New Zealand, where anti-predator nets are enclosed at the base and made from stiffened nylon, there had been no recorded entanglements (there was no further detail given of the study).

A review paper by Scordino (2010) reviewed efforts made by the National Marine Fisheries Service (NMFS) West Coast Pinniped Program to reduce salmonid predation by harbour seals and California sea lions in rivers and estuaries. This included a detailed assessment of the large number of techniques trialled: above water and underwater explosives, pulsed power devices, taste aversion, predator models, chasing by vessels, rubber bullets, physical barriers, electric barriers, capture and relocation, population control, lethal removal of problem individuals and acoustic devices including predator noises. The general conclusion was that non-lethal measures have had limited effectiveness. Work at the Ballard Locks, Seattle, over many years had shown that in order to consistently cause aversion it was necessary to inflict physical pain. Otherwise, the only effective solutions had involved the removal of problem animals.

A technical review of the noise associated with marine aquaculture in Canada (Olesiuk *et al*., 2010), included a discussion of acoustic deterrents and explosives/pyrotechnics used to mitigate pinniped depredation. The focus of the report was the likelihood of detrimental effects on target and non-target species. Acoustic deterrent were described as only being effective at deterring naïve seals and the authors suggested that benefits were minimal.

Pinniped interactions with aquaculture, and techniques for managing them, have been addressed by a number of authors in many different locations and contexts as summarised above. None have found evidence that any one method can provide an effective solution. Many suggest that a suite of anti-predator methods will be necessary in most situations, and several emphasise the need for anticipating the likelihood of predator interactions from the early planning stage so that mitigation can be factored into the cost of the facility from the start. The need for improved exclusion techniques, such as anti-predator nets, is one area where further investigation is warranted. These nets have been reported to cause entanglement and drowning of birds and seals at some sites (including many in Scotland), however several authors report that acceptable solutions to these problems were found in some locations (Anon., 2002a; Jamieson and Olesiuk, 2001; Kemper *et al*., 2003). No authors have shown convincing evidence for the long-term efficacy of acoustic deterrents. Many suggest the need for further research into the effects of ADDs on both target and non-target species (see also section 2.2.3). Emetic and conditioned taste aversion techniques have shown promise and have been described as being in need of further research in several reviews (see section 2.3.3).

2.2 Acoustic Deterrent Devices to Prevent Depredation

2.2.1 Types of ADDs in Use and Characteristics

Table 2 summarises the acoustic characteristics of the devices most frequently used in Scottish fish farms, but it should be noted that a variety of devices has existed, many of which have had ephemeral usage. Of these, interview surveys suggest that Airmar, Terecos and Ace Aquatec are most widely used in Scottish aquaculture (Northridge *et al*., 2010). Where possible we have provided both the manufacturer's figures, and independently obtained field measurements that in some cases differ substantially from those stated by the manufacturers, indicating considerable uncertainty about the actual source levels of the devices. All measurements in the following are dB re 1 µPa @ 1m. Amplitude measurements are usually taken as either:

- 'peak to peak' (the amplitude difference between the most positive and the most negative excursions of a signal, over a given time period);
- 'zero to peak', or 'peak' (the amplitude of the greatest excursion from zero over a given time period);
- or Root Mean Squared, or 'RMS' (the square root of the mean of the square of the signal from zero over a given time period).

Unfortunately, this key piece of information for comparing source level measurements is often overlooked, and we have marked these instances below with 'Unknown'.

One of the most commonly used devices is the Airmar dB Plus II and a range of sources levels have been reported for this. The manufacturer's manual provides a source level of 198 dB (RMS) but field measurements have differed widely. Jacobs and Terhune (2002) measured Airmar ADDs in the Bay of Fundy, Canada, and found source levels of only 178-179 dB (peak to peak), while Haller and Lemon (1994) reported higher values at 183 dB (RMS) (and 194 dB RMS when looking at individual pulses). Lepper *et al*. (2004) reported a source level of 192 dB (RMS), while most recently Brandt *et al*. (2012b) estimated the Airmar source level as 190 dB (RMS), with peak pressure level of 206 dB.

The manufacturers of the Lofitech device provide a source level of 189 dB (unknown), but most field measurements have suggested a higher source level. Yurk and Trites (2000) reported maximum SPL as 194 dB (unknown) and Shapiro *et al.* (2009) 193 dB (RMS). Brandt *et al*. (2012b) calculated a source level as 194 dB (RMS) with a peak pressure level of 205 dB and Westerberg *et al.* (1999) measured 191 dB (peak to peak) source level. Measurements by Graham *et al.* (2009) matched the manufacturers' specification of 189 dB (unknown). By contrast, Fjalling *et al.* (2006) measured a Lofitech device as having source level of just 179 dB (RMS).

The Terecos is one of the least powerful devices used routinely at Scottish aquaculture sites. The manufacturers do not provide a reliable source level, however Olesiuk *et al.* (2010) report the source level of a Terecos DSMS-4 to be 185 dB (unknown), whereas Lepper *et al*. (2004) found the same device to have maximum SPL of 179 dB (RMS).

The Ace-Aquatec Universal Scrammer has a source level of 194 dB (unknown) according to the manufacturer, which corresponds well with measurements of 193 dB (RMS) made by Lepper *et al*. (2004).

The large discrepancies in source levels are notable. Some of the lowest values, such as the Airmar source levels reported by Jacobs and Terhune (2002) may result from faulty or incorrectly configured equipment. Other discrepencies probably reflect uncertainties in the way in which measurements are made. For example, for pulsed and intermittent sounds, RMS levels depend critically on the time window over which mean values are calculated. In addition, the frequency ranges over which measurements are made are rarely reported. From the perspective of assessing the possible effects of these devices on auditory systems, sound exposure levels (SELs) and peak pressure levels will usually be the more relevant acoustic measurements, yet these values are rarely if ever presented.

Generally, manufacturers have not provided (nor been required to provide) data that adequately describe the acoustic output of their devices in a manner that would allow an assessment of effects on both target and non-target species to be made. Many organisations, including the OSPAR commission, now recognise that underwater noise is a form of pollution (Gotz *et al*., 2009). From this perspective, the dichotomy between the required levels of monitoring regarding chemical and acoustic pollution is striking.

KG No.	**Knowledge Gap**
8	Exact acoustic output of all devices and an appropriate metric (or suite of metrics) for comparison of different signal types.

To our knowledge, there is a maximum of five devices which are currently employed in Scottish aquaculture. These are summarised in Table 2. One of these, the

Ferranti-Thomson, is no longer produced, but we believe it may still be used by a small number of sites.

Table 2 Acoustic Characteristics of Acoustic Deterrent Devices Used at Scottish Aquaculture Sites

Manufacturer	**Device**	**Source Level (dB)**		**Frequency (kHz)**	**Reference**
		Scientific Literature	**According to Manufacturer**		
Airmar	dB Plus II	192 (RMS)	198 (RMS)	10 (tonal – with harmonics)	Lepper *et al*. (2004)
Lofitech	Universal Scarer	193 (RMS)	189 (Unknown)	14 (tonal – with harmonics)	Shapiro *et al*. (2009)
Ace Aquatec	Universal Scrammer 3	193 (RMS)	194 (Unknown)	10 – 65 (broadband)	Lepper *et al*. (2004)
Terecos	DSMS-4	179 (RMS)	None given	2 – 70 (broadband)	Lepper *et al*. (2004)
Ferranti-Thomson	4X	166 (Unknown)	200 (Unknown)	7 – 95 (broadband)	Terhune *et al*. (2002)

Figures 1 to 4 show the spectral characteristics of Ace-Aquatec, Terecos, Lofitech and Airmar devices (our own unpublished work; Gordon and Northridge, 2002). All devices have high frequency (ultrasonic) components to the sound signal, but only the Lofitech device could be seen to exceed ambient noise levels above 100 kHz. One particular harmonic band from the Lofitech sits at c. 120 kHz, in the same frequency band as the echolocation clicks of the harbour porpoise, raising the potential for masking of echolocation/communication behaviour.

It is worth noting that the of sensitivity of grey and harbour seal hearing reduces dramatically above *ca.* 40 kHz (see audiograms in Gordon and Northridge, 2002), and therefore higher frequency noise created by acoustic deterrents is effectively unnecessary.

One suggested explanation for temporary lack of efficacy from seal scarers has been low source level due to the build-up of marine fouling on the transducer elements (Olesiuk *et al*., 2002). However Northridge *et al*. (2013) found no increase in source level after cleaning very severe fouling from the transducer of a Terecos ADD at a Scottish salmon farm. The dominant fouling organisms in this case were sea squirts (which are largely water), with a relatively juvenile community of calcified organisms such as mussels, scallops and barnacles. Further colonisation of the transducer by these or other hard shelled fouling organisms may have a larger effect on source level.

Voltage drop has also been cited (e.g. Gordon and Northridge, 2002; Olesiuk *et al*., 2002) as one possible cause for occasional inefficacy of devices, but to our knowledge no study has yet demonstrated the output of the three most common devices under reduced voltage. Harris (2011), working with a Lofitech device, reports finding evidence of a 1.5 dB (presumably re 1 µPa, RMS or Peak) decrease in output signal correlating with a voltage drop of 2.6 V (from 12.5 to 9.9 V). This relatively low drop in sound output indicates that this model at least is quite robust to voltage drop. Clearly this relationship between voltage and output level could usefully be explored in other models too.

KG No.	Knowledge Gap
9	Effect of fouling and voltage drop on signal output (under full range of operating conditions).

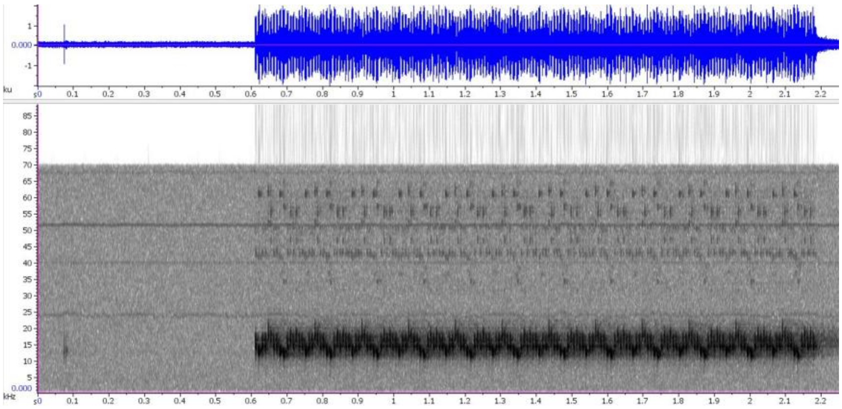

Figure 1 Waveform and Spectrogram of an Ace-Aquatec US3 (70 kHz LP filter)

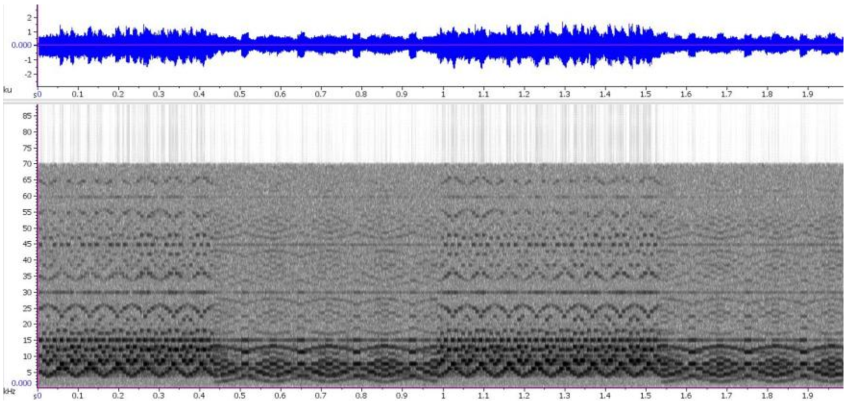

Figure 2 Waveform and Spectrogram of a Terecos ADD – program 4 (70 kHz LP filter)

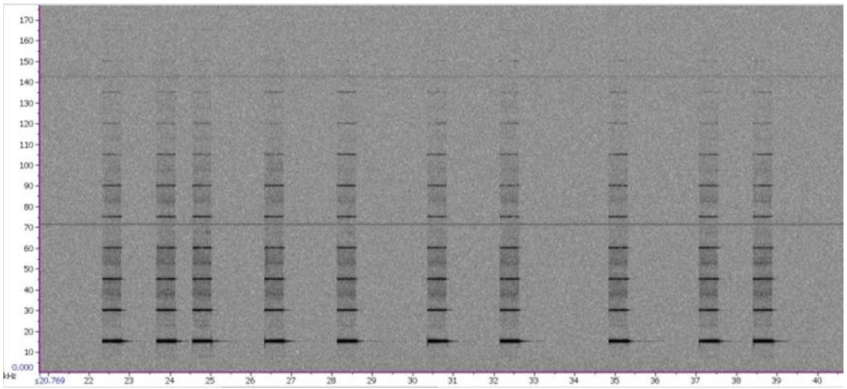

Figure 3 Spectrogram of a Lofitech ADD, showing harmonics up to c. 150 kHz

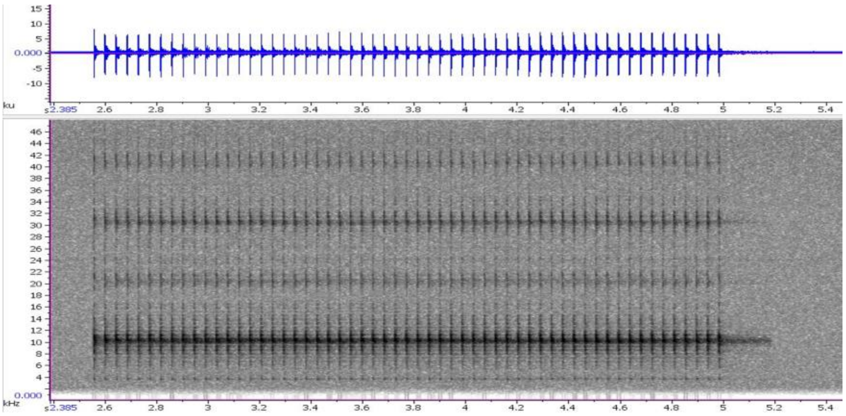

Figure 4 Waveform and Spectrogram of an Airmar dB Plus II (1 kHz HP filter)

N.B. Recordings made with PAMGUARD software, using B&K 8103 hydrophone (flat response up to 125 kHz). Analysis through Raven Pro 1.4 (Cornell Lab of Ornithology) with 2048 point FFT and 2000 sample Hamming window. Axes vary between figures.

2.2.1.1 Duty Cycles

The duty cycles of the three main devices employed in Scotland are documented by Lepper *et al*. (2004), who looked in detail at the acoustic properties of the Airmar, Ace-Aquatec and Terecos devices. They stated that:

"The Airmar system has a 1.4 ms tonal burst with 40 ms spacing. The sequence is repeated with a 50% duty cycle allowing an approximate 2s quiet period." This device has the ability to operate in a 'low-power mode', where the duty cycle is reduced from 2.5s ON - 2s OFF, to 2.5s ON - 6.5s OFF (Airmar Owner's Manual). The manufacturer states that the device should not be left in this mode for long periods, as it will '*result in less than optimal protection from predators*'.

"The Ace-Aquatec has a randomised sequence with a 50% duty cycle for a 5 s period. The relative length of pulses uniformly shortens from 14 ms to 3.3 ms followed by a shift in frequency of the tonal components and their equivalent distribution to each other."

"The Terecos has four different programs. Program 1 is a sequence of repetitive five segment (16 ms duration) continuous tonal blocks forming an up and down frequency sweep. Program 2 was a randomly timed sequence of continuous and time variant multi-component tonal blocks. Program 3 consists of sequences (Seq.2) of eight segment (8 ms duration) continuous tonal blocks forming an up and down frequency sweep combined with variable continuous multi-component tonal blocks. Program 4 has a randomly timed combined sequence of Seq.1, Seq.2 tonal blocks, continuous multi-component tonal blocks and time variant multi-component tonal blocks."

We believe that Terecos manufacturers periodically make changes to programs in order to reduce the likelihood of habituation, so the programs described here may not be typical.

2.2.1.2 Triggers

Triggers would allow activation of ADDs only when a predator is detected, or when depredation is occurring. It has long been recognised that a reliable and automated triggering mechanism would probably increase the efficacy of devices and furthermore would have the potential to greatly reduce the amount of acoustic energy released into the environment (Mate and Harvey, 1986). Several reports have also called for the development of reliable triggers, including those of Gordon and Northridge (2002),, Anon. (2002a); Kastelein *et al*. (2000) and Smith (1994).

A triggered device was reported to have been trialled in Vancouver, Canada, as early as 1988. This detector activated an acoustic device when the nets received an erratic, sharp impact (Smith, 1994), but development of this device does not seem to have gone very far. According to Olesiuk *et al*. (2010), Airmar explored the development of triggers activated by sonar or detection of predator vocalizations, but these were not successful. The product sheet for the Airmar dB Plus II model states that there is an input socket designed for the attachment of a ‘mammal detector’, or could alternatively be operated manually by a remote operator observing an attack via net monitoring video.

The only concerted attempt that we are aware of to develop effective and useful triggers has been by Ace-Aquatec, whose triggers are designed to be activated by the movement of fish in response to a seal attack (Ace-Hopkins, 2001). When a seal approaches the net, it is expected that the fish will become agitated and this movement is detected when they collide with sensors placed inside the net. Unfortunately we are not aware of any independent studies which have looked at the efficacy of these triggers, and our own discussions with site managers have suggested that false detections are not uncommon. Northridge *et al*. (2010) reported that, among their interview sample, predator triggers had been tried at 27 sites in Scotland, but none of the interview sample had judged them to be successful.

2.2.1.3 Modes of Operation

There are two broad strategies for the use of ADDs at fish farms. The first is to have the device emitting sound continuously (except during diving operations), forming a continuous sound field. Northridge *et al*. (2010) found that at 28 of 52 sites where ADDs had been deployed, the devices when deployed were left on continuously. The rationale here is that if the predator is excluded from the immediate vicinity of the farm from the outset it will never learn to associate it with the presence of a food source and should therefore have no incentive to predate on the fish there. However, continuous operation could be more likely to lead to habituation, and negative effects on non-target species due to acoustic disturbance and/or exclusion are also likely to be greater. The alternative strategy is ‘responsive’, with the device only being switched on for a limited period of time in response to either seal presence or attacks. Northridge *et al.* (2010) found that this strategy was used at 25 of 52 sites. The benefits of this approach are that the reduced duration of sound emission may limit the potential for hearing damage or habituation of local seals and reduce disturbance effects on non-target species. However, this strategy might increase the risk of seals learning that farms provide depredation opportunities before the seal has been detected and ADDs are activated. Once an association has been made in this way, the predator may be more motivated to ignore the acoustic deterrent.

In our experience, different farm managers adopt either one strategy or the other and we have therefore never had the opportunity to directly compare the two. There has, to our knowledge, been no objective assessment of the relative effectiveness of the different approaches in the context of marine aquaculture.

KG No.	Knowledge Gap
10	What is the relative efficacy of different ADD deployment ‘strategies’, and how can they be appropriately compared?

A recent undergraduate thesis examined the efficacy of different ADD strategies in mitigating seal interactions with anglers on the Ythan estuary, Aberdeenshire. During each sampling occasion (a day), angling boats employed one of three strategies; no ADD, continuous ADD or responsive ADD, where the device was only used in response to seal presence. It was found that anglers were more likely to have a successful trip if the acoustic deterrent was switched on for the duration (fish caught on 50% of trips, n = 18) than when it was used responsively (fish caught on 20% of trips, n = 7). This compared to a success rate of just 5% when the seal scarer was not used at all (n = 26) (Rae, 2013). While the experimental design of this part of the study was not perfect (data were collected by the anglers themselves, and the treatment regime is not documented and could therefore have been biased), there is an indication of a difference between predatory behaviours in response to different deterrent strategies. The context here was clearly very different from that at a fish farm but it does indicate that simple experimentation could provide useful data.

In addition to the two strategies described above, Quick *et al*. (2002) showed that some sites in Scotland use ADDs seasonally, which could be described as a sub-strategy or refinement of the approaches described above, as one or other of the broader strategies will generally be employed during the period of ADD usage. Northridge *et al.* (2010) found that at 12 of 52 sites, managers had only switched on devices when fish reached a certain size at which they were deemed vulnerable and then left them on. There is very wide variation in deployment tactics, and these are usually specific to the company or even individual site.

2.2.2 Extent of Use in Scottish Farms and Elsewhere

2.2.2.1 Current Usage

At present the use of ADDs at a site is permitted or restricted by local planning authorities as part of the planning consent process. Scottish Natural Heritage (SNH) is a statutory consultee at the planning stage and can object to the planned use of ADDs - in which case the planning authority may exclude the use of ADDs in the planning consent. At present, therefore, while no specific licence is required to use ADDs as a matter of course, a licence may be deemed necessary by SNH under the Conservation (Natural Habitats, &c.) Regulations 1994 if it is thought that their use may disturb cetaceans. Scottish Natural Heritage has objected to use of ADDs in relatively few instances so most farm sites are free to deploy ADDs, but the number of sites which have requested permission to use them, and how many have been denied, is undocumented.

KG No.	Knowledge Gap
11	How many sites have been denied approval for ADD use under planning regulations, and what criteria have been used to assess applications?

Hawkins (1985) found ADDs at 4 of 41 sites (9.7%) and soon afterwards Ross (1988) found that ADDs had been in use at 8 of the 45 sites visited (18%). This proportion continued to increase through the 1990s and Quick *et al*. (2002) found

52% of farms reported that they use ADDs, but that usage patterns varied greatly. These results are similar to those reported by Northridge *et al*. (2010) who found 40 out of 81 sites interviewed were using ADDs. Northridge *et al*. (2010) found that of farms with ADDs in Scotland, 42% were using the Terecos model, and 35% were using Airmar while Shrimpton (2001) found that the Airmar models represent approximately half of those in use (16 of 31) in another sample.

Elsewhere, Johnston and Woodley (1998) found 22-46% of sites in Bay of Fundy were using ADDs, while in Chile, Sepulveda and Oliva (2005) found that 33% of sites used ADDs in efforts to reduce interactions with sea lions. It is clear that ADDs are not universally considered essential.

KG No.	Knowledge Gap
12	Total extent and distribution of ADD usage in Scotland is currently unknown.

2.2.2.2 Propagation, Sound Fields and Ranges of Effects

The level at which an animal at a given range will receive the sound from an ADD depends on both the source characteristics of the device and propagation loss. Propagation conditions will vary between sites, being affected by parameters such as bathymetry and bottom type. Seasonal changes in variables such as water temperature profiles will also have an effect. However, propagation loss is reasonably well understood. It can be modelled using various approaches, there is a host of empirical data from representative sites, and it is also relatively easy to check predictions by making recordings at particular locations.

Predicting aversiveness relies on many contextual and species specific factors and is therefore much more complicated than prediction of the range of audibility. Audibility will be limited either by the hearing threshold of the animal or the ambient noise level, whichever is higher. Since hearing thresholds vary between different species, the range of audibility will be species dependent.

A detailed investigation of the potential sensitivity of marine mammals to acoustic deterrents at close range was conducted by Lepper *et al*. (In Review). In this report, appropriate models were used to generate lookup tables of propagation loss to apply within 500m of Scottish farm sites based on characteristics such as water depth, slope and bottom type. Simple geometric models of sound propagation have been shown to be inadequate for predicting the complex sound fields (Shapiro *et al*., 2009) typical of relatively shallow-water environments where fish farms are generally sited. Certain key parameters were therefore tested as predictors of propagation loss including: source amplitude and spectral characteristics, water depth, sediment type, seabed slope and surface roughness. The typical frequency range of ADDs in use in Scotland is 2-40 kHz, and this range was subdivided by Lepper *et al*. (In Review) into frequency bands one third of an octave wide (an octave being a doubling of frequency) in order to assess frequency dependent propagation. Other than general noise propagation, this work has particular importance for estimating the risk of hearing damage to both target and non-target marine mammal species (discussed below in section 7.2)

Predictions by Lepper *et al*. (In Review) showed a reasonable fit to empirical data collected during earlier studies (Booth, 2010; Northridge *et al*., 2010). Lepper *et al*. (In Review) used predicted noise fields for different devices to explore the potential for hearing damage at these sites for both seals and small cetaceans. The extent of this potential risk was highly dependent on the animal's behaviour and movement within the sound field but it was evident that if animals do spend extended periods close to ADDs, SEL thresholds for permanent hearing damage based on Southall *et al*. (2007) would be exceeded.

To make a crude estimate of the marine area that might potentially be affected by ADD usage, we have plotted areas based on the estimated range of effects around all of the licensed fish farm sites in Scotland (figure 5 & 6). Jacobs and Terhune (2002), using a mixed model of cylindrical and spherical spreading loss, calculated the theoretical maximum range of detection to a harbour seal (higher hearing threshold than a harbour porpoise) to be 20.2 km for an Airmar device. Using median levels of ambient noise, the zone of audibility was calculated to be 9.7 km. Brandt *et al*. (2012b) also stated that a loud acoustic deterrent (such as an Airmar) could be audible to a harbour porpoise at a range greater than 20 km. This was based on a lower rate of transmission loss in their study area (possibly due to water depth and/or bottom type), so we have taken a lower estimate of the range of audibility at 10 km. Brandt *et al*. (2012c) found a significant deterrent effect on porpoises at ranges of at least 7.5 km for a Lofitech device, which greatly increases the previous known area of disturbance found by Olesiuk *et al*. (2002) to be at least 3.5 km. Neither study looked for effects beyond these maximum ranges. Again we have taken the lower figure, and set the range of deterrence at 3.5 km. By applying these figures to the locations of all Scottish Environment Protection Agency (SEPA) licensed fish farms sites in Scotland, we estimate that the theoretical marine area of 'deterrence' is 3500 km^2 and the area of audibility to harbour porpoise could be as high as 12600 km^2 (figures 5 & 6) (assuming no shadowing of the signal by islands, as well as other assumptions). This represents around 4% and 15% respectively of the total inshore Scottish waters (<12 nm offshore).

It is important to note that these figures are not presented as estimates of the current extent of ADD audibility, but rather the potential extent, assuming that all SEPA licensed sites began using high-powered ADDs. In reality, many sites are inactive or fallow for at least parts of the year and only around half of active sites currently use ADDs. These figures also do not take into account the effect of bathymetry or the shadowing effect of landmasses, which would reduce these figures considerably. While these figures should be viewed as very rough estimates of potential maximum areas, they indicate a likely maximum percentage of Scottish coastal waters that could be ensonified, with the West Coast and Outer Isles most greatly affected.

Further research could extend this concept by incorporating realistic usage patterns and propagation models in order to achieve a more reliable estimate of the likely marine area affected. Similarly, field data, such as that collected by the Hebridean Whale and Dolphin Trust (HWDT) during routine monitoring cruises using towed hydrophones, could provide empirical data on the range at which devices are audible in ‘real-world’ noise conditions (Booth, 2010).

KG No.	**Knowledge Gap**
13	Over what maximum range are cetaceans likely to be impacted by ADDs?

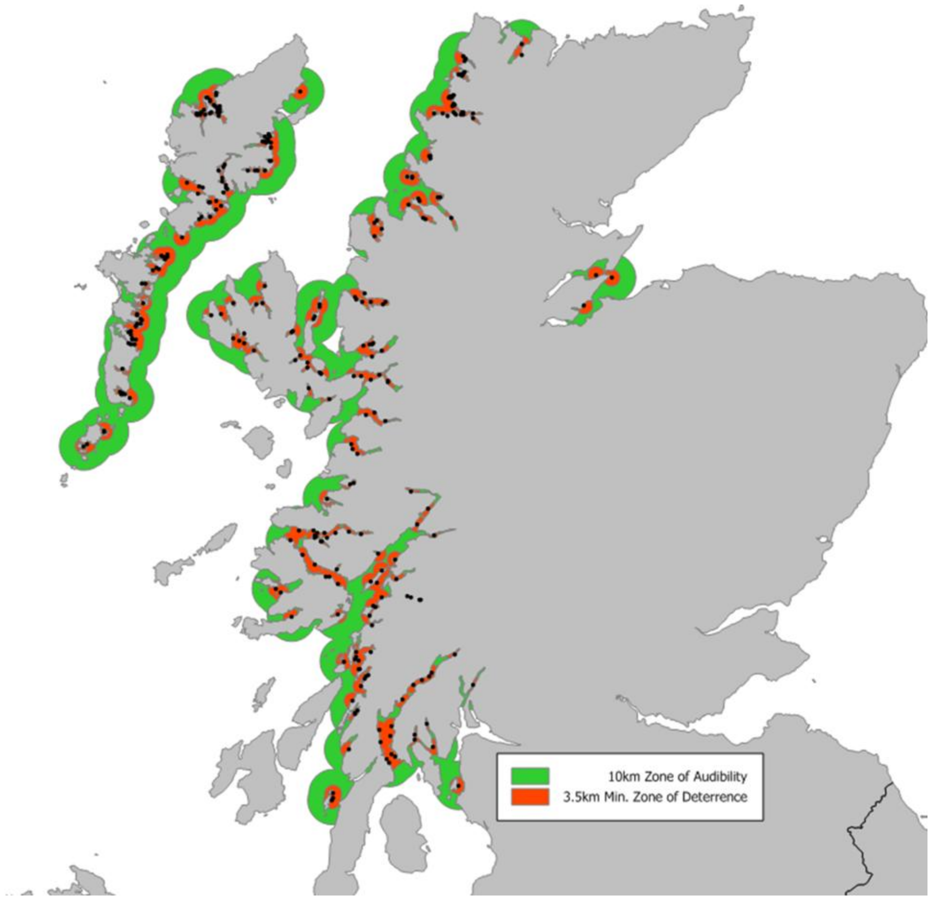

Figure 5 Map of Potential Extent of ADD Audibility to Harbour Porpoise (Mainland and Hebrides)

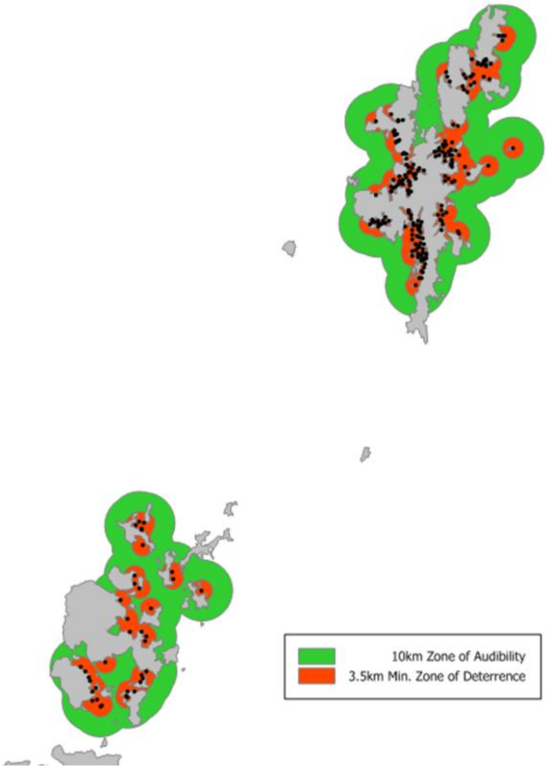

Figure 6 Map of Potential Extent of ADD Audibility to Harbour Porpoise (Northern

2.2.3 Evidence of Efficacy

2.2.3.1 Current Knowledge

Strangely, far more scientific work has been done to assess the impacts of ADDs on non-target species than to quantify their efficacy for the purpose for which they were designed. While several studies have investigated effects of deterrent devices in contexts other than fish-farms, there is remarkably little published scientific evidence supporting their long-term use as effective pinniped deterrents in aquaculture.

While it may seem sensible to draw parallels from other operations that have been studied such as coastal salmon traps and salmon rivers, it is important to remember that from the predators' perspective, the context at a salmon farm may be very different and may therefore elicit a very different suite of behavioural responses. In particular, the motivation afforded by a cage full of large salmon, probably releasing auditory and olfactory cues, may dramatically increase the attractiveness of the site to the predator. Prior hunting success at a site (e.g. before installation of anti-predator measures) could also influence the predator's choice. In addition, it is known that fish-farm sites often support an ancillary ecosystem which may include large numbers of wild fish, and anecdotal evidence from farmers suggests that these wild fish often play a role in attracting predators to the site.

Acoustic deterrents are referred to as a 'valuable tool for growers' in North America by NMFS (1996), but they present no evidence to support this claim apart from mentioning that the new high-powered (Airmar) systems were proving effective, and have become standard equipment for much of the industry in the Gulf of Maine. By contrast, Iwama *et al.* (1997), reviewed relevant literature and concluded that ADD effectiveness was highly variable among British Columbia aquaculture sites. They noted that any effect appeared to diminish with time, and that pinniped attacks continued to occur even when deterrents were present. They therefore recommended the phasing out and prohibition of acoustic deterrent devices, and this recommendation appears to have been adopted by the Canadian Department of Fisheries and Oceans (DFO) for the British Columbia aquaculture industry, who are no longer issuing letters of authority required for installation of an ADD (BC Pacific Salmon Forum, 2007).

2.2.3.2 Questionnaire Survey Studies

There have been several attempts to collect information on predator interactions using questionnaire surveys. This is a low cost method of consolidating information from a large number of geographically dispersed sites, allowing a broad perspective on the issue to be obtained. However, this technique has certain shortcomings, including the difficulty of exploring specific issues in detail, the potential for bias in the respondents to the surveys and the fact that data collected are often opinions rather than demonstrable facts. Questionnaire surveys are certainly a useful first step for exploring the problem and can generate testable hypotheses, but they should usually be followed up by directed research to collect and test real data.

Ross (1988) discussed the use of seal scarers when they were still very new to the industry; they were first trialled on Scottish fish farms in 1984-1985. Even at this early stage opinions appeared to have been mixed, with two operators reporting habituation within two weeks of use and two others reporting limited or no effect. Some operators apparently considered them still effective after several months in use, with one claiming continuing efficacy after two years of use (though ADDs were used here in conjunction with lethal removal, suggesting less than 100% efficacy). The reason for such variation was unclear, but hypotheses proposed included differences in motivation between individual seals, ADD usage patterns (i.e. intermittent vs continuous usage) and factors specific to particular sites.

Rueggeberg and Booth (1989) surveyed British Columbia salmon farms and reported that five out of eight farms that had used them rated acoustic deterrents to be effective against seals, and one found them effective against sea lions. None of these devices, however, had been in use for longer than two months. Later studies in British Columbia found no grounds to support their use and ADD use in this area is now prohibited (Iwama *et al*., 1997).

Tillapaugh *et al.* (1993), summarised by Smith (1994), reported on the results of a 1991 questionnaire survey of 40 growers in British Columbia and concluded that, "*in general, visual, auditory and sensory methods [of deterrence] were not effective*".

Arnold (1992) investigated salmon farms in Shetland on behalf of Greenpeace UK, and stated that, "*operators who have used seal scarers say that they can be mechanically unreliable and do not function for long as a deterrent due to habituation, and seals may even be attracted to the site".* In a telephone and paper based questionnaire survey of Scottish salmon farm sites, Quick *et al*. (2002) found only 23% (21 of 92) of managers considered ADDs to be very effective with 6.5% reporting them to be completely ineffective. The majority of managers who responded felt that seal scarers were at least moderately effective.

Sepulveda and Oliva (2005) used questionnaires to assess the extent of South American sea lion predation at 48 salmon farm sites in Chile. Of the 16 sites that were using acoustic devices, 2 described them as 'efficient', 2 as 'moderately efficient' and 12 reported that they were 'inefficient'. They concluded that ADDs were reported to be ineffective in the long-term. The opinion of fish farmers seemed to be that they worked for 2-4 months, and then were no longer effective.

Nelson *et al.* (2006) surveyed a total of 97 Atlantic salmon farms in Maine, USA, and modelled the influence of a number of factors, including range to haulout and ADD use on depredation losses. They found that sites which utilised ADDs had a higher incidence of predation than those that did not. The authors concluded that their results showed ADDs to be ineffective, but this seems quite over-simplistic given their limited dataset. It may have been the case, for example, that only sites with particularly high levels of predation were using AHDs. Despite these unpromising findings, 50% of farm managers surveyed felt AHDs were ‘fairly effective’ and 6% reported they were ‘completely effective’.

Northridge *et al*. (2010) conducted detailed on-site interviews with a sample of managers at salmon farms in Scotland. Three quarters (15 of 20) of sites where an opinion was expressed judged ADDs to have ‘some preventative effect’, while one quarter (5 of 20) said they had no beneficial effect.

The results of these surveys present a mixed picture. It is clear that ADDs do not provide a complete solution, but among operators and site managers there is significant support for their use. Within an area, opinions and experience of efficacy seem to be highly variable. In part this might reflect the lack of any formal experiments. Industrial practice tends to rely on perceived efficacy and there are few opportunities to risk a change in established operating procedures. In several cases there are indications that the efficacy of devices decreases with time, which could be an indication of habituation or learned strategies for avoidance or for controlling responses on the part of the seals. It is also generally true that few researchers have considered how effectiveness might be defined, because it is clear that even a marginal decrease in predation could be considered effective under some circumstances.

KG No.	**Knowledge Gap**
14	How can the effectiveness of ADDs be measured and compared, and what level of effectiveness is tolerable?

2.2.3.3 Research at Fish Farms

Several studies have made attempts to investigate the effectiveness of ADDs at fish farm sites. Most have relied on the opinions of the site managers (as in questionnaire surveys) but a few have monitored the level of predation after the introduction of a particular acoustic device. None, however, has involved a robustly designed, long-term experimental approach that might unequivocally determine the degree of effectiveness of a specific device. It is important to remember that effectiveness might, in this context, mean a modest reduction in the rate or severity of predation, as long as this reduction can be clearly demonstrated.

Pemberton and Shaughnessy (1993) described studies with two types of seal scarer (about which further information is unavailable) at fish farms in attempts to deter Australian fur seals. One operated at 28 kHz, the other at 10 kHz, and they tested each at fish-farms as well as haulout sites. The higher frequency scarer was tested at three farms over 6 months, during which 60 attacks were recorded. The lower frequency scarer trial ran for just two weeks during which three major attacks were recorded within five metres of the device. The authors noted that they were not able to determine whether the rate of attack was reduced by the ADDs due to experimental design, however, this level of predation was clearly unacceptable and these devices could not have been considered as useful management tools.

Unfortunately they did not specify the make or source level of the devices tested, making their results impossible to generalise.

Several unpublished documents summarising field research by the ADD manufacturer *Ace-Aquatec* claim high levels of success at deterring depredation (Ace-Hopkins, 2002a; Ace-Hopkins, 2002b; Ace-Hopkins, 2002c; Ace-Hopkins, 2004; Ace-Hopkins, 2006). Ace-Hopkins (2002a) claimed 100% efficaciousness (in medical research *efficaciousness* indicates success in controlled experimental trials, as opposed to *effectiveness* which describes 'real-world' results), at sites where no previous ADDs had been used. A farm in one trial was losing around 50 smolts per week to depredation until the Ace-Aquatec ADD was installed, after which the author states that no further losses were reported, although he does not state details of how this was measured. At another site where an ADD had previously been ineffective the Ace-Aquatec ADD did not solve the problem. It is encouraging that this one manufacturer has conducted research and presented results openly and they are to be commended for doing this. These reports certainly indicate that useful data can be collected in a relatively straight-forward manner with a modest research effort assuming industry co-operation. Ideally, such studies should be longer, more rigorous, should incorporate better controls and have more extensive reporting. Of course, credibility would be improved if they were conducted by independent researchers not affiliated with an ADD manufacturer or the industry.

Stewardson and Cawthorn (2004) make reference to a trial conducted by the New Zealand King Salmon Company, to deter fur seals from aquaculture sites. A Poseidon T88 ADD was tested over a thirty day trial at two sites. They reported that, "*results suggested that an ADD used in conjunction with other measures may, at least have a temporary effect in reducing seal attacks"*. Unfortunately, more detailed information on this study and the device used is not available.

The only attempt to conduct a controlled trial of which we are aware is reported by Vilata *et al*. (2010). They tested the effectiveness of an Airmar device against South American sea lions by comparing predation between two sites. The sites were both stocked with fish of the same size and in the three months prior to the installation of the ADD the biomass of salmon predated was not significantly different at the two sites. After three months of preliminary data had been collected an ADD was introduced at one of the sites. Over the subsequent three month experimental period, there were statistically lower levels of predation at the site with the ADD. They also found that the site with the ADD experienced significantly less predation than it had done during the same period in the previous year. This work shows that an experimental approach is possible and can provide useful results. The authors note that their sample size was small and that replicates are required before conclusions can be drawn. Furthermore, the experimental period was just three months, which may not be long enough to show effects of habituation. The authors also mention another adjacent site where the same model of ADD was installed at the same time and found to be "totally ineffective".

2.2.3.4 Playbacks at Haulouts

Designing and implementing experimental trials on the effectiveness of ADDs at operational sites is extremely challenging and would necessarily involve exposing caged salmon to predation risks that would probably be deemed unacceptable to site operators. For this reason attempts have been made to examine relevant literature from other comparable scenarios.

Acoustic playback studies at haulout sites have been used as one way to assess pinniped responses to particular signals. The main benefit of this type of experiment is that animals can be reliably found in useful numbers, and relatively large amounts of behavioural data can be collected over a short period of time.

A brief description of an early playback experiment by Pemberton and Shaughnessy (1993) reported that Australian and New Zealand fur seals were not deterred by either of two devices, one operating at 10 kHz, the other at 27 kHz. Ten trials were conducted with each device and the behaviour of the animals was noted. Seals reportedly continued with pre-playback behaviour, approached the device or raised their head from the water and looked toward the scarer.

The reaction of harbour seals to an Airmar ADD was investigated by Jacobs and Terhune (2002), who recorded seal behaviour using video while measuring distances from the sound source using an optical range finder. They conducted 16 treatments over 6 days, including 5 controls where transducers were placed into the water but no sound was played. No apparent difference in behaviour was found between treatments when the ADD was active and inactive, and no observable reactions (such as rapid swimming or hauling out) were noted. The closest sighting of a seal while the device was active was 43m. They also tested whether an active ADD would prevent movement of seals through a channel by counting the number of animals at a haul-out which could only be accessed by passing within approximately 600m of the device. No effect was observed between treatments and seals were observed as close as 44m from the sound source.

Stewardson and Cawthorn (2004) describe the results of an experiment in New Zealand, where fur seals at coastal haulout site were exposed to a device manufactured in Sweden by Kemers Maskin AB. The device had a source level of 200 - 210 dB (re 1 µPa – RMS or peak not stated), with a frequency of 10 kHz. Animals were classified into size classes in order to look for differences between the responses of age groups. Small and medium sized fur seals made “convulsive changes of direction and porpoised [rapid surfacing during directed swimming behaviour] rapidly from the sound source”. In contrast however, large adult males were reported to “initially show indifference before making a positive response to the sound of the ADD.”

Götz (2008) tested the response of grey seals to eight different sounds (including white noise, a 500 kHz sine wave and those produced by currently available seal scarers - Lofitech, Airmar, Ace-Aquatec and Terecos), at haulout sites in the Tay Estuary, Scotland. Playbacks were done from the stern of an anchored boat, using visual counts on animals within five distance bins (0 – 20, 20 – 40, 40 – 60, 60 – 80 and 80 – 100 m) to compare between pre-sound, sound and post-sound treatments. During control experiments, when no sound was played, no significant changes in animal numbers were shown. For all tested sound types (except one – the Terecos sound type), there was a significant decrease in the number of animals in at least one of the distance ranges (repeated measures ANOVAs all $p < 0.05$). To test for evidence of habituation within each day, they counted the total number of seals within 60m for each playback. There was no significant relationship between playback number and count of seals, and therefore no evidence of decreasing deterrence effect or habituation. They also did not find any evidence of animals being attracted to the sound source, as was reported by Pemberton and Shaughnessy (1993).

These studies show that playback experiments in the wild may be a useful tool for assessing the relative aversiveness of particular signal types. However, the context is different from that at a fish farm in several important ways. For instance, depredating animals may be highly motivated to feed on an abundant food source and ADDs are often in operation for much more extensive periods of time which may have an effect on the way the signal is perceived. In addition, avoidance tends to be measured at quite large ranges whereas depredation reduction could result from animals being deterred by just a few metres in order to reach the nets. We therefore question how appropriate or useful such studies are for informing depredation management strategies.

KG No.	Knowledge Gap
15	The effectiveness of ADDs in reducing seal depredation to stocked fish remains unclear. An experimental approach to address this fundamental uncertainty is difficult for economic and fish welfare reasons.
16	Effect of motivational state and context in mediating and modifying aversive response to ADDs.

2.3 Alternative Approaches to Managing Seal Interactions at Fish Farms

2.3.1 Containment

Northridge *et al*. (2010) reported that fish farm operators had suggested that problems with seal depredation have generally improved over the past decade or more. It is clear that this improvement is not the result of any increase in the overall proportion of sites using ADDs, which has remained around one half since the study by Quick *et al*. (2002). Most respondents indicated that improved containment and better husbandry have been the primary drivers behind the improvement. Without access to detailed industry data it is impossible to be sure how effective such measures have actually been in reducing seal depredation, but Scottish Government figures do at least suggest a decrease in the numbers of fish that are reported to have escaped due to breaches in cages over the past ten years (Northridge *et al*., 2013).

The particular measures that may have been responsible for a reduction in seal depredation at Scottish salmon farm sites also remain unclear, but several trends were noted by Northridge *et al*. (2012). Nets have for example generally increased in size over the past ten years or more, and salmon stocking density has been reduced. It has been suggested that high stocking densities may have made depredation easier for seals, and that lowering fish densities (for welfare and for improved productivity) may therefore have helped reduce depredation. Larger nets may also have made access to fish within nets more difficult for seals if fewer fish are to be found close to the net perimeters.

KG No.	**Knowledge Gap**
17	How does stocking density influence seal behaviour and depredation rate?
18	Salmon behaviour within nets and in response to depredation is poorly documented, particularly at night.

It should be stressed that at present we have very limited information on how seals actually take fish from inside nets without actually breaching the containment wall of the net pen itself. Net breaches are relatively rare, and by far the most common means of depredation appears to be grabbing fish through the meshes of the net wall or floor of a fish pen and sucking flesh through the netting. Exactly how this is usually done is unknown, although there are a few anecdotal accounts (see section 2.1.3 for more detail).

The second change that has occurred in Scottish fish farms has been the gradual increase in weighting used to maintain net shape and prevent deformation by tidal currents through improved net tensioning. Surprisingly little research has been conducted in this field, and we were only able to identify one field study that has examined net deformation in salmon cages under different weighting regimes and tidal current systems. Lader *et al*. (2008) compared the net deformation in two sites with different weighting systems and with exposure to different current regimes in Norway and in the Faroe Islands. At one site with square pens and with current speeds of 0.13 ms^{-1} (0.25 knots) there was an estimated 20% reduction in net volume at peak tidal flow, while in the other a 40% reduction in circular pen volume was measured when current speeds reached around 0.35 ms^{-1} (0.68 knots). The square pens were fitted with weights of 2 x 600kg, 400kg and 300kg at each corner and 2 x 125 kg weights on each of two sides and 2 x 80kg weight on each of the other two sides. This is more than is normally found at Scottish square pen sites. The circular pen was fitted with a sinker tube (single ring weight) of 1700kg. Neither of the current speeds in this study was particularly fast compared with those experienced in Scotland. We have been told that individual weights used on Scottish net pens have increased from 20kg to 80kg or more over the past ten years, and, during visits, we have also observed some extreme net displacement at Scottish fish farm sites at peak tidal flows despite this increase in weighting.

Net displacement decreases the volume of the net (see Figure 7 below from Northridge *et al*., 2013). This not only increases the effective stocking density but also likely results in net deformations that may make it easier for a seal to attack salmon through the meshes, especially where pockets are formed (see also Section 2.1.3).

There has also been a trend in Scottish farms towards the use of circular pens which are usually weighted with a circular basal weight of 1.5 tonnes or more. This system is likely to maintain net structure more firmly through the tidal cycle and thereby reduce the chances of net pockets or other deformations arising. Preliminary evidence suggests that successful depredation is more limited in circular net pens than in the older square pen designs (Northridge *et al*., 2013; Thistle Environmental Partnership, 2010).

It is therefore likely that increased weighting and better net tensioning could have played a significant role in diminishing seal depredation, and it remains possible that further improvements in this respect may lead to further declines in seal depredation.

KG No.	**Knowledge Gap**
19	How does net tensioning affect the ability of seals to remove fish?

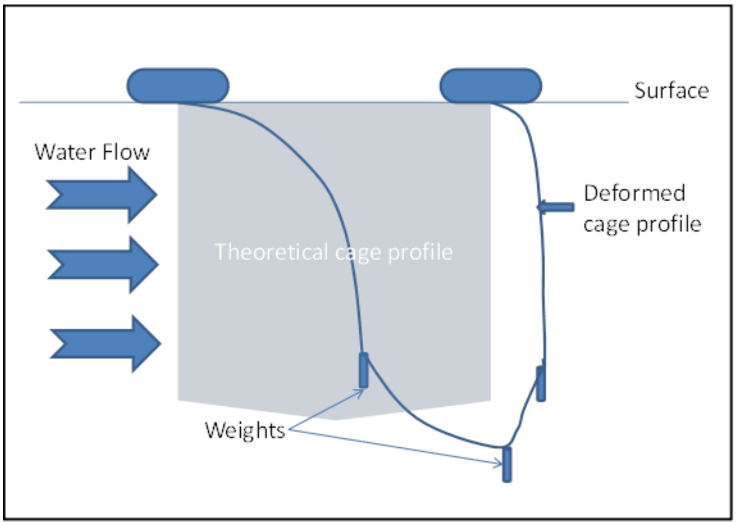

Figure 7 Net displacement as a result of tidal flow

Other measures that have been cited as possible means of minimising seal depredation include the use of anti-predator nets, the use of seal blinds and prompt removal of salmon ‘morts’ (dead fish) from cages. There is no empirical evidence to show how effective these measures may be. There is a widespread belief within industry that dead salmon attract seals (through smell), make easy pickings and also encourage depredation more generally. The extent to which this is actually true is not known.

Seal blinds are relatively small sections (e.g. 2m x 2m) of small meshed netting that are sewn into the base of cages, at the deepest point or vertex of the cone or pyramid that forms the net base, where dead fish are likely to accumulate. The idea is to prevent seals from seeing dead fish and make the net stiffer and more difficult to deform. Some nets use seal blinds made from stiff plastic mesh rather than netting. The efficacy of this strategy has not been evaluated objectively, but the fact that seal blinds are not uncommon design features of net cages suggests that they must be at least be perceived as partially effective.

KG No.	**Knowledge Gap**
20	How important are dead fish (morts), and their removal or concealment in motivating or preventing seal depredation?

Anti-predator nets are additional, usually large mesh, nets that surround each pen within a farm site. They may be deployed as curtains from the outer edge of the walkway around each pen falling to the seabed, or alternatively may be rigged as box nets to surround the sides and base of a net, or may even surround the entire site. Although Hawkins (1985) found they were used at 88% of Scottish farms, such nets are now rarely used in Scotland because they are difficult to manage, are liable to foul the propellers of tending boats, add to mooring problems caused during bad weather, impede the flow of water through the pens, can catch large numbers of sea birds and other marine wildlife including seals and cetaceans, and are anecdotally not thought to be very effective, as seals are often able to penetrate them anyway. Northridge *et al.* (2010) found anti-predator nets in use at just one of 136 sites. Despite these domestic reservations, such nets are widely used in other countries (Canada, Chile and Australia), and it is as yet unclear how or why they appear to be effective in these countries.

KG No.	**Knowledge Gap**
21	How are anti-predator nets utilised internationally to avoid common problems experienced in Scotland?

One possible reason for the continued international use of predator nets is that there has been some degree of dedicated research into the most effective net types and configurations elsewhere. These research efforts appear to have made some progress toward limiting the problems commonly associated with anti-predator netting in Scotland. Schotte and Pemberton (2002) report that anti-predator nets were often used to protect Tasmanian salmon farm sites from New Zealand fur seal (*Arctocephalus forsteri*) and Australian fur seal (*Arctocephalus pusillus*) once fish were over 300g. One common problem encountered with their use was that even under modest degrees of current the two layers of netting (anti-predator and growth netting) can come together. To overcome this, tensioning weight must be distributed between the two nets, and various practical methods of doing so were described. The use of neutrally buoyant steel pipes, individually cut to length and known as ‘separation sticks’, was also found to increase the distance between the nets and prevent them from coming together. This method was particularly recommended for use between the base of the growth and anti-predator netting, where seals are thought to push nets upward in order to scavenge dead fish.

Schotte and Pemberton (2002) also developed a scale model to investigate the effects of water flow on different configurations of tensioning weight. They found that net shape (e.g. the degree of tapering between the waterline and net base) was an important factor but was very difficult to perfect in practice, due in part to shrinkage after deployment. Based on this work they recommended that a minimum of 20% of available buoyancy should be used for net tensioning, distributed as appropriate between the two layers of netting. For a 120m circular pen (the largest used in Scotland) this would mean the use of 2.4 tonnes of weight. They also recommend a minimum spacing between the growth and anti-predator netting of 2m. This distance is practically achievable when suspended from the outside of steel walkways, but for plastic circular walkways would probably involve the addition of an extra ring (which would also increase the amount of buoyancy available for tensioning weight).

In conclusion, there is some evidence that improvements in containment may have helped reduce incidents of seal depredation at Scottish salmon farms. Various individual measures have been proposed as being responsible, but as yet it has not been possible to separate out the effects of each of these gradual improvements. It is entirely possible that further improvements (for example in net tensioning) may further reduce seal depredation, but there are no ongoing studies to assess these issues at present.

2.3.2 Lethal Removal

The lethal removal of predators (as an act of last resort) is an emotive issue and raises conservation, ethical and welfare concerns. Shooting seals at fish farms has been carried out since the industry was first established in Scotland, but has become more strictly controlled in recent times. Hawkins (1985) found that 20 of 41 sites used shooting to protect stock, and this remained true until at least 2001, when Quick *et al*. (2002) again found shooting at approximately 50% of sites – though the total number of animals was not given.

The Scottish Salmon Growers Association, as early as their 1990 code of practice, adopted the policy that lethal removal should only be used after all reasonable attempts have been made to exclude seals with non-lethal methods, and this has been adopted in the most recent code of good practice (2010):-

“Seals should not be shot during their close seasons (common seals 1 June to 31 Aug; grey seals 1 Sep to 31 Dec) unless all reasonable attempts have been made to

apply exclusion measures, these have proved to be ineffective, and there is a significant risk of damage to fish and fish farms."

A licensing scheme covering lethal removal has now been introduced under the Marine (Scotland) Act 2010 which is providing, for the first time, data on the number of seals lethally removed from fish farm sites.

The logic of selective lethal removal as a management action depends largely upon there being a small number of "rogue" animals causing the majority of the damage at a site, and on the ability of a marksman to reliably identify and remove these individuals. It is typically the case that there will be many seals at a fish farm site for extended periods with no serious depredation incidents (Northridge *et al*., 2010). Many fish farm managers believe that problem animals exist and can be identified and removed, but there is no independent evidence to support this assertion. The main indication that rogue seals exist and can be removed in this way is that farmers often report at least temporary relief from seal depredation after one or more seals have been removed by shooting. This information is largely anecdotal in the fish farm context however. One scientific discussion of lethal removal can be found in an article by Pemberton and Shaughnessy (1993), who dismissed shooting as ineffective, although it is not clear from their work whether they are referring to lethal removal, or simply its use as a deterrent. They refer to one seal which was 'shot at' at least 30 times and did not appear to leave the area. An alternative explanation could be that shooting frightens the remaining seals rather than removing a particular culprit.

KG No.	**Knowledge Gap**
22	The "rogue seal" hypothesis, and the rate at which removed seals are replaced is currently unclear.

Despite a lack of evidence about the efficacy of lethal removal as a management technique, this is certainly an area where objective data could be relatively easily collected. For example, such data might include: the recent history of depredation incidents at a farm site; the number, species and identity of seals seen at sites during these incidents (using photo-id); the number, species and identity of seals removed and details of any subsequent depredation. If carcasses of shot seals were recovered then their identity and recent diet could be determined, which would be highly valuable in determining efficacy of lethal removal methods. These carcasses would also be a uniquely valuable source of data for other applied research, including population studies.

It is a condition of the licence agreement under the Marine (Scotland) Act 2010, that, "The licensee must take all reasonable steps to recover the carcases of shot seals but only when it is safe to do so. … Even a carcase which has been in the water for several days should be retrieved wherever possible.*"* It is however, difficult to recover carcasses in practice, and there is a logistical limit on the ability of the Scottish Rural College (SRUC) to recover such animals. Anecdotal discussion with experienced marksmen suggests that approximately half of shot seals will immediately sink. Thus far, very few carcasses have been recovered from several hundred shot at fish farms annually.

KG No.	Knowledge Gap
23	How can recovery of seal carcasses be improved?

Animal welfare concerns relating to lethal removal focus on the possibility that seals may not be killed instantly and could be injured and suffer serious pain as a result. Licensing conditions reduce the possibility of this occurring by specifying the type and calibre of weapon that should be used and the experience of marksmen employed. We believe that larger fish farm companies are increasingly using a small number of experienced marksmen to carry out lethal removals, which will be helpful. Information on the reliability with which seals are shot “cleanly” could be collected by independent observers and by post mortem of carcasses of shot animals (as is currently the case for the few animals recovered).

Conservation concerns will arise if lethal removals at salmon farms are contributing to a level of mortality which is unsustainable or prevents recovery of depleted populations. In Scottish waters, these concerns will be higher for harbour seals, whose populations have declined substantially in some areas in recent years, rather than for grey seals (SCOS, 2011). The Scottish Licensing scheme allocates “quotas” to the industry which should ensure that total removals do not exceed Potential Biological Removal (PBR). This system requires that the species of seals being removed is determined reliably and that certain demographic components of the population are not over-represented. This is another area where observer data and recovery of corpses could provide useful data.

KG No.	Knowledge Gap
24	How can information about the demographic parameters of seals shot be improved?

Seals are an important part of Scotland’s ecotourism resource and there is a conflict of interest when lethal removals take place in areas where seals are an important source of income for ecotourism operators. Lethal removals could potentially affect these activities by reducing numbers, displacing animals from local haulouts and making them less approachable, and possibly discouraging tourists.

A further factor which must be considered is the wider societal concern over lethal removal of wild animals (particularly iconic mammals), especially without a clear and proven link to effective management. This means of management could damage the public perception of individual salmon farming companies, the retailers that sell their products and the Scottish aquaculture industry as a whole. A number of campaigning organisations are opposed to seal shooting even under licence.

It is therefore important to establish as clearly as possible whether lethal management is effective in minimising damage to fish farms.

KG No.	Knowledge Gap
25	It is unclear to what extent lethal removal is effective in minimising damage. No studies have looked at how depredation rate is affected by lethal removal.

2.3.3 Conditioned Taste Aversion

2.3.3.1 Conditioned Taste Aversion and its Application for Controlling Terrestrial Predators

Conditioned Taste Aversion (CTA) is a process by which an animal “learns” to avoid food which has made it ill in the past. Once an animal has been made ill by eating poisoned or tainted food it will usually exhibit disgust and may vomit when it encounters that food again. The ability to avoid ingesting poisonous or harmful substances is of such fundamental survival importance that CTA is found in all animals, from humans to sea anemones. This involves a specific form of learning mediated by dedicated neural pathways operating within the more ‘primitive’ parts of the nervous system and resistant to the influence of higher cognitive processes. Typically, this aversion is learnt after a single trial and persists for months or years. Conditioned taste aversion is also known as the “Garcia Effect” after John Garcia, an American psychologist who discovered that if an animal was made ill by some other mechanism, for example by exposure to radiation, it would develop a CTA response to a novel though harmless food stuff it had ingested during a time period before the sickness was induced. Thus, animals can “learn” an aversion to a food type even though it might have been made ill by some other agent.

Wildlife managers in other industries have made use of this phenomenon to develop non-lethal methods to reduce depredation by predators. The process usually involves lacing bait made from the flesh of the animal to be protected with an emetic (a substance that will induce vomiting) which itself is not detectable by taste. For example, in an early series of experiments (Gustavson, 1977; Gustavson *et al*., 1974; Gustavson *et al*., 1976) coyotes and wolves were fed minced sheep flesh laced with lithium chloride (an emetic) and wrapped in sheep wool (to provide cues similar to those a wolf would experience when attacking its prey). The predators became nauseous after eating the LiCl laced bait and after recovery they showed a marked reluctance to attack the prey they had been conditioned against. Gustavson and colleagues went on to show that wolf and coyote depredation of domestic sheep could be greatly reduced in this manner (e.g. Gustavson, 1982; Gustavson *et al*., 1982).

There have been many attempts to control predation of terrestrial animals using CTA but not all have been successful (e.g. Conover, 1989; Conover and Kessler, 1994). Some of the failures may be due to unrealistic presentation of the baits and lack of attention to detail.

Several particular aspects of CTA are important from the perspective of its use in predator control (Cowan *et al.*, 2000):

- CTA is a form of learning that takes place very quickly, usually after only a single exposure, yet can be long lasting, persisting for months or years.
- The neural processes underpinning CTA take place within the oldest and most primitive part of the brain: the hind brain. Inputs can arrive from receptors in the gut as nerve signals transmitted via the vagus, part of the sympathetic nervous system, involved in regulating the bodies' internal activities and state. Chemicals in the blood stream may also stimulate areas of the hind brain directly. Thus, this primitive form of learning is subconscious and deep-seated, in fact it is impervious to influences from higher levels of the nervous system and the conscious mind.
- During the CTA process, an aversive association is established with substances that had been ingested within a time window, typically of one to six hours, before the onset of nausea. This interval matches the time that it would normally take for a toxic substance to be ingested, for digestion to begin and for it to either trigger toxin receptors in the stomach or for chemicals to enter the blood stream and have a direct effect in the hind brain.
- The taste, smell and flavour associated with the "suspect" food are the most readily and strongly conditioned cues. However, associations can also be made with other triggers, including visual cues, although this may require repeated exposures. CTA seems to be most easily established if the food stuff is novel but aversion can also be established for previously encountered foods.
- CTA is not associated with a particular location and the aversion applies to the food type wherever and in whatever context it is encountered.
- CTA can be very specific. For example, aversion will usually apply to one particular prey species. This allows a predator to avoid poisons while excluding as little from its normal diet as possible.
- CTA conditioned animals of different species have been described as behaving in very similar ways when exposed to the conditioned food. For example, when mammals such as coyotes and wolves taste or smell the conditioned food stuff, they shake their heads from side, wretch, urinate and move away.

2.3.3.2 CTA to Protect Salmon from Pinnipeds

There have been several attempts to use CTA to curb the predatory behaviour of pinnipeds and in particular to reduce predation on both wild and farmed salmon.

Lithium chloride is the most straight-forward emetic but its use has proven problematic with some terrestrial predators because they are able to sense its slightly salty taste. One might conjecture that this is unlikely to be a concern for a seal feeding in seawater.

The most complete and best controlled trials, reported by Kuljis (1984), were carried out with captive Californian sea lions (*Zalophus californianus*) in the USA. Four male yearling sea lions were fed twice a day on a diet of herring and mackerel, with the fish species being alternated between feeding sessions. Both species of fish were highly preferred food and the sea lions always ate all the fish presented to them. After a 21 day pre-test period, two of the animals were fed mackerel laced with lithium chloride capsules. The other two seals were fed unadulterated mackerel. Within half an hour, both of the treated sea lions began vomiting and this continued for around 20 minutes. After an hour they seemed to recover fully and returned to their normal behaviour. The next feeding trial was of herring and all animals ate all of the fish presented to them. On the next mackerel feed however, the first fish offered was taken and then dropped. Subsequently, one of the treated sea lions refused to eat any mackerel for the next 19 days. The other treated sea lion returned to eating mackerel after 3 days. This sea lion was then given a second dose of lithium chloride after which its mackerel consumption was virtually eliminated. After 15 days, when some recovery in mackerel consumption had taken place, all four seals were dosed with LiCl at a lower concentration. All four then ceased taking mackerel for the next two days, after which the trial was terminated for unexplained reasons.

The treated animals were not offered any alternative source of food, so during the trials they were living on half the ration they had been used to before the trials began yet continued to refuse the mackerel offered them. The health of the subjects was carefully monitored through the trials and regular blood samples were taken. Blood parameters were within the normal range. In a subsequent set of trials, conducted to investigate potential health issues, herring were laced with emetics and the test subjects ceased feeding on them but continued to feed on mackerel (Costa, 1986). More detailed blood tests during these experiments failed to reveal any significant changes. Field trials with wild pinnipeds were later conducted as part of attempts to reduce sea lion predation of wild salmonids migrating through locks in rivers in Oregon. Freshly killed steelhead trout were suspended on a line in the water near the locks. Once sea lions were taking these unadulterated baits routinely, trout laced with LiCl were substituted. Two sea lions that could be identified in the field took these treated trout, they then disappeared from their normal foraging locations but returned within 2 hours. These animals would no longer take the tethered fish but it was not clear whether this apparent aversion had been extended to an avoidance of live fish too.

Conditioned taste aversion trials have been carried out at salmon farms in Tasmania where the main pinniped predators are large male Australian fur seals (*Artocephalus pusillus doriferus)*. Pemberton and Shaughnessy (1993) summarised the results of 26 trials each initiated by seal presence at a fish farm site. Trials started with a period during which unadulterated whole salmon baits were presented. These were then replaced by LiCl treated baits. On 21 of 26 occasions fur seals took the treated bait and on four of these, seals were seen convulsing and vomiting by either researchers or fish farm workers and subsequently left the fish farms. These preliminary trials were considered successful and Pemberton and Shaughnessy (1993) recommended that the technique should be further developed. However, in spite of this encouraging start, no further work seems to have taken place.

No CTA trials have been attempted at Scottish salmon farms, nor indeed with any phocid seals. However, in 1988 some ad hoc tests of repellents were undertaken in Loch Sunart. Salmon of large smolt size were laced with chilli and curry powder and suspended on lines from fish farm cages. Seals, believed to be grey seals, took these baits and although seals continued to take bait over the period of the trials and were not repelled, seal problems at the farm reportedly ceased during the trial. Unfortunately, the experiment was not taken any further. It is important to emphasise that this was a trial of a repellent and not of conditioned taste aversion. In conditioned taste aversion it is important that the predator should not detect any difference, especially in taste, between the bait and the prey species generally. In this way, protection should be generalised. This brief trial illustrates that wild Scottish seals will readily take whole dead salmon bait presented at a fish farm.

2.3.3.3 Research and Development

While the research projects summarised above provide strong grounds for optimism, it is clear that should CTA be developed to a state where it can be used as a routine method for controlling seal depredation additional trials and research would need to be carried out in several areas.

KG No.	Knowledge Gap
26	Which emetics are most effective and what are the minimum doses required for CTA?
27	Are there any harmful physiological effects on seals treated with CTA, and if so, how can they be minimised. Is CTA sufficiently specific to salmon to leave the seals' normal diet of wild fish unaffected?
28	Are there any environmental effects of CTA?
29	How can baits for CTA best be prepared and presented to wild seals at salmon farms?
30	What patterns of "treatment" are most effective? Should baits be presented routinely or only when problems become evident?
31	Are there seasonal difference in when and how CTA should be use? Should there be "closed seasons"?

Answering these questions should be relatively straight-forward and could be achieved using routine research methods applied to both captive animals (KG numbers 23, 24 and 28) and trials with wild seals at fish farm sites (KG numbers 25, 26, 27 and 28).

2.3.3.4 Conclusion

The work on conditioned taste aversion for controlling depredation by pinnipeds is, taken as a whole, rather encouraging, especially when the rather meagre research effort expended is taken into account. Given this, it is surprising that there has so far been little appetite for developing this methodology for use in Scotland. There seem to be concerns within the industry of a public perception that seals being made ill by eating adulterated salmon could indicate that farmed salmon is itself tainted. Good public awareness initiatives linked to publicity of the real welfare and environmental issues that CTA could circumvent, should diffuse this perceived issue.

2.3.4 Electric Fields

Protecting caged fish from attacks by seals usually relies on producing an avoidance reaction at sufficient distance to dissuade seals from approaching nets. Such methods have generally relied on acoustic deterrents of some form, as described above. An alternative approach may be to produce an avoidance reaction over a very small range to prevent the seals from pushing against (or biting through) the net itself. This approach has the advantage that it produces the minimum possible change in the behaviour and distribution of predators.

Studies in fresh water appear to indicate that seals may respond to electric fields at strengths significantly lower than those which cause behavioural responses in salmonid fish. Forrest *et al*. (2009) have shown that seals can be excluded from some freshwater systems by the use of electric fields. A useable freshwater deterrence system has been developed and tested in the US and Canada on both captive and wild, free ranging seals and sea lions with promising results (Forrest *et al*., 2009).

The North American installations were operated in low conductivity water (25 to 250 µS/cm [micro Siemens per centimetre]) yet still required substantial (kilowatt) power supplies. Unfortunately, replication of the same approach in seawater would require large amounts of electrical power. This is because the electric field required to stimulate an organism is likely to reduce only slowly with increasing water conductivity (Lines and Kestin, 2004) while the power required to sustain an electric field in water increases in direct proportion to the water conductivity and water volume. Sea water has a conductivity of 45000-60000 µS/cm – far more conductive than the water used by Forrest *et al*. (2009) so the power requirement to replicate their setups in sea water would be between 200 and 1000 times greater than that used in the original trials.

The very large electrical currents needed to sustain an electrical field in sea water means that there is little chance that this fresh water approach would be practical in the marine environment. It should however be possible to produce local electric fields within a few centimetres of a net wall with deterrent capabilities that could eventually be developed into a system for preventing direct attacks on net cages.

Milne *et al*. (2012) describe a preliminary series of behavioural response trials to assess the effectiveness of pulsed low voltage electric fields to deter trained captive seals from entering a feeding station. Seals were trained to enter an outer tube and maintain station with their noses close to and usually in contact with a Perspex feeding port within which they could see a small food reward. A Perspex window above the outer tube allowed the observation of any behavioural response. Seals were required to hold station for approximately 3 seconds before the port was opened to allow access to the food reward.

During trials electrodes were placed at either side of the entrance to the feeding port so that seals needed to position their heads in between the electrodes in order to gain access to food items. A single test comprised a series of 5 control trials with the device off followed by 5 trials with the electrodes energised. Trials were carried out at a range of voltages 12, 18, 24, 30 and 36 V and for each voltage at a series of different pulse durations of 10, 20, 50, 100, 200, 500 and 1000 micro-seconds and at pulse rates of 10, 50 and 100 Hz. Trials were carried out with juvenile grey seals, juvenile harbour seals and an adult male harbour seal. To avoid accidental exposure to painful stimuli the trials were not carried out in a randomised sequence. Instead seals were exposed to gradually increasing field strength, signal durations and pulse rates, starting at levels that were expected to be undetectable.

Results clearly show that both seal species are able to detect low voltage pulsed electric fields. There is also strong evidence that the level of response is affected by changes in the combination of pulse duration, voltage and pulse repetition rate. None of the seals showed any signs of detecting or responding to the electric field at short pulse durations of 10 or 20 µs, but all seals showed clear aversive responses when exposed to longer pulse durations and higher voltages. This was especially apparent at high pulse rates (100 Hz) where there was clear evidence of avoidance with seals refusing to push through the field to access food items.

These reactions were transitory in that all seals continued to use the feeding system after they had refused to enter the feeding tube. In all cases seals returned to use the feeder during the same experimental session. After refusal there were indications that seals were more cautious in their approach on the next trial, but thereafter they returned to the device as usual. The preliminary results showed no clear sign of either sensitisation or habituation, but the trials conducted so far have had limited power to detect either.

In all cases the extent of the electric field or at least the extent of the effect zone was small. At the higher voltages, pulse lengths and pulse rates the seals pulled back from the entrance to the feeder where the field was most intense. However, even at the highest settings the seals usually stayed inside the outer tube and held station within 30 cm of the feeding port.

These results are encouraging and suggest that low voltage, low duty cycle, pulsed electric fields might prevent seals from pushing against a net. However, the results are preliminary and further trials will be required to assess the effectiveness of different electric field patterns with reduced energy input in order to approach a useable net protection method.

KG No.	Knowledge Gap
32	Behavioural aspects of electrical deterrence: how will behaviour be modified by context and motivation?
33	Practical aspects of electrical deterrence: engineering solutions are lacking and will be required before deployment in real-world applications can be feasible.

2.3.5 Trapping for Translocation, Conditioning or Lethal Removal

Capturing problem pinnipeds in traps has been a routine management method applied for protection of migrating salmonids at locks in rivers in the USA (Brown *et al*., 2008). Capture and removal has also been used at some salmon aquaculture sites in Tasmania (e.g. Robinson *et al*., 2008b) and in specially adapted salmon traps in the Baltic Sea (Lehtonen and Suuronen, 2010). Designs for a floating trap for this purpose are available in a patent (Sandlofer, 1989) and Brown *et al*. (2008) describes the use of a significant number similar devices at locks on rivers. Once seals were captured at aquaculture sites, farm managers would be able to make an informed assessment of whether or not the captured seal was a “problem animal”. Certainly, they should be much better able to do this reliably than could a marksman. Stomach lavage or scat analysis might reveal evidence that salmon had been eaten, for example. There might also be an immediate indication of whether depredation at the site had ceased. Confirmed “problem” seals could be translocated and released in another location, conditioned to avoid salmon or euthanized.

Capture and translocation has been used extensively in the Tasmanian aquaculture industry, where 4517 translocations of Australian and New Zealand fur seals were made between 1990 and 2005 (Robinson *et al*., 2008b). This was done as a commercial enterprise with some cost absorbed by the Government Department of Primary Industries, Water and Environment. Seals were moved approximately 400km along the coast before being released, but a high number of animals found their way back to the original sites. In 2001, 38% of those animals captured had previously been translocated. The average interval between recaptures was calculated as 38 days for NZ fur seals and 30 days for Australian fur seals, showing that a short-term respite from attacks can be achieved (Robinson *et al*., 2008a).

Where this approach has been applied it has often provided only short term relief due to animals returning (Anon., 2002a). In Scotland, there is such a high density of aquaculture sites on the west coast and Western and Northern Isles that it would seem likely that a “problem animal” might also soon find an alternative farm and translocation might be a case of moving a problem rather than solving it. Moving animals from the west coast to the east (where salmon farms are absent) could lead to concerns amongst wild salmon fishermen and sportsmen who also experience seal depredation. Brown *et al*. (2008) reported that in the US some trapped animals are provided to captive facilities. If the number of seals trapped was to match the numbers currently shot in Scotland (several hundred per annum) it is unlikely that UK or even European captive facilities would have the capacity to accommodate the number of animals involved.

Another potential alternative would be to condition the captured animals to avoid salmon. This might be done using conditioned taste aversion for example (see section 2.3.3). If the captured animals had to be destroyed (as a last resort) then at least they could be killed humanely after a reasonable and justifiable assessment had been made that they were indeed the culprit animal. Traps would need to be specially built and tended, so this would certainly involve expenditure. However, seal depredation can result in very substantial losses and this approach might not necessarily be more expensive than other options, such as expensive ADDs and the cost of bringing in a specialist marksman. It is a method that could be applied as soon as a seal depredation problem started.

KG No.	Knowledge Gap
34	What legal and ethical restrictions would affect the use of trapping for translocation, conditioning or lethal removal?
35	What would the monetary cost of implementing such a trapping system be?

3 Acoustic Deterrents in Capture Fisheries

3.1 Nature of the Interactions

There is a long history and extensive literature on the issue of marine mammal depredation on, and bycatch in, capture fisheries (Northridge, 1984; Northridge, 1991; Wickens, 1995). Pinnipeds are widely reported to interact with fishing operations practically everywhere the two overlap (Wickens, 1995). Many cetacean species also interact with fisheries in a variety of detrimental activities as well as some mutually beneficial ways. Problems from the fishery perspective include depredation – the removal of fish from nets - and damage to fishing gear. Problems from the perspective of the marine mammals include bycatch and injurious retaliation from fishermen.

Konigson (2006) categorised depredation type interactions in much more detail using as her template interactions between grey seals and static net fisheries in the Baltic. These are reproduced below:

<u>Losses due to seal attacks</u>

Visible and direct losses

- Damaged catch
- Damage to fishing gear

Invisible direct losses

- Catch removed completely from the fishing gear
- Fish scared away from the fishing area

Indirect losses due to damaged fishing gear

- Loss of catch due to damaged fishing gear
- Costs of new material
- Time spent repairing fishing gear
- Reduced life of the fishing gear

Indirect additional losses

- Increased time and fuel consumption due to checking and hauling the fishing gear more often
- Longer fishing trips to areas where there is less seal interference
- Lost fishing opportunities, due to both fishing grounds and fishing gear not being worth using any more as a result of seal interference

The same list would apply in many other situations, including those involving cetaceans. Damage to fisheries by cetaceans includes the depredation of longline fisheries by killer whales, sperm whales (*Physeter macrocephalus*) and other large toothed cetaceans (Hamer *et al*., 2012), and damage to coastal gillnet and trammel net fisheries by bottlenose dolphins (Bearzi, 2002; Read, 2008) among some other species.

Bycatch is recognised as being the single greatest conservation threat to marine mammals globally, with (very crudely estimated) annual totals of over 300,000 cetaceans and a similar number of pinnipeds drowning in fishing gear globally (Read *et al*., 2006).

Within Scotland, gillnet fishing is limited to a small number of vessels, but bycatch and depredation are recorded from such fisheries nonetheless (SMRU unpublished data). Seal bycatch has also been recorded to a limited extent in trawl fisheries in Scotland, while damage by seals is widely reported in trap net (bag net) fisheries for salmon, and in salmon rod and line fisheries, where the mere presence of seals in the vicinity of rod and line fishing can be enough to reduce catches to zero. As a consequence, seals are shot under licence at river fisheries and at netting stations, with 225 having been reported shot in such circumstances during 2012[11].

Although there has as yet been no comprehensive assessment of seal bycatch in Scotland or in the UK, published estimates for South-Western waters (England and Wales) suggest an annual take of several hundred (mainly grey) seals in static net fisheries.

3.2 Minimising Interactions Using Pingers

Globally, there has been a great deal of attention devoted to the use of acoustic deterrent devices in attempts to minimise both depredation and bycatch involving marine mammals. This research can best be examined by focusing on the broad fishery type.

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[11] http://www.scotland.gov.uk/Topics/marine/Licensing/SealLicensing

Dawson *et al*. (2013) have provided a recent review of efforts to minimise both bycatch and depredation in gillnet fisheries. The authors tabulated 28 acoustic deterrent devices from 12 different manufacturers, a few of which are now no longer being marketed. These devices are primarily used to minimise bycatch of cetaceans, but at least seven of these devices have also been tested as potential deterrents of depredation by cetaceans. Most of these devices are relatively low powered, use alkaline, lithium-ion or rechargeable batteries, and are designed to be small enough to hang from a gillnet. Such devices are generally referred to as 'pingers' (See section 1.3)

Some 19 controlled experiments were reviewed by Dawson *et al*. (2013), in which the use of pingers was tested in nets fished against control sets without active pingers. Fourteen of these trials were targeted at reducing harbour porpoise bycatch, and in all but three of these there was a clear reduction in porpoise bycatch. In three experiments either no bycatches were observed at all, or pingers showed a degree of mechanical failure. In five other studies pingers were shown to reduce bycatch of common dolphins (*Delphinus delphis*) and other pelagic cetaceans: striped dolphins (*Stenella coeruleoalba*), franciscana (*Pontoporia blainvillei*) and bottlenose dolphins. Bycatches of common dolphins were reduced in two fisheries, as were those of beaked whales and franciscanas. Bycatch rates of striped dolphins were lowered in a controlled experiment in the Mediterranean, but did not continue at the low rate shown in the experiment once pingers were more widely used in the fishery in an extended trial. Bycatch rates of bottlenose dolphins were not significantly reduced in the final study, but the sample size was small. Evidence from a variety of other trials suggests that bottlenose dolphin bycatch cannot easily be reduced using pingers, and that some pingers may have the opposite effect of arousing an antagonistic reaction in this species. Overall, the review concludes that pingers appear to work well with shy and neophobic species but are less likely to succeed with species like bottlenose dolphins that appear to be bolder.

Pingers have also been used to try to reduce bottlenose dolphin depredation of set nets in seven experimental trials. Some of these have shown limited reductions in net damage or fish removals, but the results overall have been inconsistent and unconvincing, and Dawson *et al*. (2013) point out that they were unaware of any fisheries in which fishermen have been using such devices voluntarily for any significant length of time in order to address the issue of dolphin depredation. Two other unpublished pinger studies were identified that had resulted in no effect on depredation by cetaceans.

Pingers are generally considered ineffective in minimising seal depredation of gill nets, and there is more concern that pingers deployed to minimise cetacean bycatch may end up increasing pinniped depredation. Such effects have been demonstrated in Argentina (Bordino *et al*., 2002) for South American sea lions (*Otaria flavescens*) and for grey seals in Sweden (Stridh, 2008). Carretta and Barlow (2011) found an increase in sea lion entanglement and an increase in depredation after pingers had been introduced to the California driftnet fishery for swordfish and sharks, but found this was most likely not due to the pingers themselves but to other factors including increasing sea lion numbers. They also noted a decrease in elephant seal (*Mirounga sp.*) bycatch after pingers became mandatory.

Marine mammal interactions with longlines also include both bycatch and depredation. Hamer *et al*. (2012) have reviewed the records of cetacean entanglement and depredation in such fisheries, and they report at least 15 cetacean species either depredating or becoming caught in longline fisheries. In higher latitudes where demersal longlines are most common, sperm whales and killer whales are the species most frequently involved. In lower latitudes where pelagic longlining for tuna is common, false killer whales and pilot whales (*Globicephala spp.*) are most frequently recorded. In at least two cases Hamer *et al.* (2012) state that there is evidence of cetacean population declines (for a false killer and a pilot whale population) as a result of these interactions. Losses to fisheries have been estimated in a couple of locations as running into several thousand dollars per day per vessel. In some areas fishing is no longer economically viable and fishing is diverted away from areas of high depredation.

Unsurprisingly, given the high economic costs involved, several companies market or plan to market acoustic deterrent devices intended to minimise whale depredation of longlines. Tests of such devices are limited. Mooney *et al*. (2009b) tested one device (Savewave) with a captive false killer whale (*Pseudorca crassidens*) in Hawaii. They found that the device initially disrupted the animal’s ability to detect targets, but that the device became less effective with time. A new version of this device is now marketed by Savewave as the Orca Saver[12], but there appear to be no independent tests of its efficacy.

Nishida and McPherson (2011) tested two STM products (Dolphin Dissuasive Device, or DDD and Dolphin Interactive Dissuasor, or DiD) in the Japanese longline fishery in the Pacific where they were attempting to prevent toothed whale depredation (mainly by killer whale and false killer whale). Preliminary results suggested that both devices ‘probably’ caused a reduction in depredation.

We are aware of at least two other companies that intend to market, or are already marketing, acoustic deterrent devices to longline fisheries[13 & 14]. The effectiveness of these devices and this approach remains untested.

KG No.	**Knowledge Gap**
36	Efficacy of devices designed to deter depredating odontocetes in capture fisheries is currently unknown.

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[12] http://mustad-autoline.com/products/orcas_saver/

[13] http://www.lofitech.no/

[14] http://www.aceaquatec.com/scareroffshoretest.htm

Interactions between large whales and static gear including fish-traps and creels are well known from many parts of world, where substantial mortalities may occur. Early research in this area was undertaken in Newfoundland by Jon Lien, who was one of the pioneers of acoustic deterrence. Lien and colleagues showed that a prototype pinger could be used to minimise humpback whale (*Megaptera novaeangliae*) collisions with fish traps (Lien *et al*., 1992).

Acoustic alarms (pingers) have been used by the Queensland Shark Control Program (QSCP) since 1992 (Erbe and McPherson, 2012) and are also used in other Australian states as well as South Africa to prevent both dolphin and whale entanglement. It is as yet unclear how effective these devices have been, with conflicting reports in the literature due in part to the low background rates of entanglement of just a few animals per year (McPhee, 2012). Several devices have been trialled, including a newly marketed device, the Fumunda/Future Oceans 3 kHz whale pinger, which is intended to work at frequencies aligned to humpback whales' peak hearing sensitivities. Promotional material from future oceans[15] suggests this device is effective, though we have yet to see the results of any independent trials[16].

KG No.	Knowledge Gap
37	Efficacy of low frequency devices for deterring baleen whales is unknown.
38	There is general lack of understanding of the response of marine mammal species to different signal-types and how these responses are modified or mediated by context.

3.3 Use of Seal Scarers in Capture Fisheries

Seal scarers similar to (or in some cases the same as) those used in fin-fish aquaculture have been used by some other marine industries, including wild capture fisheries, to try to limit seal depredation. These have all been louder devices than the pingers discussed above. Acoustic deterrent devices used in these circumstances tend to require large amounts of power, necessitating either mains electric or generator supply, or the use of large lead-acid batteries. Such devices are problematic to deploy directly in the open sea. At least one manufacturer advertises their product as being effective at deterring seals and sea lions, as well as cetacean species, from trawl and longline fisheries[13]. The Lofitech ADD has also been trialled, with some success, as a predator deterrent in salmon fisheries of the UK and Sweden (e.g. Graham *et al*., 2009; Konigson, 2006; Westerberg *et al*., 1999).

Conflicts between pinnipeds and salmonid fisheries in America have driven the development and testing of several different anti-predator devices/techniques, some

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[15] http://www.futureoceans.com/products/future-oceans-3-khz-whale-pinger

[16] See also press report: http://www.alaskajournal.com/Alaska-Journal-of-Commerce/June-Issue-3-2012/Pingers-show-promise-to-keep-whales-away-from-nets/

of which may have application elsewhere. The original research and development for the “sealchaser” by Oregon State University was largely intended for the defence of salmon hatcheries and wild salmon stocks returning to spawn. Migrating fish, restricted by structures such as locks and dams, were found to be particularly vulnerable to pinniped attacks (Mate *et al*., 1986a). Between 1980 and 1984 the device was tested at three study locations. This device was found to have a significant effect in reducing the number of foraging seals at three study sites.

A report in Mate and Harvey (1986) by Andrew Rivinus found a device to be effective for around two years when used to protect a fish ladder and salmon release facility in Yaquina Bay, Oregon. Few details were reported, but after two years of apparently no interactions, seal activity in the vicinity of the transducers was noticed and this continued in subsequent years with two to four animals seemingly unaffected by the device.

Geiger and Jeffries (1986) reported on the use of acoustic deterrents to carry out a ‘drive’ designed to flush harbour seals from Youngs River, Washington, using a technique previously tried by Mate and Miller (1983). Two boats motored slowly down the river while towing acoustic deterrents until they reached the mouth of the river where an ‘acoustic barrier’ (sound emitting devices arranged in a line across the river mouth) was switched on. Interviews with local fishers were used to assess the effect of the ‘seal drive’. They reported a temporary reduction in seal interactions which quickly returned to maximum levels after just 2-3 days. Seals seemed to quickly learn strategies to avoid the barrier, with an account of at least one seal swimming near the sound source with its head out of the water. They concluded that AHDs were not completely successful, and after longer periods of use in attempts to deter seals from gill-nets, predation returned to previous levels or even higher when the device was active.

Westerberg *et al*. (1999) used a Lofitech device to protect salmon and whitefish trapnets in the Bothnian Gulf during 1997 and 1998. The ADD was activated on an intermittent schedule, and by comparing the proportion of catch that was damaged by seals during on and off periods, they showed that four of five trials experienced significantly lower predation rates while the device was active. Again, it is interesting to note that despite experiencing damage levels of up to 50% of the catch when the device was active, the subjective opinion of the fishermen was that the ADD had been effective at deterring grey seals. This highlights the fact that ‘effectiveness’ can be a relative metric, dependent upon expectations as well as economics.

Yurk and Trites (2000) tried to prevent harbour seal predation on out-migrating salmonid smolts, occurring under two bridges across the Puntledge river in Courtenay, BC. The (Airmar) ADD was found to be the most effective of the methods employed, significantly reducing the number of seals feeding. However, the trial was short at just 14 days and thus does not provide any information on long-term efficacy of acoustic deterrents.

A limited trial of acoustic deterrents to prevent fur seal bycatch and depredation in the New Zealand hoki fishery was reported by Stewardson and Cawthorn (2004 appendix 5.1a). Initial tests in 1990 used an ADD manufactured by a Swedish company ‘Kemers Meskin AB’, a highly directional device, apparently emitting between 200 and 210 dB re 1 µPa (RMS or peak not stated) with peak frequency at 10 kHz. They stated that the system was tested in both near-shore and offshore waters as well as coastal locations close to haulout sites. Offshore results were reported as ‘equivocal’ with some fur seals moving rapidly away while others remained within 1-2m of the transducer for 15-20 minute periods. Analysis showed no significant avoidance behaviour. Near shore results were positive for small and medium sized animals, while larger animals initially showed indifference and later came toward the device. As discussed above, the same device had limited success at evoking an aversive response from juvenile fur seals at a haulout site.

An investigation by the North Eastern Sea Fisheries Committee (NESFC), UK, showed some effect of a Lofitech device on the rate of depredation experienced by salmon and cod fishermen operating on the Yorkshire Coast (NESFC, 2008). By recording the proportion of the catch which showed bite-marks, they found an average predation rate of 12.3% in 2006, which fell to 6.5% in 2007 after the introduction of four acoustic deterrents. A longer controlled study and more detailed analysis are needed to show that this effect was really due to the ADD. Perhaps more interesting is the feedback from the fishermen who used the devices, all of whom believed that the system had a positive impact on the quantity of undamaged fish that was landed.

Graham *et al*. (2009) installed Lofitech scarers in shallow sites in two Scottish salmon rivers, the North Esk and Conan, in an attempt to prevent seals from moving upstream. They estimated the number of seals in each river based on the number of coincident observations and the positions and timing of sightings. Although they were not able to carry out photo-identification, they claim that the absolute abundance of seals in the river did not change after the introduction of the ADD. They did show, however, that the number of seals upstream of the seal scarer was significantly reduced (by around 50%). It is not clear why such a difference should exist between this and other studies using the ‘acoustic barrier’ technique (Geiger and Jeffries, 1986), but possibilities include the very shallow water increasing the efficacy of the ADD and/or the motivation of the seals, which may have been lower at this site than elsewhere. Nevertheless, this study shows the difficulty in generalising from individual field trials.

The Lofitech device was also used by Harris (2011), who tested its effectiveness at reducing depredation of fixed, near shore salmon nets by grey and harbour seals in Scotland. Observations of seal interactions with the nets were made during 124 trial periods over two years (mean observation period 1.6 hours). The number of sightings was significantly reduced, as was the amount of time seals spent in the area. While the ADD was on, catch per unit effort also increased by approximately

33%. In the first year, 2009, no seals were seen within 80m of the device, but in 2010 there were 7 sightings within this area, potentially suggestive of habituation. 56% of seal sightings were photo-identified and this showed that 63% of encounters were with just two seals, indicating that only a small number of seals were using the site.

KG No.	**Knowledge Gap**
39	What proportion of seals have naturally impaired hearing? How does this change with age?

Scordino (2010) summarises the use of Pulsed Power Devices (PPDs) in efforts to reduce pinniped predation on salmonids in North America. These devices rely on high amplitude acoustic signals creating an aversive response and it is therefore included as an acoustic device. First tested on pinnipeds in the early 1980s, these devices discharge high levels of electrical energy, creating ionised gas across the ‘arc-gap’. A wave of compression then emanates from the PPD, followed by an acoustic wave calculated at 240 dB re 1 µPa (peak). The pulse duration was below 500 microseconds, and the energy released was 1.8 kJ. This type of device was tested on captive California sea lions by Finneran *et al*. (2003), who found temporary avoidance of the device, and no evidence of hearing damage (although the device tested here had a much lower output of <183 dB re 1 µPa RMS). Scordino (2010) notes, however, that these devices have yet to be tested in ‘field conditions’, and the size of the device, at 98kg and 2 metres in length, could make deployment impractical.

3.4 Conclusions

Overall, it is clear that pingers are effective in minimising bycatch of some small cetaceans. They appear to do this by displacing the target animals (Dawson *et al*., 2013). Pingers may also be effective in some cases in minimising whale entanglement, but this remains to be fully explored. They do not appear to be effective in reducing seal bycatch, and may indeed increase seal/net interactions by acting as a “dinner bell” when signal frequencies are within seal hearing ranges.

This effect can be contrasted with the much more powerful ADDs which have been shown to be effective to some degree at reducing pinniped depredation, for limited periods of time at least. The Lofitech device in particular has shown promising results in Scottish and Swedish capture fisheries. No studies have found complete cessation of depredation, and in some cases there may have been a small number of individual animals which were unaffected by the ADD (e.g. Harris, 2011).

Several devices are being marketed to minimise cetacean depredation in longline fisheries, but studies on their efficacy are too limited to draw any conclusions. Less powerful pingers used in gillnet fisheries have yet to be proven as a means of minimising depredation by cetaceans in such fisheries, at least beyond the short term.

4 Acoustic Devices to Reduce Risks Associated with Pile-Driving

4.1 Introduction

Some anthropogenic maritime activities bring with them acute and short term risks of damage to marine mammals. Two examples in Scottish waters are the use of explosives and pile driving. Explosives have been widely used in Scottish waters, for example during oil field decommissioning, to sever well heads. The use of explosives is believed to be declining as alternative mechanical cutting technologies are introduced. By contrast, the extent of offshore pile driving has grown enormously over the last decade or so because it is the favoured method of sinking the monopile foundations for offshore wind farms. This trend is set to accelerate; not only are more piles being driven but the diameter of piles and with it the level of acoustic energy output during piling has also increased substantially. Explosives certainly have the potential to cause severe injury or death to marine life including marine mammals. While pile driving is unlikely to cause mortality or tissue damage it is generally believed that pile driving could result in permanent hearing damage for marine mammals at substantial ranges. The traditional approach to mitigation for these activities is to determine an exclusion zone within which animals are thought to be at risk and then to search in this area using visual monitoring (sometimes supplemented by passive acoustic monitoring methods), to determine that no animals are present before the activity (explosive detonation or pile driving) can take place. It is well known that neither visual nor acoustic monitoring is entirely effective at detecting animals, especially small or shy marine mammals such as seals or harbour porpoises, and visual monitoring will be particularly ineffective during poor weather conditions and at night. Providing mitigation monitoring offshore can be a very expensive undertaking often involving a team of several qualified marine mammal observers (MMOs), specialist acoustic monitoring equipment and a dedicated vessel.

One approach which has the potential to mitigate risk by directly reducing the noise created by pile-driving is the bubble curtain. This technique has been tested in a number of projects (e.g. Lucke *et al*., 2011; Matuschek and Betke, 2009; Reyff, 2003; Würsig *et al*., 2000) and has been shown to reduce broadband noise emissions by approximately 5 - 10 dB re 1 µPa.

Another approach to mitigating such acute short-term risks, which could be used as an alternative to, or enhancement of, monitoring, is to use an aversive sound to move animals to a “safe distance” before pile driving or explosions take place. Ideally, a signal of this type would reliably elicit the desired behavioural response without adding significantly to the subjects’ acoustic dose. Aversive sound mitigation has the potential to offer a greater degree of risk reduction and to be very much more cost-effective than traditional monitoring mitigation. The methodology has still to be developed, however, and if it is to offer reliable and quantifiable risk reduction the performance of any system needs to be carefully measured (as, for example, by

Brandt *et al*., 2012b). It is also important that any induced behavioural responses should not be so severe as to lead to adverse consequences such as mothers and calves losing contact with each other, nor animals being caused to strand, nor that widespread and intensive use should clear animals out of large parts of their foraging habitat. Recognising the potential of this approach, the Collaborative Offshore Wind Research in the Environment (COWRIE) commissioned a review to explore the potential of the approach (Gordon *et al*., 2007). Below we briefly summarise the main findings of that review and update it with some recent research.

4.2 Risks and Required Mitigation Performance

The first requirement in assessing a mitigation system is to understand the circumstances and ranges in which different types of marine mammals might be at risk, because it is this information that determines the specification and the performance that any mitigation procedure needs to achieve. UK and European regulators have not put forward any clear criteria for unacceptable physical effects or for the exposure thresholds at which these might take place. US regulators, however, have been more proactive and have provided a series of thresholds for unsafe exposure. In their review, Gordon *et al*. (2007) proposed thresholds for exposure based on values available from US regulators in 2007, and also on their own interpretation of marine mammal research on Temporary Threshold Shifts (TTS). A very useful initiative from the US has been completed and published since the report by Gordon *et al*. (2007), namely a series of workshops of North American experts which critically reviewed available information, explained a procedure for deriving thresholds for exposure for different classes of marine mammals and proposed thresholds for exposure based on the best available evidence. This process is described in an important peer-reviewed publication (Southall *et al*., 2007). This work is relevant to many different parts of the current review and is discussed at greater length in section 7.2 of this report.

Southall *et al.* (2007) put forward two different types of criteria for hearing damage. One was based on sound level, the peak pressure level (in dB re 1 µPa) of a sound, however short, that should be considered unacceptably likely to cause hearing damage. The second was based on received acoustic energy or sound exposure level (SEL) in units of dB re 1 $\mu Pa^2 s^{-1}$. This is a measure of the acoustic dose received over a period of time (nominally 24 hours).

The received pressure level for an animal at a given range from a source can be estimated by applying a propagation loss to a source level. Propagation loss is typically a function of range but the precise nature of the relationship with range varies with environmental factors. Acoustic propagation in the marine environment is a topic of very general relevance. It is of great interest to the military for example and it has consequently been an area of extensive research. Models of propagation loss perform well and are able to make reliable predictions if the environmental parameters (such as water depth, bottom types, sound speed profile etc.) are accurately known. In addition, sound propagation can be readily measured in the field. Thus, ranges at which a certain peak pressure will be expected to occur, required for the Southall *et al*.'s peak pressure criteria, are relatively easy to predict. Sound exposure level for a mobile receiver is more difficult to calculate however. Source level and propagation loss are of course important for defining a sound field around the noise source, but the length of time that the source is active and, critically, the way in which the receiver moves within the sound field are additional and highly influential parameters. Animal movements during pile driving exercises have not been measured. It is assumed that sensitive animals move away from the sound source. Observations of reduced densities over extensive ranges after pile driving (e.g. Brandt *et al*., 2012a) certainly indicate movement away from pile driving activity, but they don't provide information on the speed or directivity of movements.

Gordon *et al*. (2007) used a simple movement model (an animal moving directly away from a sound source at plausible swimming speeds) and values of source level and propagation loss from published field observations of pile-driving operations, to determine the starting range at which various thresholds for exposure might be exceeded and thus, the range at which mitigation systems would need to be effective. For this report we have repeated these calculations using the threshold values proposed by Southall *et al.* (2007) and also new thresholds that we have derived by applying the Southall methodology to new research findings. The most important of these newly reported research findings in this context are contained in a paper by Klaus Lucke and colleagues (Lucke *et al*., 2009). This reports on a series of trials which measured TTS caused by exposing a harbour porpoise to airgun pulses. An airgun was used in these experiments as a surrogate for pile driving: Airguns produce intense low frequency signals with similar acoustic characteristics to pile driving pulses but they are relatively easy to operate close to captive animals. Lucke *et al*., (2009) showed that TTS was induced in harbour porpoises at an unexpectedly low sound exposure level of 164 dB re 1 µPa² s^{-1}. Applying Southall *et al.*'s logic and methodology (which assumed that the injury threshold was 15 dB above the threshold for TTS) provides a predicted SEL injury threshold for porpoises of 179 dB re 1 µPa² s^{-1}. This was much lower (some 19 dB less) than the levels suggested by Southall *et al.* (2007) for high frequency cetaceans, and which had been based on experiments with bottlenose dolphins and beluga whales. Lucke *et al*.'s findings were also unexpected because, airgun pulses, like pile driving noise, are dominated by low frequency sound, which is far below the frequencies at which porpoises are most sensitive and also the frequencies (4 kHz) at which TTS was measured by Lucke *et al* (2009). Although these trials were limited to one animal, they have the very significant advantage of having tested the right type of sound (low frequency pulses) on the cetacean species most likely to be affected by pile driving in Scottish waters (the harbour porpoise).

Figures 8 - 11 summarise our modelling results. They show plots of the maximum "starting range" at which cumulative SEL thresholds for PTS would be exceeded for animals that moved directly away from the piling noise in a straight line for the duration of piling. The plots are for a 4.7 and 6.5 m diameter pile (less than the maximum likely for some Scottish sites). Values for a range of likely "escape speeds" and propagation loss relationships are shown. It is clear that the "mitigation range" to which animals should be moved before piling starts, varies greatly with propagation conditions, speed of movement and source level. In addition, mitigation range varies between species groups, and those with better low frequency hearing such as seals having the greatest ranges.

KG No.	Knowledge Gap
40	Empirical measures of displacement movement rates are required in order to improve the TTS risk modelling approach. Appropriate movement models are the limiting factor in predicting risk of TTS.

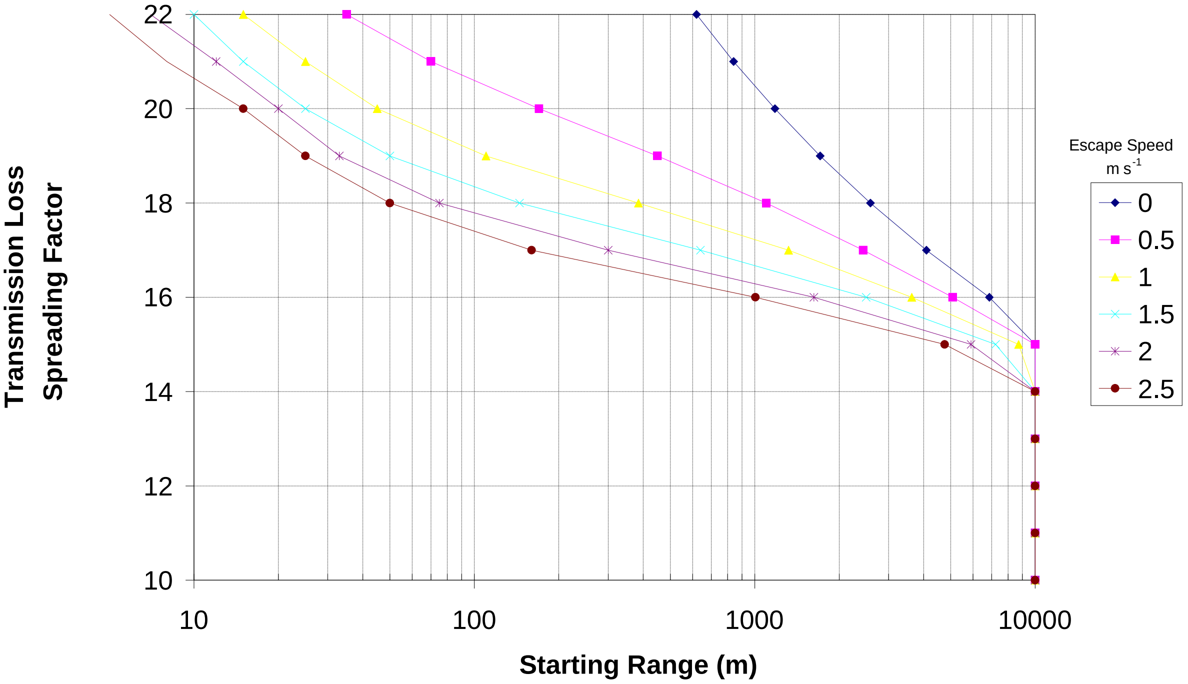


Figure 8 High Frequency Cetacean, 6.5m Pile, Southall *et al*., SEL 198 dB (MHFC)

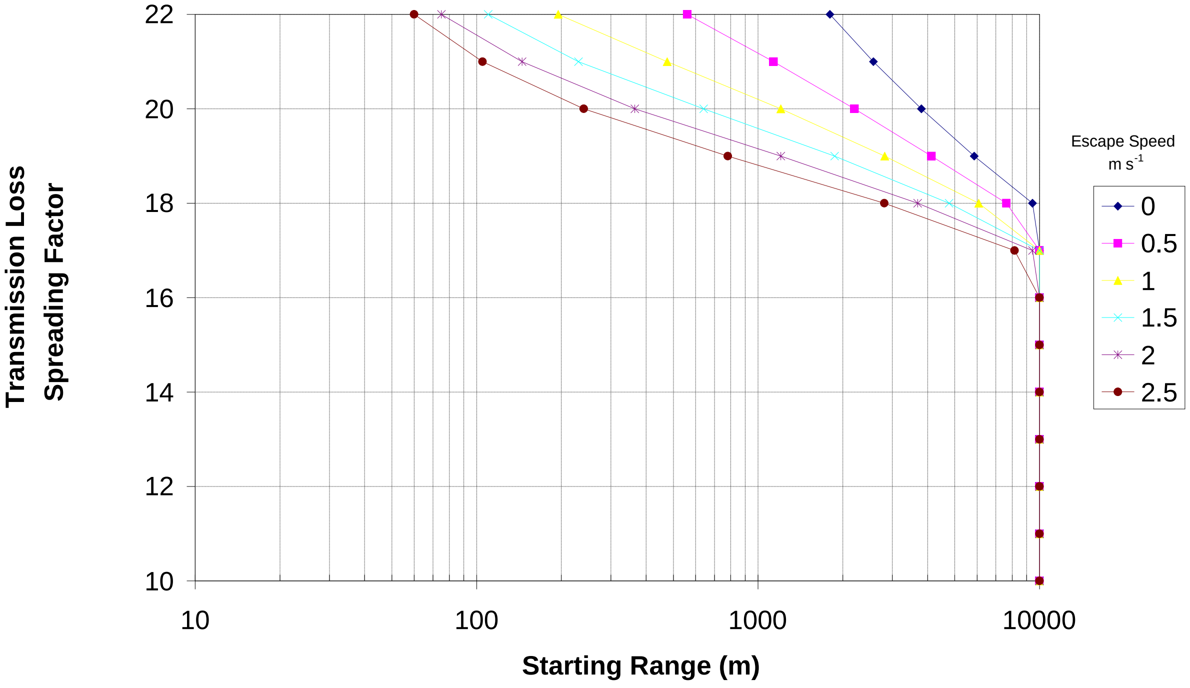


Figure 9 Seals 6.5m Pile, Southall *et al*., SEL 186 dB (Mpin)

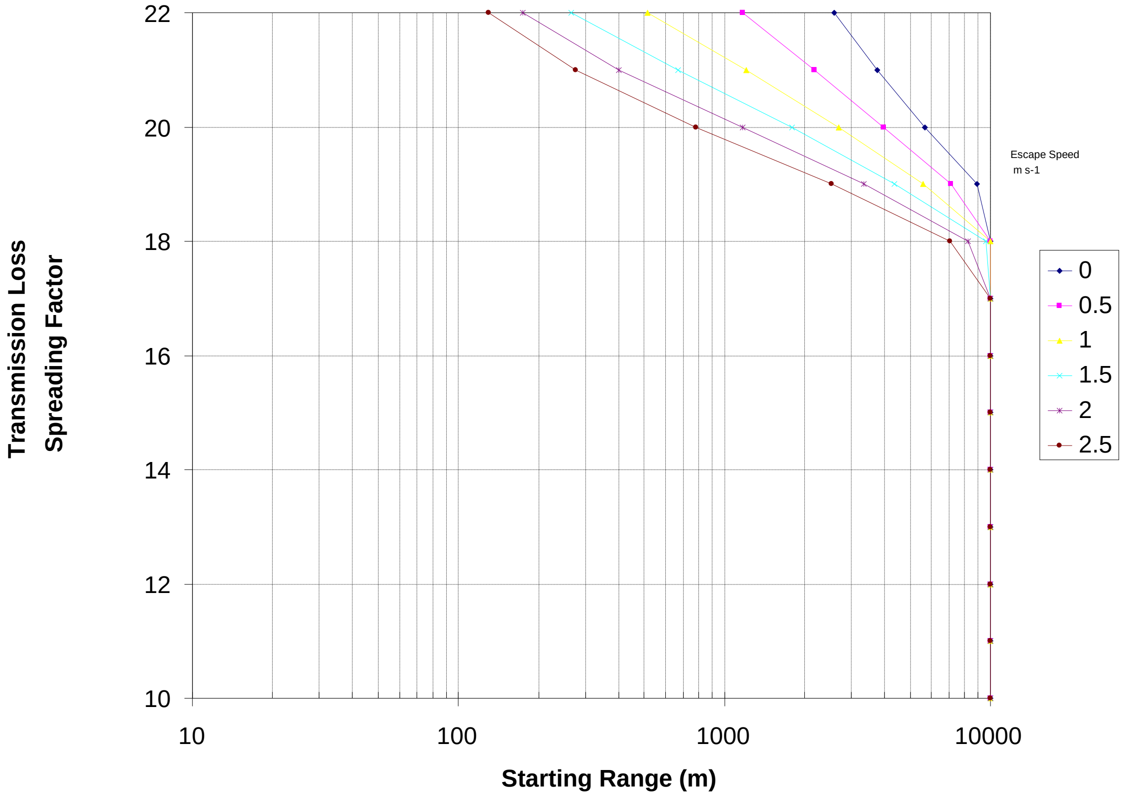


Figure 10 Porpoise 4.7 m Pile, extrapolation from Lucke *et al*., SEL

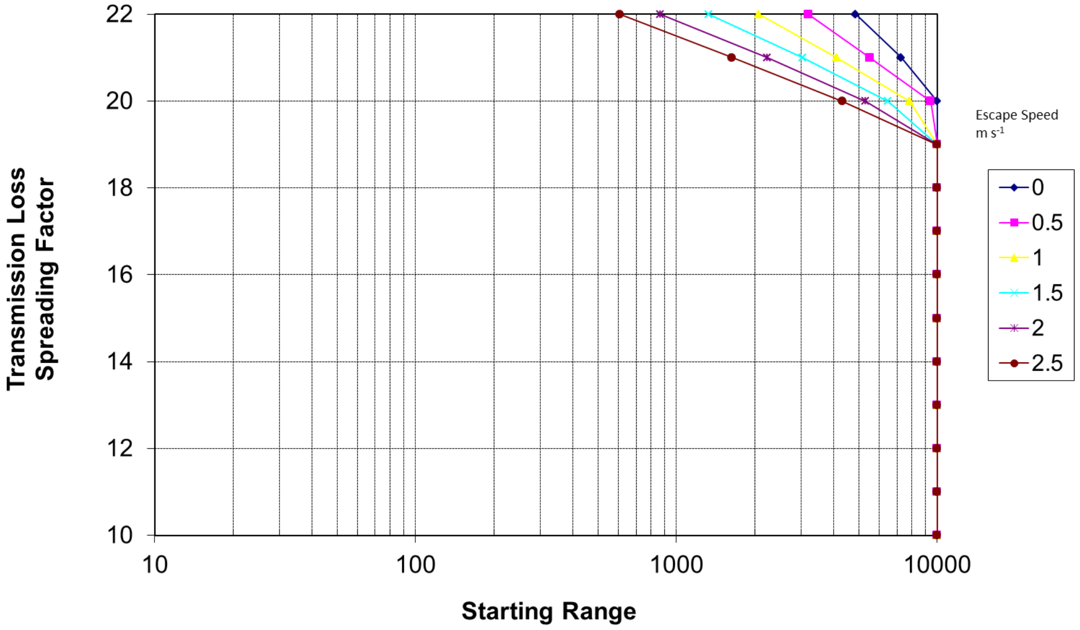


Figure 11 Porpoise 6.5 m Pile, extrapolation from Lucke *et al*., SEL

Figures 8 – 11 show plots of maximum "starting range" at which thresholds for PTS would be exceeded. In each case cumulative exposure was modelled for an animal as a set "starting range" at the start of piling. The animal moved directly away from the piling at a fixed speed throughout the piling episode. The sound field around the pile was determined by a simple propagation loss model PL = TLF Log(range). Plots are shown for a range of transmission loss factors (TLFs) from 10 dB (cylindrical spreading), through 20 dB (cylindrical spreading) up to 22 dB. Scenarios were modelled for a 6.5 m diameter pile with 3000 impacts at full power and a 600 impact "soft start" source level energy flux density of 226 dB 1 µPa^2 s^{-1} for seals and for high frequency cetaceans. See Gordon *et al*. (2007) for additional details.

This is in line with some other similar modelling exercises. For example, a recent environmental impact assessment for a wind farm construction (SmartWind, 2012) suggested that for an 8.5 m diameter pile, a typical range at which the Southall *et al* (2007). SEL threshold for Permanent Threshold Shifts (PTS) would be exceeded for a fleeing porpoise would be 850 m, while for seals the range for exceeding the SEL PTS threshold from a single hammer strike would be 220 m. In this case presumably the range for an entire pile driving exercise would be very much greater.

It is clear there that there are large uncertainties and that mitigation ranges will vary between species and with conditions. However, these modelling exercises do at least indicate that there is a real risk of hearing damage from pile driving and also serve to roughly quantify the performance that an aversive mitigation system needs to achieve: it must be capable of reliably moving animals to ranges of many hundreds or even thousands of meters from a piling location before piling begins and ideally it should do so while adding a minimum additional acoustic dose.

4.3 Candidate Aversive Sound Types

Two different classes of sound might be considered as likely candidates for mitigating pile-driving interactions; those with biological significance (either innate or learned), such as alarm calls or the vocalisations of predators, and those without biological significance, or “inherently” aversive sounds.

In humans, sounds with certain characteristics seem to be inherently unpleasant. Zwicker and Fastl (2004) reviewed psycho-acoustic work in this area and found that measures of annoyance were best explained by a sound’s loudness, fluctuation strength and “sharpness” (sharpness describes a sound having a narrow frequency emphasis within a critical frequency band - higher frequency sounds exhibit this quality more strongly). Other general properties of sounds that are “inherently” aversive to humans include unpredictability (such as randomly modulating amplitude) and dissonance. Dissonant sounds are composed of tones which are not simple ratios of each other. By contrast, humans prefer combinations of tones varying by simple ratios, such as whole octaves: called consonant sounds. Attempts to find a similar preference for consonant sounds in another primate, the cotton-top tamarin (*Saguinus oedipus*), were not successful (McDermott and Hauser, 2004). Thus, findings from human research may be difficult to transfer to other species and these sounds are unlikely to be sufficiently aversive to induce movements over the ranges required.

KG No.	**Knowledge Gap**
41	It is unclear whether auditory preference/aversion is transferable between species.

The startle reflex is a widely exhibited response elicited by loud sounds that have a sufficiently rapid onset. This response is likely to be exhibited by all mammals and is experienced as being unpleasant. Stimuli that induce the startle response are therefore avoided after multiple exposures. Götz (2008) and Gotz and Janik (2010) have explored the use of the startle response sounds as the basis for more effective acoustic deterrent devices. However, elicitation of a sound must be received at a high level and with a rapid onset time. Both of these characteristics will be reduced with range from a sound source as received levels fall and reverberation and absorption reduce the signal rise time. Thus it seems unlikely that it will be practical to induce a startle reflex at substantial ranges except with very powerful noise sources, which might in themselves be considered likely to cause hearing damage.

Absorption and reverberation will affect any and all signal types, such that beyond a given range they may lose their aversive sound characteristics. The range at which aversive characteristics are lost will depend on the complexity of the signal as well as the source level. In this respect, it is the simplest signal types, such as the pure tones produced by the Lofitech device, which will be least affected by increased range.

KG No.	Knowledge Gap
42	Effects of absorption and reverberation on different signal types have not been shown, and could be prohibitive to long-range effectiveness of complex signals.

There are many examples of aversive sounds being used to frighten terrestrial animals away from agriculture. Gordon *et al*. (2007) reviewed several case studies from which a number of useful insights can be taken. Generally, animals habituate quickly to sounds which are repeatedly presented and are not reinforced (with a negative association). Thus, signals should be broadcast for the minimum length of time and if possible should be associated with reinforcement. Typically, sounds that had biological significance, such as alarm calls or predator vocalisations, proved more effective in keeping animals away from crops and were less readily habituated to. A typical course of events was for manufacturers to quickly bring acoustic devices to market, based on initially encouraging results, only to find their effectiveness waned as habituation occurred. Thus, it is important that devices are extensively tested before they are widely introduced.

4.4 Examples of Marine Mammals Moving in Responses to Aversive Sounds

4.4.1 Predator Vocalisations

The killer whale is a predator of most marine mammals, and a number of studies have reported marine mammal responses to broadcast of killer whale calls. For example, Fish and Vania (1971) played killer whale vocalisations to reduce beluga predation of salmon smolts. Beluga showed a strong avoidance. They also avoided playback of 2.5 kHz pulsed tones, however, suggesting a more general avoidance of sounds with acoustics characteristics similar to those of killer whale calls, or simple aversion of unfamiliar sound-types (neophobia). Gray whales (*Eschrichtius robustus)* have also been observed to react to playback of killer whale calls (Cummings and Thompson, 1971; Dahlheim, 1987).

Grey and harbour seals in the Baltic showed strong responses to playback of killer whale calls by either swimming to a resting site and hauling out or moving away to a range of ~1km from the playback (Anon., 2002b; De La Croix, 2010). Similar apparently adaptive anti-predator responses have been observed after opportunistic playback of killer whale calls to grey seals in open water (David Thompson, pers. comm.). Deecke *et al*. (2002) reported a more nuanced response. They broadcast calls of both fish-eating and mammal-eating killer whale pods to seals swimming in the water at haul out sites and measured a smaller behavioural response to the call types from fish eating than from mammal eating killer whales. This suggests that in areas where killer whale pods that do not feed on marine mammals are present it will be necessary to avoid using local call types as aversive mitigation signals.

4.4.2 Sonar

There are a number of reports of strong responses to different types of mid-frequency sonar. After the Second World War whalers hunting baleen whales started to experiment with adapted military sonar units. They soon found that these military units were of marginal value for detecting and localising whales but they scared baleen whales so consistently that the animals would flee on the surface, making their movements predictable and rendering them easier to catch. Special versions of the sonar called “whale starters” were later developed to maximise these aversive effects (Mitchell *et al.*, 1981).

Over the last decade or so it has become clear that mid-frequency military sonar can cause mass stranding and mortality in cetaceans. Beaked whales seem to be the most vulnerable group (Cox *et al.*, 2006). It is now widely believed that the mechanism behind these stranding events involves dramatic behavioural responses of marine mammals to sonar signals received at relatively low levels (Tyack *et al.,* 2011), which, in the case of beaked whales at least, may lead to decompression sickness and mortality (Fernandez *et al*., 2005). Field observations of responses to sonar trials, analysis of stranding events and some extensive on-going behavioural response studies, show that a range of cetacean species including beaked whales (Tyack *et al*., 2011), sperm whales (Watkins *et al*., 1985), minke whales (*Balaenoptera acutorostrata*) (NOAA/DON, 2001), killer whales (Fromm, 2006; NMFS, 2005), melon-headed whales (*Peponocephala electra*) (Southall *et al.*, 2006), pilot whales (Rendell and Gordon, 1999) and a variety of dolphins (NOAA/DON, 2001) all respond strongly to mid-frequency sonar signals. Some have suggested that one of the reasons for this strong avoidance might lie in the acoustic similarities between mid-frequency military sonar and some killer whale vocalisations.

4.4.3 Airguns

Airguns are devices used during seismic surveys to produce very powerful, predominantly low frequency, sound pulses. Concerns about the damaging effects that airguns could have on marine mammals has led to a large amount of research measuring behavioural response (e.g. see review by Gordon *et al*., 2004). Most marine mammals do show avoidance responses, though there are few cases where dramatic behavioural change or large-scale exclusion has been measured. With most of their energy below 200 Hz, airgun pulses lie outside the range of most sensitive hearing for most odontocetes. One of the clearest examples of a short-term behavioural avoidance of a small airgun comes from a series of controlled exposure experiments which were carried out on seals in Scottish, Norwegian and Swedish waters (Thompson *et al*., 1998). A single airgun or small array was activated for an hour at ranges of between 1.5 and 2.5 km and the movements and behaviour of seals was monitored using VHF and acoustic telemetry. Strong avoidance behaviour was exhibited during six out of eight trials with harbour seals, while one animal showed no response. Clear avoidance was also shown by grey seals. Some animals close to land hauled out, while others moved away. As part of the same project, however, Gordon *et al*. (1998) investigated responses of harbour porpoises to both the same small airguns and to full scale commercial arrays by comparing detection rates on towed hydrophones. They were not able to show any statistically significant effects.

Airguns require compressed air to operate so there may be some practical and safety issues with deploying them at sea. Airguns produce powerful acoustic pulses which may contribute significantly to sound exposure, potentially leading to TTS. For example, Lucke *et al.* (2009) used a small airgun to induce TTS in porpoises. The apparently high potential for inducing hearing damage, combined with the lack of clear aversive behavioural responses shown by some species and practical difficulties of deployment in the field, argue against the use of airguns as a mitigation tool.

4.4.4 Acoustic Deterrent Devices

Examples of harbour porpoise and killer whales avoiding acoustic deterrent devices designed for use at aquaculture sites are reviewed in detail elsewhere in this report (section 7.3). In many cases cetaceans have been shown to be deterred at ranges that would be useful for pile driving mitigation (e.g. Olesiuk et al., 1995). Based on these results the use of ADDs has been recommended under the Joint Nature Conservation Committee protocol for mitigation of pile driving (JNCC, 2010). Several recent studies have explored the use of ADDs in this context with promising results.

4.4.4.1 Bioconsult Trials with Wild Harbour Porpoises

One of the most recent and complete set of trials of acoustic deterrents for mitigation to have been conducted since the Gordon *et al*. (2007) report was carried out by the German environmental consultancy, Bioconsult, with funding from the German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety and the Danish Offshore Demonstration Program for Large-scale wind farms. This study was designed to specifically investigate the use of an ADD (a Lofitech seal scarer) for pile driving mitigation with harbour porpoises. Research was carried out at two contrasting field sites. One was an inshore site in Danish Baltic waters where observations of porpoise locations and movements could be made from cliff-based shore station and pods could be used to monitor porpoise presence (Brandt *et al*., 2013). The other site was offshore in the German North Sea. Here, an array of PODs was used to monitor porpoise presence and aerial surveys were also conducted. Results from both are presented in a project report (Brandt *et al*., 2012b) and the offshore work has also been published in the primary literature (Brandt *et al*., 2012c).

At the offshore site, PODs were deployed along three “transect” lines extending from the central location where the seal scarer was positioned during trials. Each line was oriented at approximately 120 degrees to the others with five PODs located along each transect at ranges of 750 m, 1500 m, 3000 m, 5000 m and 7500 m from the central ADD location. A single pod was located in the centre close to the ADD location. Thus, in total there were 16 PODs with three PODs at each of five ranges and one at zero range. Ten ADD broadcast trials were completed. During each trial a boat motored out to the central location, turned off its engine, and then activated the ADD for 4 hours. POD data for 19 hours before and 18 hours after the start of each trial were analysed, grouped into three hour blocks around the start time of each trial. The first hour of each trial was not analysed because it was feared it might be confounded by the influence of the boat arriving. The proportion of porpoise positive minutes in the different three hour blocks were compared for each location. Porpoise detection rates were lower when the ADD was active at all ranges from zero to 7500 m. However, this effect was not significant at two of the five ranges (1500 m and 5000 m). These were two ranges at which porpoise detections were always low and thus would have had lower power to show a change. At zero range, porpoise were almost completely absent when the ADD was active and detection rates were 86% lower at 750 m and 96% lower at 7500 m. Effects seemed to be greatest at locations that had the highest detection rates during control periods. There was no clear evidence of a reduction in the exclusion effect with range and therefore no indication that 7500 m was the maximum range at which reduced densities should be expected. Detection rates “recovered” after the cessation of the trials and in the three hour analysis block between 9 and 12 hours after the trial they were no longer significantly different from pre-trial controls. Brandt *et al*. (2012b) also measured sound levels at different ranges in this environment and calculated propagation loss. These measurements showed a good fit to the “Theile approximation” for propagation loss in this type of environment with a 194 dB re 1µPa (RMS) source level, which gives a received level of ~142dB re 1µPa at 750m and of 115 dB re 1µPa at 7500 m.

On one occasion, visual aerial surveys were carried out immediately before and during ADD activity allowing porpoise densities at the site to be compared. Aerial surveys covered an approximately 30km x 30km square survey block centred on the ADD location and followed a standard line transect protocol. Overall density was significantly reduced, by some 80%, during ADD playback. Before the ADD was active nine porpoises were sighted within 7500 m of the ADD location, while during ADD broadcast one porpoise was sighted in this area (at a range of 6300 m from the ADD). Although the aerial survey data were less extensive than the static acoustic monitoring data, they were very useful in showing that the reduced acoustic detection rates are probably due to animals leaving the area rather than simply changing their vocal behaviour.

One short-coming of these observations from the perspective of assessing ADD use in mitigation is that they measured responses integrated over a 3 – 6 hour period. For practical reasons, and to minimise disruption and the risk of habituation, one would hope to be able to achieve the desired effect of moving animals out of the mitigation zone over as short period as possible. Thus, it is animal movements and density changes in the first hour or so of operation, data which were discounted from this analysis, that are of prime relevance.

Brandt *et al.*'s second study (2013) was conducted at Fyns Hoved, a site in Danish Baltic waters where an elevated vantage point (a 20m cliff) overlooks sheltered waters with a high porpoise density. Visual observations were made from a shore base to a range of approximately 1 km. Porpoise sightings were recorded during standardised 10 minute scans of the area (out to a range of approximately 1000 m) and a theodolite was used to fix the location of porpoises observed at the surface at ranges out to 800 m. A mooring for a broadcast vessel was located below the shore station and 200 m from the shore and a small boat with an ADD was moored here during trials. Four PODs were also deployed: one at the broadcast mooring, and three at a range of 450 m from the broadcast mooring (Brandt *et al*., 2012b). Another one was positioned directly offshore from the mooring and the other two either side of it on a line parallel to the shore. On each trial day baseline observations were made for about an hour after which the shore team would find a group of porpoises within range and track them for long enough to obtain at least five locations before deciding that the trial should start. The skipper would then either activate the ADD for four hours or not activate it. The decision as to whether to activate the ADD was based on the flip of a coin and the shore observers were blind as to whether the ADD was active or not. These trials were supplemented by four days of “response observations” during which the responses of animals to the ADD deployed at ranges beyond 1000 m were observed.

Three types of data were examined for effects of ADD activity: visual sighting rates, acoustic detection rates from the PODs and tracks of animals from theodolite fixes. Sighting rates over the whole observation area, out to 1000 m and analysed in 4 hour blocks, fell from 31 sightings per 4 hours when the ADD was not active to 0.3 sighting per 4 hours when it was active (1.2% of the control value). Both of the sightings during ADD activity occurred at the edge of detection range and occurred after 85 and 21 minutes of ADD activity. To investigate effects on sighting rate statistically, Brandt *et al*. (2012b) constructed a model to predict sighting rate; the hour of the day and sea state were included as significant predictors. When data from the time when ADDs were active were included in the model it became the factor explaining most of the variation. Acoustic detection rates on PODs also fell dramatically and significantly, decreasing from a median of 0.83 porpoise positive minutes in the four hours before ADD activity to zero during the 4 hours that the ADD was active. On average there was a gap of 131 minutes before porpoises were again detected once the ADD was turned off.

Even though porpoises were being tracked before the ADD was activated, it proved very difficult to follow their movements once the ADD was active. In fact the focal animal immediately disappeared from the surface in six out of seven active trials and was not seen again. One animal was seen for four separate surfacings after ADD activation on one occasion and was obviously swimming away from it. During fifteen “response trials” the ADD was activated after porpoises had been tracked at greater ranges. Avoidance was assessed by direct observation and more objectively by combining a range of movement parameters. A porpoise being tracked at a range of 1.1 km immediately disappeared. During four trials at ranges between 1.6 and 2.4 km the animal turned away from the ADD and swam away in a more directional manner. Animals in six trials at ranges of 2.1 - 3.3 km showed no clear avoidance. Animals showing avoidance whose tracks could be determined moved with a mean speed of 1.6 m/s.

Propagation loss of the ADD signal was measured at the Baltic site and found to be much higher than was the case at the North Sea site. Brandt *et al*. (2012b) compared the predicted source levels for avoidance ranges seen at both the Baltic and North Sea sites, fairly complete deterrence appeared to occur at levels of 132 dB re 1 µPa and higher and there seemed to be not clear indications of avoidance at levels below 119 dB re 1 µPa.

These studies complement each other and, taken together, they provide a rather complete picture. The North Sea data were collected in an offshore location typical of those for which mitigation will most often be required in the real world. Here, the POD data revealed effects over large spatial and temporal scales while the aerial survey was very valuable in showing that reduced POD detections reflect a much lower porpoise density, rather than a change in acoustic behaviour. The data collected from the Baltic complements this by revealing the behaviour and movements that lead to exclusion and the speed with which these occur. The Baltic data provided higher resolution information on acoustic received level thresholds for response and it is encouraging that these broadly agree with those from the North Sea.

It is unfortunate however that the research used an aquaculture ADD as their aversive sound source. As noted elsewhere in this report (section 2.2.3) there is little evidence that seals are excluded completely from fish farms by acoustic deterrent devices, and some seals are reported to tolerate ADDs even at farms where they are not depredating the farmed fish. Reports of initial success of ADDs when first introduced do suggest some deterrence effects on naïve animals but, as far as we are aware, no one has measured avoidance in seals over the ranges required for pile driving mitigation. Given seals’ propensity to range over wide areas and the near ubiquitous use of ADDs in some regions (particularly in Scottish waters for aquaculture) it is quite possible that seals have learned not to avoid particular ADD signals and their use at pile driving sites may therefore be ineffective. Existing ‘aquaculture’ ADDs then could be an unwise choice as a tool for mitigating effects of pile driving and other high risk activities on seals.

KG No.	**Knowledge Gap**
43	To what extent can a learnt response to a specific signal (e.g. non-response

	to aquaculture ADDs) be transferred to a different context?

4.4.4.2 Research with Captive Harbour Porpoise and Harbour Seals

A second substantial piece of work that was intended to investigate the feasibility of using aversive sounds for mitigation of pile driving, and funded by COWRIE (The Crown Estates Offshore Wind Research Fund), was a set of captive studies by Kastelein *et al.* (2010) of responses of a harbour porpoise and two female harbour seals to signals from acoustic deterrents, including a pinger (Netmark 100) and two commercially available seal scarers (the Ace Aquatec and the Lofitech). This team measured the detection level for signals from the three devices in both harbour seals and the porpoise. They found them to be very similar to those predicted on the basis of the animals' audiograms. To measure the signals' capacity to deter animals from an area and thus assess their potential as mitigation tools the researchers allowed the subjects (seals or porpoises) to move freely in a pool which contained a speaker broadcasting recordings of ADD signals. Using a speaker rather than the devices themselves allowed broadcasts at lower intensities. One signal was used in each trial and was broadcast at one of three source levels, a level just below that at which a clear response had been observed, a level with a moderate response and a level at which high level of response was expected (in the case of seals this response often involved hauling out to remove themselves completely from the underwater noise). These levels differed somewhat between devices. During trials surfacing rate and an assessment of swim speed were scored and specific behavioural responses, including leaping and holding their heads out of the water in the porpoises, and hauling out for seals, were scored. Trials lasted for 30 minutes and mean received level for sessions was assessed by noting the location of surfacing and relating these to sound levels previously measured in different areas of the tank. Porpoises swam significantly faster, showed more leaping behaviour and had a greater mean distance from the device at higher broadcast levels. Seals also behaved in ways that distanced them from the sound source as levels increased. Kastelein *et al*. (2010) concluded that the Netmark 100 would be unlikely to deter porpoises while the Ace Aquatec and Lofitech would be likely to deter porpoises at ranges between 0.2 and 1.2 km. For seals they suggested the Netmark 100 would be unlikely to have a deterrent effect but the Ace Aquatec and Lofitech should be effective at ranges of between 0.2 and 4.1 km.

It is very difficult to relate observations of trained captive animals in the highly constrained and artificial environment of a test tank to behaviours that might be expected to be elicited from the same species in the wild. In the first place, the received signal itself might be quite different in a constrained reverberant tank. In addition, the context for a trained captive animal will be quite different to that in the wild. The captive animal is probably well-fed and cared for and should be used to being exposed to experimental procedures that do not ultimately harm it. Fear of predation is also unlikely to be a strong motivation. Furthermore, in this case, the animals' ability to display the very behaviour of interest, removing itself from an aversive sound by swimming to a significant distance, was eliminated by the pool size. It is informative therefore to compare Kastelein *et al.*'s (2010) prediction of maximum deterrence range for the Lofitech ADD for harbour porpoises (0.2-1.2 km) with the real world, field observations of (2.4 to 7.5 km+) made by Brandt *et al*. (2012). The work described by Kastelein *et al*. (2010) was carried out by SEAMARCO (Sea Mammal Research Company), one of the world's premier dedicated captive marine research facilities and there is no question that the research was carried out to a very high standard. It is clear, however, that results from captive studies, no matter how well executed, do not provide useful predictions of behaviour in the wild. Behaviour of wild marine mammals, especially straight-forward activities such as movements, can be measured directly and it is only this approach that we believe will provide reliable results.

4.5.5 Discussion

Aversive sound mitigation is essentially a straight-forward concept and we judge the potential for success to be high.

The examples reviewed above provide many instances of marine mammals moving substantial distances in response to sounds well below the level at which hearing damage would be a concern. Indeed, marine mammals seem more likely to move significant distances in response to sound than do terrestrial mammals. Several biological factors may contribute to this. In the first place marine mammals are acoustically oriented animals; they have very sensitive hearing, sound travels very efficiently underwater and their primary sensory modality is acoustic. They also live in a habitat that might favour flight as a strategy for avoiding threats. For many terrestrial animals, crypsis and/or hiding represent good strategies to adopt in response to a frightening signal and to avoid predators. For marine mammals in the open sea this is unlikely to be an option for two reasons: there are few refuges or hiding places at the surface in the open sea, and the length of time they can remain still and hidden underwater, near the bottom for example, is limited by the need to return to the surface to breathe. For these reasons, aversive signals may be more likely to cause displacement in marine mammals than in many terrestrial animals and we might expect to achieve better results than have been shown in some terrestrial studies.

Many attempts to use aversive sounds to keep pests or predators away from sensitive areas such as agricultural sites (including the use of ADDs at fish farms) have shown reduced success over time because of declining responsiveness of animals that may be highly motivated to feed on the food resource being protected. Neither of these concerns should apply in this case. Clearly, a food resource is not being protected so there should be no strong motivation for the animals to remain in the area. Habituation is also unlikely because the signal need only be broadcast for a short period of time (this is one of the reasons why it is important not to use signals such as ADDs that other marine uses may leave activated for long periods). In addition, in this case, if any learning does take place, we might expect it to result in sensitisation because the animal may learn to associate the ADD signals with the unpleasant sensation of pile driving that follows.

While the concept of aversive sound mitigation is straight-forward many details still need to be explored. In particular, a range of appropriate signals must be tested in field conditions on the range of species of concern to provide regulators with reliable and auditable foundation of knowledge with which to justify amended mitigation protocols.

5 Active Acoustic Devices to Reduce Risk of Marine Mammal Collisions with Tidal Turbines

5.1 Background

The renewable energy industry already makes up a significant proportion of Scottish energy production and consumption. The Scottish Government has set the ambitious target of generating the equivalent of 100% of Scotland’s gross annual electricity consumption from renewable sources by 2020. Scotland is well supplied with many forms of renewable energy, including hydro (which is already heavily exploited), wind, and wet renewables (wave and tidal). It is recognised that an effective strategy for a low carbon future will require the utilisation of all of these options. Within the portfolio of renewable energy sources, tidal power has the unique advantage of being highly predictable. It has been estimated that Scotland has some 14GW of tidal potential and has already become a world leader in developing tidal power technologies. A number of tidal generation devices have been undergoing tests for several years at the European Marine Energy Centre (EMEC) in Orkney and the first commercial arrays are slated to start construction within the next few years in the Sound of Islay and the Inner Sound.

Tidal turbines are driven by some type of rotating blade, often with quite considerable tip speeds. Most prototypes resemble the typical wind-turbine design, with an axis of rotation parallel to that of the water-flow, and these designs may either be ducted or un-ducted. There are also devices such as the TidGen device made by Ocean Renewable Power Company, Maine, USA, which have an axis of rotation perpendicular to the water current. It is possible that these (and other) variations will have relevance if different degrees of collision risk are found, but this cannot be meaningfully considered at present due to lack of information. The potential for larger marine animals, in particular marine mammals, to be in collision with these rotating blades has been raised as potentially serious risk and remains a major environmental concern (Linley *et al*., 2009) which could slow the pace of development of this important technology.

The current embryonic stage of the industry means that a variety of questions concerning marine mammal interactions are currently unanswered. The most fundamental questions are whether or not a genuine collision risk exists and whether or not this risk is sufficiently great to pose a significant concern.

5.2 Assessment of Risk

The possibility that marine mammals will be hit by rotating turbine blades is seen as one of the most serious acute environmental risks posed by tidal stream electrical generators (Wilson *et al*., 2007; Wilson and Gordon, 2011). Simple modelling exercises indicate that significant numbers of marine mammals would be struck if they do not take action to avoid tidal turbines (Wilson *et al*., 2007). We will not know how marine mammals respond to these devices until turbines are deployed in the marine environment and appropriate observational research is conducted to track animal movements and responses in their vicinity. However, given the low water visibility at Scottish tidal rapid sites, it is clear that the main means for detecting these devices at sufficient range will be acoustic.

Odontocetes, which have well developed echolocation abilities, will be able to detect turbines using both active and passive acoustic sensing, while seals and baleen whales will be reliant on passive acoustic cues. A pertinent question then becomes whether marine mammals will be able to detect turbines acoustically at a sufficient range to be able to take appropriate evading action. Tidal turbine devices certainly generate underwater noise. It is likely that much of this will come from the machinery in the gearboxes and generators within the device. Tidal turbine development is still at an experimental stage with a diversity of different device types being trialled. It is probable that they will differ in their underwater noise output and so far, few data on acoustic characteristics are openly available. Background noise levels in strong tidal current areas can be quite high and variable due to the effects of water turbulence and sediments moving in tidal streams. Such tide-induced noise also varies temporally, being strongest when currents are highest, and the distribution of some noise, especially sediment movement noise, varies spatially, often occurring in quite discrete patches which may correlate with sediment patches (Gordon *et al*., 2011). These high levels of noise could mask turbine sound making these devices more difficult to detect.

KG No.	**Knowledge Gap**
44	The acoustic output of tidal energy devices in all states of operation is unknown.

The only source of empirical data about potential collision risk is the SeaGen installation in Strangford Lough. The SeaGen tidal device in Strangford Lough consists of two 16m diameter turbines, which slide up and down a 3m diameter pile. The blade angle is adjustable so that a maximum tip-speed of around 12m/s can be maintained. Marine mammal observers were stationed on the pile for the first year of installation, allowing collection of data which has since been used to inform the use of active-acoustic monitoring. The turbine was shut down if marine mammals were detected by observers or on active acoustic systems. The minimum range at which a marine mammal was allowed before shutdown was initiated was gradually reduced over this time from 250 m to 50 m, and 15 shutdowns were conducted in the first year. Shoreline surveillance has also been conducted in order to examine any carcasses for evidence of interaction with the turbine, but no collisions have been reported. The requirement to shut down and the emphasis on this type of mitigation monitoring has meant that less has been learned about the extent to which animals detect and avoid operating turbines.

5.3 Potential Use of Acoustic Deterrents

If it transpires that the devices' self-noise is insufficient to alert marine mammals to their presence in the ambient noise field and collision risk does become an issue then it may be necessary to use acoustic alerting devices to make animals aware of the presence of tidal turbines. In a report for the Scottish Government, Wilson and Carter (2013) reviewed this topic, provided some new data on noise levels in some strong tidal current environments and provided some consideration of how acoustic devices might be used to mitigate tidal turbine collision risks. They suggested that to be useful a device should have seven attributes. These were that: (1) The signal must elicit an appropriate response. It should either cause the animal to avoid the immediate vicinity of a device and/or, in the case of small cetaceans, draw attention to it so that active acoustic sensing (echolocation) can be used. However, because devices would likely be used over the lifetime of the turbine arrays, which should be many years, it will be important that they should not cause large scale habitat exclusion, especially from any high energy tidal habitats that may be highly preferred by marine mammals (Gordon *et al*., 2011; Pierpoint, 2008). (2) The emission schedule of the device need not be continuous but must suit likely approach velocities. An approaching animal, which may be traveling quickly if it is moving with the current, must be able to detect intermittent pulses with sufficient time to be able to take avoiding action. (3) The emission frequencies must be audible to target species. This is a function of both auditory sensitivity at different frequencies of the suite of species involved but also the frequency spectrum and levels of background noise in the area. (4) Amplitudes must be appropriate for the necessary detection ranges and sites. (5) Signals must be directionally resolvable. Animals will only be able to take avoiding action if they can locate the direction that sounds are coming from. Sounds with different characteristics can be more or less readily localised. (6) The warning should be coordinated with the threat. The threat is greatest when the current is strongest and the turbines are turning. There may be a case for only having a device active when turbines are rotating quickly enough to cause injury. (7) The location of the sound sources at a turbine or within an array must facilitate appropriate spatial responses. Scenarios may become more complicated when many devices are deployed in arrays. Then consideration will need to be given to encouraging avoidance of arrays as a whole and avoiding entrapment.

For echolocating animals we suggest that it will be particularly important to consider whether devices affect echolocation behaviour. Animals that are alarmed by a sound that they might perceive as a predatory threat might well cease echolocating to avoid detection and flee. If this occurred it would be counter-productive as the possibility of detecting the turbines using echolocation would be diminished. Wilson and Carter (2013) investigated the likely detection range for two types of existing active acoustic devices: low power anti-bycatch pingers (section 3.2) and high power aquaculture anti-predator devices (section 2.2). Their results suggested that, in noisy areas, the former would not be picked up at useful ranges while the latter could cause habitat exclusion for some species and might even carry a risk of causing hearing damage. Wilson and Carter's (2013) detection range modelling may be a little pessimistic in that they assumed a rather wide critical ratio for masking and did not allow for a marine mammal's ability to localise sounds (Branstetter and Mercado, 2006), which may reduce the likelihood of masking. Nevertheless, their general conclusion, that a bespoke sound source may need to be developed for this application is, we believe, a valid one. However, we question whether it is sensible to begin work to develop such a system at this stage when the nature of the collision process and the behaviour surrounding it is unknown, as is whether there is indeed a problem that requires intervention.

There are a variety of questions which need to be addressed in order to make a more informed assessment of the severity of animal-turbine collision risk:

KG No.	**Knowledge Gap**
45	At what range will tidal turbines be detectable above ambient/background noise?
46	To what extent can noise hotspots in tidal areas be predicted based on parameters such as benthic composition? How stable are they spatially and temporally?
47	A greater understanding of the response elicited by existing deterrent devices, how this varies between species and contexts, and how this is likely to change over time.
48	A greater understanding of how marine mammals currently utilise tidal environments, and how this is likely to be affected by new structures and activities and additional sound sources.

6 Collisions between Marine Mammals and Vessels

Marine mammals which are in collision with vessels (ship strikes) are often seriously injured or killed. This is certainly an animal welfare issue and for some whale populations, such as North Atlantic right whales (*Eubalaena glacialis*) (IWC-ACCOBAMS, 2011; Knowlton and Kraus, 2001) and Mediterranean fin whales (*Balaenoptera physalus*) (David *et al*., 2011) and it is a major conservation issue as well. In some cases whale collision can also lead to costly damage to vessels and even injury or mortality for passengers and crew (Carrillo and Ritter, 2010; Kato *et al*., 2012). Small cetaceans, whales and pinnipeds all suffer mortality from vessel collisions (Byard *et al*., 2012) and indications are that the number of vessel strikes and the rate of mortality is growing. This is likely to be the result of a greater number of ships travelling at higher speeds (Gerstein *et al*., 1996; Laist *et al*., 2001). The marine mammal ship strike issue is receiving increasing attention in international fora, for example it is on the agendas of both the International Whaling Commission (IWC) and the International Maritime Organisation (IMO). The IWC maintains a database of known ship collisions and this problem, how to measure it and potential solutions, have been the subjects of a number of workshops (e.g. IWC-ACCOBAMS, 2011).

A number of different solutions have been proposed. Clearly, separating vulnerable animals and ships is a sensible action in locations where shipping lanes and predictable areas of high marine mammal abundance coincide and it is feasible to move the shipping to pass through an area with a lower density (Vanderlaan *et al*., 2008). This approach has been applied successfully off the East Coast of Canada in the Bay of Fundy, where a small change in the route of traffic separation zones has resulted in a much reduced risk of collision. Another strategy is to reduce vessel speed and to request seafarers to maintain higher levels of vigilance, especially if vulnerable animals have been sighted in an area. This has been applied adaptively in the shipping lanes for vessels using Boston Harbour which pass through right whale habitat. While these measures will be effective in some locations they do not provide a general solution.

It may initially seem unexpected that marine mammals appear not to detect oncoming vessels and either dive or move out of their way. It could be that animals detect the ships but either do not perceive them as a threat or may lack an innate or learned behavioural repertoire to respond appropriately to vessels moving at these speeds. It could also be the case that they do not detect the vessels in time to take avoiding action. Although large vessels travelling at speed radiate high levels of noise, especially at low frequencies, this is not transmitted equally and there is hypothesised to be a quiet sector directly ahead of large vessels where the noise from the vessel’s propellers and machinery are shielded by the boat’s hull (see Figure 12). In addition, downward diffraction of sound and the Lloyd mirror effect (a form of destructive interference) may reduce sound levels near the surface (Blue *et al*., 2001; Gerstein *et al*., 2011). If this is the case, then an additional acoustic signal which would cause animals ahead of the vessel to move out of the way might be helpful in reducing collisions. Indeed, one potential configuration for this has been patented (Gerstein *et al*., 1996). Ideally, these alerting signals should be directional, so that only those animals ahead of the boat and at greatest risk of being hit would be induced to move, and the sound should cause animals to move to the side, or to dive.

One major concern would be the potential for substantial disturbance that could result if many vessels used such devices continuously, it might therefore be preferable to activate them only in areas of high risk.

The marine mammal for which there has been the most concerted effort to develop an acoustic alerting device intended to minimise ship strikes is the West Indian manatee. These slow moving animals are often hit by speed boats in inshore waters in Florida and some other southern states of the USA (O'Shea *et al.*, 1985) and elsewhere in their range. Gerstein *et al.* (2011) described the development of acoustic alerting devices to warn manatees of the approach of vessels and reported on some encouraging initial trials.

Workshops convened to discuss the vessel strike problem with cetaceans and how to address it have given little attention to the use of acoustic alerting signals. For example IWC/ASCOBANS did not list this as a mitigation option worthy of discussion, while Silber *et al*. (2009) quickly dismissed it, citing the lack of evidence to show that it would work, the potential for habituation and concerns about causing disturbance. One attempt has been made to measure the behavioural response of a right whale to a potential alerting signal (Nowacek *et al*., 2004). In a trial in the Bay of Fundy, focal animals responded to playback of the alerting sound, but not in a way that was thought likely to reduce collision risk: they tended to surface. Unfortunately this single preliminary set of experiments has not been extended to test other signals types or scenarios.

The lack of enthusiasm for using alerting signals is understandable, but may be premature. It is certainly sensible to prioritise the low risk management solution of separating whales and shipping in situations wherever this is feasible but this can only address a small subset of what is a global problem and more proactive measures may therefore be required to provide a more general solution. The first task will be to find signal types that can cause animals to move in an appropriate manner and that are suitable for broadcast from a bow-mounted projector. The research required to achieve this will involve controlled exposure experiments to a range of species of wild animals in real world locations, with observations of behavioural responses being made using an appropriate mixture of telemetry, direct visual observation and passive acoustic tracking. Later work to develop practical and cost effective hardware which can be retro-fitted to existing vessels and to make measurement of responses in increasingly realistic scenarios will be contingent on the results of these trials.

KG No.	**Knowledge Gap**
49	Signal types which can reliably elicit a predictable and useful response in reducing risk of ship-strikes are currently unavailable.

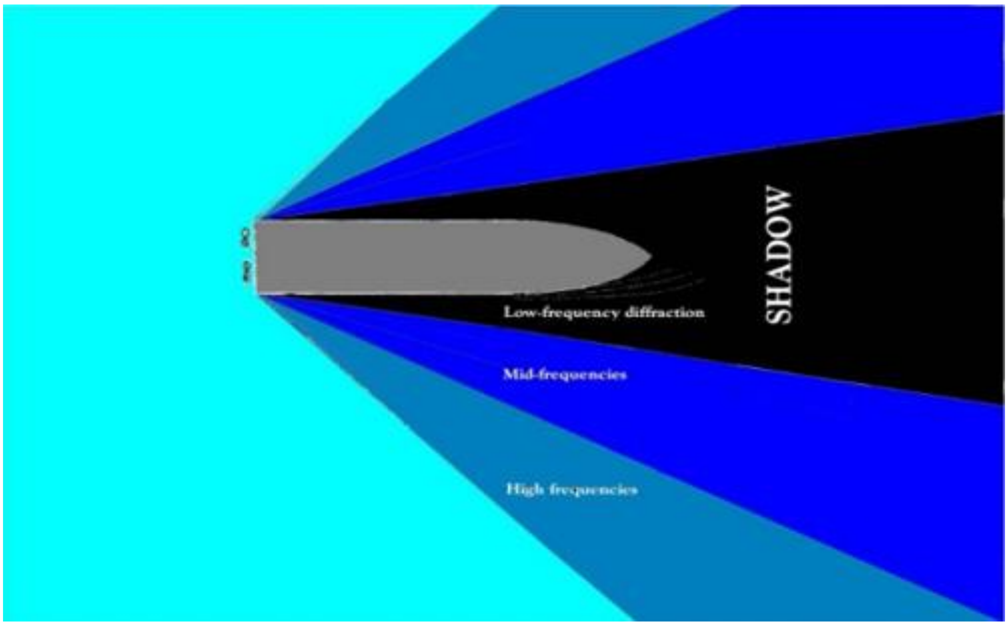


Figure 12 Hypothesised patterns of radiated sound from a ship underway from Gerstein *et al*. (2011). See also Trevorrow *et al*. (2008).

7 Concerns over the Use of ADDs

The primary function of acoustic deterrents is to reduce the impact of human activities on a particular group of marine mammals. In order to deliver an ecologically coherent assessment of ADDs, the benefits created for the target group, or species, must be compared against any potential negative effects upon that group, or any other affected group. Only once a reliable assessment of the likely environmental impacts has been made, can an informed appraisal be made comparing and evaluating the predicted merits with the likely costs.

It is also important to note that what may be regarded as a negative impact in one application (e.g. the displacement of certain species) could be considered as a desired impact in another application. The discussion below relating to disturbance, exclusion and behavioural effects considers these impacts in regards to non-target species, where any impact is conceptually negative. In another instance, such as pile-driving mitigation, where all species might be described as ‘target species’, less species discrimination will be necessary and these impacts should not be considered as negative.

7.1 Reduction in Responsiveness over Time

Many of the studies discussed in this document have reported a reduction in responsiveness over time (Arnold, 1992; Rueggeberg and Booth, 1989; Sepulveda and Oliva, 2005). This is often loosely referred to as “habituation” but could in fact result from a combination of effects. Habituation can be defined as a decrease in a behavioural response to a recurring stimulus. In the case of humans, we know that habituation in this sense results when we no longer pay attention to the recurrent stimulus. Reduced effectiveness of ADDs at fish farms, for example, might also result from animals learning strategies to avoid responding to these signals, or to reduce their effects. For example, some have reported seals swimming with their heads above water, presumably minimising the impact of underwater sound (e.g. Mate *et al*., 1986a). Animals might also learn to approach powerful ADDs between transmissions or find "holes" or "shadows" in the sound field. Northridge *et al*. (2010) report an instance where seal depredation at a site started after the failure of a single transducer in a multi-transducer system. This may have provided a gap in the acoustic field allowing the seals to reach the net. Reduced effects of ADDs on seals could also result from permanent threshold shift, a reduced sensitivity through hearing damage. Götz (2008) highlighted the fact that the early stage of hearing damage often affects the outer hair cells which act to amplify signals within the cochlea.

In practical terms it may be important to distinguish between these different mechanisms for reduced effectiveness in order to find strategies to counteract them. For example, habituation is known to be stimulus specific, and the behavioural response (deterrence) may return when presented with a new stimulus or if the sound source is active only intermittently. A model of ADD which has been designed to generate a diversity of signals, presumably to minimise habituation is the Terecos DSMS-4 (section 2.2.1).

The distinction between habituation and hearing damage is also very important in this context. When the fatiguing stimulus is withdrawn from a habituated animal for a period of time, the response is known to recover at least partially (Rankin *et al*., 2010). This is obviously not the case for permanent hearing damage.

While reduction in efficacy has been reported in the majority of studies, exceptions include the work of Graham *et al*. (2009) who tested ADDs in Scottish salmon rivers and stated that they found no evidence of reduced effectiveness over a five month trial period, and that of Kastelein *et al*. (2006) who found that while captive animals exhibited slight habituation within a 45 minute sound exposure, this did not transfer between days. Neither of these studies was conducted at a fish farm and for both of them the sound source was active for relatively short periods of time. Similarly, Dawson *et al.* (2013) found that there was no evidence of habituation, or any diminution of the response of cetaceans (as measured by bycatch rates) to long-term exposure to pingers on gillnets, and Morton and Symonds (2002) found no reduction in the displacement of killer whales by ADDs over several years. In part, this variation can probably be explained by motivation, or lack thereof. In the context of pingers preventing bycatch in gillnets, there is no strong motivation for cetaceans to approach nets, whereas for seals at aquaculture sites, this may not be the case. Gotz and Janik (2010) for example showed that captive seals rapidly stopped showing an aversive response to a received level of up to 146 dB re 1 μPa (RMS) when food was provided as a motivation to stay close to the loudspeaker.

The work of Götz and Janik (2011) measuring startle responses is unique in that in their trials the animals seemed to show sensitisation and increasing responsiveness with repeated exposure. As part of work to develop a more effective ADD based on the startle reflex they exposed seals in captivity to loud, fast onset sounds, designed to elicit a startle response. Startle sound were preceded by a quieter alerting signal. They report increasing responsiveness to the signal. Eventually animals would react to just the alerting signal by leaving the feeding station and hauling out. Trials are now underway to explore whether this will translate into real-world application in ADDs that are really effective in context of a commercial fish farm.

7.2 Hearing Damage

7.2.1 Thresholds and Criteria for Hearing Damage from Sound Exposure

To effectively manage risks resulting from the exposure of marine mammals to loud sounds, regulators need to work with agreed criteria for acceptable exposure, and to establish thresholds below which exposure might be considered to be of minimal concern. This is a difficult task, in part because, until recently, very little information on the effects of noise on marine mammal hearing existed and, although studies have been carried out over the last decade or so, information is still sparse. Regulators in Europe and the UK have not proposed any science-based thresholds themselves; however, more progress has been in made in North America. Here, the US National Oceanographic and Atmospheric Administration (NOAA) funded a series of workshops for a panel of experts charged with developing criteria for noise exposure for marine mammals. This group was able to find little basis for proposing generally applicable thresholds for behavioural responses to sound. Effects of sound on marine mammal hearing however, which largely result from a combination of mechanical and physiological processes, have proven more amenable to prediction. A review of much of the research that supported their deliberations, a detailed explanation of how these were then used to determine criteria and the proposed thresholds themselves, were published in a peer reviewed paper (Southall *et al*., 2007). These criteria are often termed the “Southall Criteria”.

Noise can result in hearing damage via two mechanisms. Exposure to extremely loud acoustic pressures or impulses can cause instantaneous damage mechanically. Sound exposures at lower levels over longer periods of time can also result in permanently impaired hearing which is more likely to be related to metabolic exhaustion of sensory cells from over-stimulation. In this case, as a first approximation, the total amount of sound energy received over a time period, the sound exposure level (SEL), is a more useful metric than sound pressure level (SPL).

Reflecting these two mechanisms, Southall *et al.* (2007) proposed a dual set of criteria: **sound pressure level** thresholds determining the maximum allowable peak pressure exposure, however brief; and **sound exposure level thresholds** defining the maximum allowable dose of acoustic energy received over an extended period (up to 24 hours).

7.2.2 Measuring Hearing Damage (Temporary and Permanent Threshold Shifts)

It is considered unethical to directly damage the hearing of marine mammals experimentally, so instead, as is the case with most human research, the phenomenon of temporary threshold shift (TTS) has been studied. As its name suggests, TTS is an impermanent reduction in sensitivity (increase in threshold) resulting from exposure to sound. Hearing returns to pre-exposure levels after a recovery period of minutes to hours. Temporary threshold shift is not in itself considered harmful and is a phenomenon that we all experience and adapt to in our daily lives. It is considered unlikely that occasional TTS is of biological significance for wild animals. Its importance in this context is as an indicator of the exposure levels at which hearing damage might occur. Generally, the greater the sound exposure, the greater will be the reduction in sensitivity. Southall *et al*. (2007) reviewed available marine mammal TTS studies which included data for two species of odontocete, bottlenose dolphins and beluga, and three pinnipeds, the harbour seal, the elephant seal and the California sea lion. In reviewing this literature and the more detailed research with humans and other terrestrial mammals they also found general support for the contention that the total acoustic dose, the sound exposure level (SEL), correlated well with TTS onset over a range of different exposure periods. This relationship is the basis for the so called “equal energy” hypothesis, which states that equal amounts of acoustic energy (measured as SEL) will cause equal amounts of hearing impairment, regardless of how this energy is distributed over time. The studies available provide data on sound exposures leading to TTS for a limited number of marine mammals. It was necessary to extrapolate from these to exposures likely to result in permanent threshold shift (PTS). Based largely on studies of terrestrial mammals and humans, Southall *et al*. (2007) proposed levels of additional exposure required to induce PTS for several different sound types and species groups. They proposed that for continuous sound exposures, levels for PTS should be the levels causing TTS plus 20 dB for all marine mammals. For single or multiple pulses PTS threshold should be that for TTS plus 15 dB.

7.2.3 Frequency Weighting

Different species show both a difference in absolute sensitivity (i.e. in the quietest sounds they can hear) and also some variation in their relative sensitivity at different frequencies. Typically, this frequency dependent variability in auditory sensitivity reflects a species’ life style and the spectral range of its vocalisations. Thus, within marine mammals, high frequency specialists such as the harbour porpoise, have extremely good sensitivity in the high ultrasonic, specifically around 120 kHz - the dominant frequency in their echolocation clicks. Seals have best sensitivity at lower frequencies (in the mid-10s of kHz), as well as having poorer overall sensitivity than porpoises and dolphins. Baleen whales, which predominantly produce low frequency vocalisations, have auditory systems that have adapted to be sensitive mainly to low frequency sound (Ketten, 1997; Ketten, 1998).

It is likely that their differential hearing sensitivities make species more or less vulnerable to the damaging effects of noise at different frequencies (e.g. high frequency specialist might be more likely to have their hearing affected by high frequency fatiguing noise than would low frequency specialists). The most common way of measuring frequency-dependent differential sensitivity is to measure the quietest pure tones that can be just detected at a series of frequencies across the animal's hearing range. A plot of these minimum thresholds against frequency is called an audiogram. For marine mammals, audiograms can be obtained either behaviourally, where a captive animal is trained to respond in a particular way when a sound is detected; or electro-physiologically, by measuring electrical signals from the auditory brain-stem response (ABR) using surface electrodes. Behavioural audiograms are considered superior, but are very difficult and time consuming to obtain. Currently, audiograms have only been measured from a limited subset of marine mammal species and much of the available audiogram data are summarised in Nedwell *et al.* (2004). An audiogram can be a useful basis for determining parameters directly related to the detection of low level sounds, such as the maximum range at which a sound can be detected in a low noise environment. However, it may not be a reliable or appropriate metric for predicting hearing damage caused by exposure to intense sounds.

KG No.	Knowledge Gap
50	Reliable audiogram data (or equal loudness contours) are not available for several of the species found in Scottish waters (e.g. minke whale, white-beaked [*Lagenorhynchus albirostris*] and Atlantic white-sided [*Lagenorhynchus acutus*] dolphins).

Patterns of differing sensitivity to different frequencies reflect in how loud the sound is. "Loudness" is a psychological term (not a direct physical one) which describes how a subject perceives sounds of different intensities and is measured in phons. Measuring loudness for a human is quite straight forward. For example, a subject might be asked to compare their perception of the loudness of tones at different frequencies and adjust the levels of two tones until they are perceived as being the same. In this way plots of how loudness is perceived at different frequencies can be derived (Fletcher and Munson, 1933). By convention, loudness is referenced to the perception of a tone at 1 kHz. Plots of equal loudness (frequency versus loudness in phons) for very quiet sounds generally follow the u-shaped curve of an audiogram. However, as the intensity of signals being tested increases, plots of equal loudness tend to become "flatter". In other words, the differences in perception of loudness with frequency become less pronounced as a sound's intensity increases (Figure 13). The risk of inducing hearing damage from sounds of different frequency is thought to reflect these "flattened" phon plots for more intense sounds.

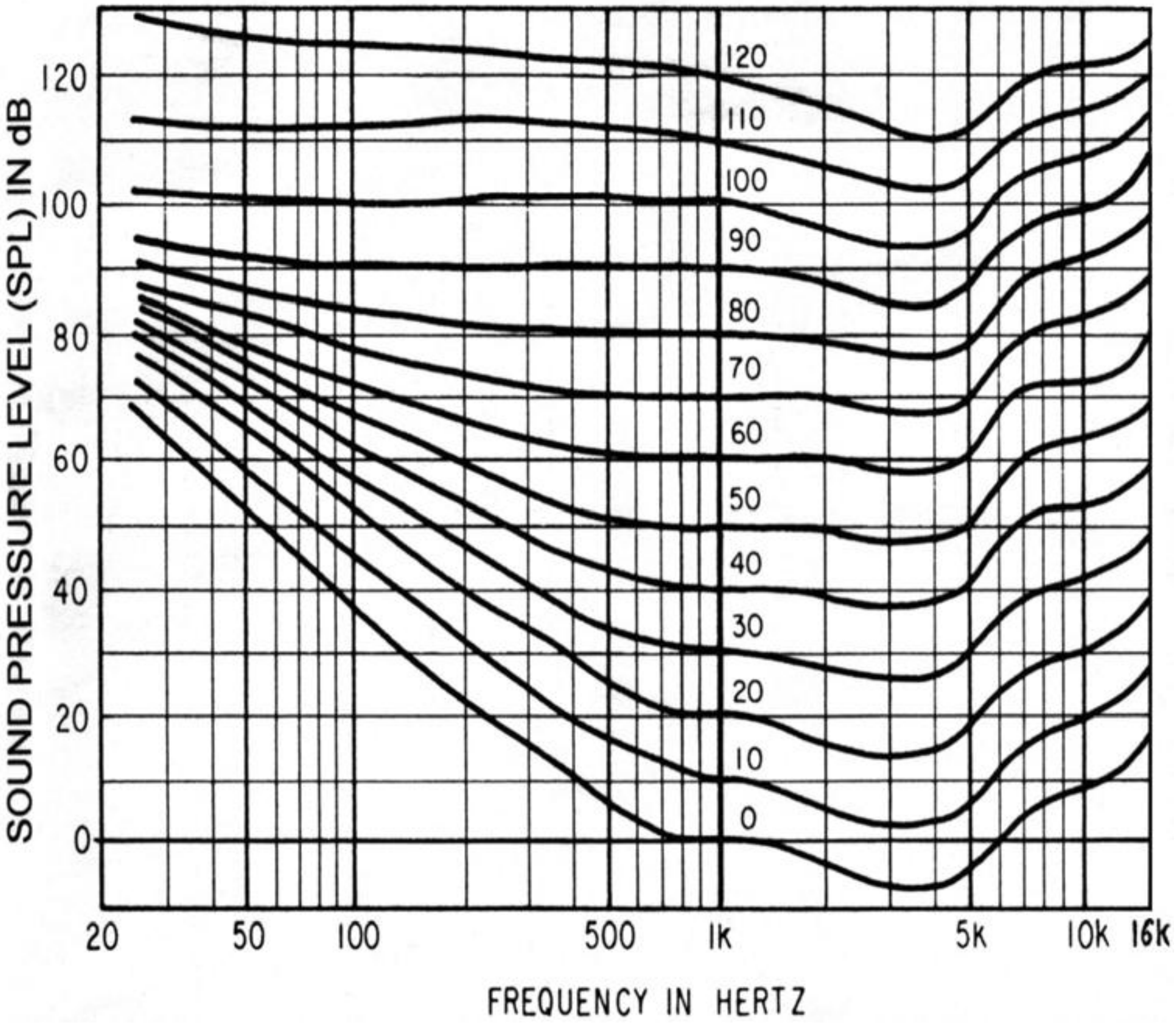


Figure 13 Fletcher-Munson curves: plots of equal loudness for sounds of different intensities and frequencies (Fletcher and Munson, 1933)

Appropriate Fletcher-Munson curves (or their revised modern equivalents) are the basis for the acoustic filters used to provide frequency weighting when assessing the effects of different types of noise on humans. Thus, when considering annoyance effects from relatively low level noise, the so-called “A-weighting”, based on the 40 phon curve, is applied, while for the assessment of the effects of intense sounds a “C-weighting" filter based on the equal loudness curve at 100 phons is more appropriate. (40 phons is approximately the noise level in a quiet home, 100 phons would be experienced close to noisy machinery such as a petrol-driven chainsaw.)

Equal loudness contours had not been measured for any marine mammals when Southall *et al*., (2007) were reviewing the available literature for their report (some data, however, are now available for bottlenose dolphins and harbour porpoises). Given this lack of data, Southall *et al.,* (2007) derived frequency-selective weighting functions for four groups of marine mammals based on the shape of the human C-weighting function and knowledge of the functional hearing range of the species groups concerned. Their intention was that, given the considerable uncertainty in this area, the application of these filters should lead to precautionary assessment of hearing risks. The functional hearing groups for which they proposed frequency weighting filters were:

- Low frequency cetaceans (baleen whales)
- Mid-frequency cetaceans (57 species of odontocetes ranging from sperm whales to oceanic dolphins)
- High-frequency cetaceans (20 species producing narrow band very high frequency clicks including porpoises, *Kogia spp.* and *Cephalorhynchu*s *spp.* dolphins)
- Pinnipeds in water
- Pinnipeds in air

7.2.4 Thresholds for Permanent Threshold Shifts (PTS)

Southall and colleagues were able to calculate sound exposure thresholds for two different types of criteria (sound pressure level and sound exposure level) over the four different marine mammal auditory groups (low frequency cetaceans, mid frequency cetacean, high frequency cetaceans, pinnipeds in water and pinniped in air) for three different sound types (single pulses, multiple pulses and non-pulsed). They achieved this by combining results from available studies of TTS in marine mammals, adding the suggested additional exposure required to induce PTS and applying appropriate frequency-dependent filters. The calculated thresholds are outlined in Table 3

The sound pressure level thresholds are only likely to be reached as a result of explosions or be found close to powerful impulsive activities such as pile driving. These levels are therefore not relevant for exposures to ADDs used at Scottish salmon farms, but they may be at marine construction sites. In the context of this review, it is the sound exposure level (SEL) thresholds that are more likely to be exceeded through prolonged exposure to ADD sound fields. These thresholds relate to cumulative exposure over an extended period. To assess this, in addition to the sound source level, propagation loss and sound field, one needs to consider the duty cycle of the signal and, most importantly, how focal animals behave and move in its vicinity. In fact, in many cases it is this simple behavioural information which remains as the most critical data gap, limiting the calculation of more realistic thresholds. Behavioural responses to sound will be modified by many factors including experience, learning and motivational state and may be fundamentally unpredictable. Behavioural responses can, however, be directly measured, and in most cases they must be.

Table 3 Proposed injury criteria for individual marine mammals exposed to “discrete” noise events (either single or multiple exposures within a 24-h period)

	Sound type		
Marine Mammal Group	**Single Pulses**	**Multiple Pulses**	**Non-Pulsed**
Low-frequency cetaceans			
Sound pressure level	230 dB re: 1 μPa (peak) (flat)	230 dB re: 1 μPa (peak) (flat)	230 dB re: 1 μPa (peak) (flat)
Sound exposure level	198 dB re: 1 μPa^2 s^{-1} (Mlf)	198 dB re: 1 μPa^2 s^{-1} (Mlf)	215 dB re: 1 μPa^2 s^{-1} (Mlf)
Mid-frequency cetaceans			
Sound pressure level	230 dB re: 1 μPa (peak) (flat)	230 dB re: 1 μPa (peak) (flat)	230 dB re: 1 μPa (peak) (flat)
Sound exposure level	198 dB re: 1 μPa^2 s^{-1} (Mmf)	198 dB re: 1 μPa^2 s^{-1} (Mmf)	215 dB re: 1 μPa^2 s^{-1} (Mmf)
High-frequency cetaceans			
Sound pressure level	230 dB re: 1 μPa (peak) (flat)	230 dB re: 1 μPa (peak) (flat)	230 dB re: 1 μPa (peak) (flat)
Sound exposure level	198 dB re: 1 μPa^2 s^{-1} (Mhf)	198 dB re: 1 μPa^2 s^{-1} (Mhf)	215 dB re: 1 μPa^2 s^{-1} (Mhf)
Phocoenids			
Sound pressure level	199.7 dB re: 1 μPa (peak) (flat)	199.7 dB re: 1 μPa (peak) (flat)	199.7 dB re: 1 μPa (peak) (flat)
Sound exposure level	179.3 dB re: 1 μPa^2 s^{-1} (Mhf)	179.3 dB re: 1 μPa^2 s^{-1} (Mhf)	184.3 dB re: 1 μPa^2 s^{-1} (Mhf)
Pinnipeds (in water)			
Sound pressure level	218 dB re: 1 μPa (peak) (flat)	218 dB re: 1 μPa (peak) (flat)	218 dB re: 1 μPa (peak) (flat)
Sound exposure level	186 dB re: 1 μPa^2 s^{-1} (Mpw)	186 dB re: 1 μPa^2 s^{-1} (Mpw)	203 dB re: 1 μPa^2 s^{-1} (Mpw)
Pinnipeds (in air)			
Sound pressure level	149 dB re: 20 μPa (peak) (flat)	149 dB re: 20 μPa (peak) (flat)	149 dB re: 20 μPa (peak) (flat)
Sound exposure level	144 dB re: 20 μPa^2 s^{-1} (Mpa)	144 dB re: 20 μPa^2 s^{-1} (Mpa)	144.5 dB re: 20 μPa^2 s^{-1} (Mpa)

7.2.5 Relevant findings since Southall *et al*. (2007)

One of the strengths of Southall *et al*. (2007) is that it lays out a logical framework for determining thresholds and meticulously describes how this was applied using the information available at the time. This makes it possible to apply the same method to new research findings as they become available. Indeed, facilitating this process of revision was Southall *et al.*’s stated intention. Here we review some relevant work in this area which has been completed since the publication of their report. Some of this work provides new information on required data, such as TTS thresholds, while other findings address certain aspects of their approach.

7.2.5.1 Temporary Threshold Shifts (TTS) in Porpoises

Harbour porpoises are the most common marine mammal in Scottish coastal waters and the species of cetacean most likely to come into contact with, and be affected by, ADDs at Scottish aquaculture sites or marine energy development sites. Southall *et al.* (2007) did not include any data on hearing effects on porpoises or other high frequency specialists. However, the bioacoustics of this species are quite different from that of the better studied mid-frequency odontocetes and some earlier papers (e.g. Verboom, 2000) had suggested that harbour porpoise would be more vulnerable to auditory damage than mid-frequency odontocetes.

Concerns about the effects that pile driving might have on the hearing of harbour porpoises led to a series of experiments in which captive porpoises were exposed to impulses from a small (20 cubic inches) airgun. The airgun produced powerful low frequency sound pulses with peak frequency below 500Hz, although significant energy also extended to frequencies up to 20 kHz. With these acoustic characteristics the airgun served as a convenient surrogate sound source for pile driving noise (Lucke *et al.*, 2008; Lucke *et al*., 2009). Hearing thresholds were measured at frequencies of 4, 32 and 100 kHz before and after exposure. Exposure levels were increased during trials until a clear TTS was evident. TTS was induced at 4 kHz (but not at the two higher test frequencies) after relatively low exposure of 199.7 dB re 1 µPa peak to peak (193.7 dB re 1 µPa peak) and a sound exposure level of 164.3 dB re 1µPa^2 s.

These results were noteworthy for several reasons. They were the first data on TTS for any phocoenid. It was also notable, and perhaps surprising, that TTS could be induced by noise so far below the frequency range of best hearing (which in porpoises is at around 100 kHz). In fact the peak frequency and the bulk of the sound energy from the airgun pulse would fall outside the frequency-weighting filters for high frequency cetaceans proposed by Southall *et al*. (2007). In other words, if the Southall process was applied to these new data, the effective SEL of an airgun exposure would be rather low (see Table 4).

Some more recent studies provide further evidence that phocoenid auditory systems might be particularly vulnerable to being damaged by noise. Popov *et al.* (2011) report on an extensive set of trials with Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*). They exposed two study animals (one male, one female) to half-octave band noise and measured thresholds at frequencies of 32, 45, 64 and 128 kHz. Greatest levels of TTS were measured when the noise band centre frequency was 0.5 octaves below that of the test frequency. Lower frequency noise seemed to have a stronger effect in inducing TTS than did high frequencies. The study mainly focused on patterns of TTS development and recovery and threshold exposures for TTS are not explicitly stated. However, their results indicated that large TTS, up to 30 dB, was induced by an exposure of 150 dB re 1 µPa for 1 minute, equivalent to an SEL of 168 dB re 1 µPa^2 s^{-1}. This was very much in line with Lucke *et al.*'s threshold value for harbour porpoise of 164.3 dB. Their results did not fully support the "equal energy hypothesis" in that, for signals of equivalent acoustic energy, higher amplitude sounds appeared to cause greater threshold shifts than longer duration sounds. A possible explanation for this would be that some recovery had taken place during the exposure period. The time taken for TTS to recover to pre-exposure levels however, seemed to be more effected by exposure duration than signal amplitude, particularly for low frequency sounds. While this paper does not provide a threshold value for TTS, the substantial TTS they induced at relatively low SEL is in line with Lucke *et al.*'s (2009) suggestions of low thresholds for TTS in harbour porpoises.

Table 4 Revised thresholds for PTS for porpoise and harbour seals calculated by applying the "Southall et al." method to new TTS threshold data

Marine Mammal Group	**Single pulses**	**Multiple pulses**	**Non-pulsed**
Phocoenids Lucke *et al*., 2009			
Sound exposure level	179.3 dB re: 1 µPa^2 s^{-1}	179.3 dB re: 1 µPa^2 s^{-1}	184.3 dB re: 1 µPa^2 s^{-1}
Phocoenids Kastelein *et al*., 2012b			
Sound exposure level	166 dB re: 1 µPa^2 s^{-1}	166 dB re: 1 µPa^2 s^{-1}	171 dB re: 1 µPa^2 s^{-1}
Harbour Seal (in water) **Kastelein *et al*. 2012a**			
Sound exposure level (short exposures- 15 mins)	193dB re: 20 µPa^2 s^{-1} (Mpa)	193 dB re: 20 µPa^2 s^{-1} (Mpa)	198 dB re: 20 µPa^2 s^{-1} (Mpa)
Sound exposure level (long exposures- 60 mins)	185dB re: 20 µPa^2 s^{-1} (Mpa)	185 dB re: 20 µPa^2 s^{-1} (Mpa)	195.5 dB re: 20 µPa^2 s^{-1} (Mpa)

The most recent and most complete set of measurements of TTS in porpoises is reported in Kastelein *et al*. (2012b). They exposed a young male harbour porpoise to octave band noise centred at 4 kHz at sound exposure levels ranging from 151 to 190 dB re 1 µPa^2 s^{-1}. They achieved this using 18 different combinations of three sound pressure levels (124, 135 and 148 dB re 1 µPa)$^)$ and 6 exposure durations ranging from 7.5 to 240 minutes. The lowest SEL that induced a significant TTS was 151 dB re 1 µPa^2 s^{-1} (124 dB re 1 µPa for 7.5 mins) while the greatest exposure, an SEL of 190 dB re 1 µPa^2 s^{-1} (148 dB re 1 µPa for 240 minutes) caused a TTS of 15 dB. This study indicates a threshold for TTS of 151 dB re 1 µPa^2 s^{-1}, even lower than that indicated by Lucke *et al*. (2009). Comparison of TTS induced by equivalent

SEL produced by exposures of different durations indicated that longer exposures at lower sound pressure levels were more effective in inducing TTS.

7.2.5.2 Temporary Threshold Shifts (TTS) in Harbour Seals

An extensive exploration of TTS in harbour seal have recently been reported by Kastelein *et al*. (2012a). They exposed two harbour seals to octave band white noise centred at 4 kHz and measured changes in threshold at 4 kHz. Exposures were made up from a combination of three sound pressure levels 124, 136 and 148 dB re 1 µPa and six different durations from 7.5 to 240 minutes. The thresholds for significant TTS were at 170dB re 1 $\mu Pa^2\ s^{-1}$ for longer exposures (60 minutes at 136 dB) and 178 dB re 1 $\mu Pa^2\ s^{-1}$ for shorter exposures (148 dB over 15 minutes). These are somewhat lower than the value of 183 dB re 1 $\mu Pa^2\ s^{-1}$ for onset of TTS in harbour seals used in Southall *et al*. (2007) which were derived from results reported by Kastak *et al*. (2005). They too found that longer exposures were more effective in eliciting TTS than were shorter exposures of more intense sounds with the same SEL.

7.2.5.3 Observations of the Relative Effects of Intensity and Duration on TTS

Usually, a longer exposure to sound at a particular intensity will result in a greater TTS. The method of Southall *et al*. (2007) assumed that sound intensity and duration contribute equally to TTS and that a dose of a particular amount of acoustic energy would have the same effect, however it is administered. As we have seen above, several marine mammal TTS studies do not support this assumption of a simple exchange between level and duration.

A study designed specifically to explore this phenomenon was reported in Mooney *et al*. (2009a). They exposed a male bottlenose dolphin to octave band noise (4-8 kHz) at a range of sound pressure levels and over durations from 2 to 30 minutes. When sound exposure level was held constant they found that the size of TTS induced increased with the exposure duration suggesting that duration had a stronger effect than sound pressure level on TTS. Mooney *et al*. (2009a) fitted a model to their results which suggested a logarithmic relationship between duration, SPL and TTS development. At this stage however, it is not clear whether this is a general relationship that could be applied to other species and other types of fatiguing noise or one that is specific to this particular case.

Its seems then that the equal energy assumption incorporated in the Southall *et al*. method may be an over-simplification, but it is as yet not clear what should replace it. What is evident though is that TTS thresholds based on observations of short-term exposure are likely to underestimate the levels of TTS induced by long-term exposures. Much of the early work on marine mammal TTS in the USA involved short exposures to high intensity fatiguing noise, for example 1 second pure tones (Schlundt *et al*., 2000) and short intense water gun pulses (Finneran *et al*., 2000). Thus, the existing thresholds proposed by Southall *et al*. (2007) may be far less precautionary than these authors intended.

In the context of ADD exposures these findings might indicate that we should perhaps be more concerned about the effects of noise on marine mammals that remain within a few hundred metres of an ADD for extended periods than the effects of occasional short, high level exposures.

Mooney *et al*. (2009a) also point out that other properties of noise, such as its acoustic characteristics and duty cycle may also influence how effectively noise induces TTS. Given these complexities and resulting uncertainties, it will always be safest to make an assessment of hearing damage risk using data from the species and noise of concern with levels and patterns of exposures that closely match those likely to be encountered in real life situations.

A complex relationship between noise and hearing damage in marine mammals should surely be expected. The auditory system of marine mammals is the product of millions of years of evolution, which have seen it adapt to function as animals moved, over evolutionary time, between the hugely different acoustic media of air and water at least five times. It is hardly unexpected then, that this exquisitely sensitive but idiosyncratic organ, should be vulnerable to being damaged by intense sound in a variety of ways, and that relationships between acoustic dose and hearing impacts are likely to be complex and non-linear.

KG No.	**Knowledge Gap**
51	Equal energy hypothesis for TTS does not seem to hold in all circumstances. A universal relationship between signal duration, intensity and hearing impact has not yet been described.

7.2.5.4 Species Specific Frequency Weighting

It is likely that species will be more vulnerable to TTS from noise at frequencies to which they are most sensitive. However, simple audiograms do not provide a good indication of what the frequency weighting function should be. In humans, plots of perceived loudness for higher intensity sounds have been used to derive frequency dependent weighting filters for use in assessments of noise impacts. Measurements of a dolphin’s perception of “loudness” for sounds of different frequencies and intensities have recently been made from a bottlenose dolphin and reported by Finneran (2012). For these experiments, a dolphin was trained to indicate to its trainers which of two sounds it perceived as being louder. Data collected over a long series of trials were combined to generate a series of equal loudness plots for sounds of the same intensity at different frequencies (similar to the human derived Fletcher Munson plots shown in Figure 13). These plots indicated that, much as has been shown in humans, equal loudness contours were flatter for more intense sounds. If more data of this type were to be obtained from a wider range of species they could provide the basis for more reliable frequency weighting functions for species groups, though it might be noted that even in humans the extent to which equal loudness contours improve predictions of hearing loss is still an area of research. Ron Kastelein's group, working in Holland, are exploring the potential of a different approach, which had previously been used to measure loudness contours in monkeys by Stebbins (1966). This makes use of the fact that response time to a signal correlates well with its perceived loudness. If animals are trained to respond to a signal in a specific way then their response latency can be measured using video analysis. This method does not require the same degree of training and should therefore yield results much more quickly, allowing a broader range of species to be tested. An initial study tested the feasibility of the techniques with a harbour seal using only low level signals close to the animal's hearing threshold (Kastelein *et al*., 2011). Results from an extensive series of trials with a harbour porpoise to derive equal loudness plots for sounds of differing frequencies and intensities are expected soon.

7.2.5.5 Summary

Southall *et al*. (2007) remains the most comprehensive attempt to provide a consensus for science-based thresholds for hearing damage. It has been a helpful document providing criteria and guidance that have been widely adopted, including by regulators in the UK and Scotland. However, it is clear that some revision is needed to incorporate both new measurements of sound levels causing TTS and new research findings that question some fundamental assumptions within the Southall *et al*. (2007) model, for example the equal energy rule. Most of the new studies have indicated that marine mammals are more vulnerable to hearing damage than was assumed by Southall *et al*., thus, the assessments of risk provided by applying the Southall *et al.* procedure should not be considered precautionary.

7.2.6 Biological Significance of Hearing Damage

Despite its apparent complexity, reduction of hearing sensitivity is a straight-forward sensory phenomenon; understanding the biological significance of a threshold shift, however, is less clear-cut. It is widely accepted that acoustics is the primary sensory modality for long-range underwater sensing in marine mammals. They make use of the vocalisations of conspecifics to maintain contact and to communicate; odontocetes detect the faint echoes of their echolocation signals to navigate and hunt prey and they attend to the myriad of passive acoustic cues in the environment (the acoustic scene) to provide information on prey location, to detect predators and for orientation.

A loss in sensitivity means an animal is able to hear fewer of the quieter sounds and this equates to a reduced range over which they can detect acoustic cues. The scaling between changing threshold and number of cues within range will vary depending on propagation conditions. If we assume spherical spreading, however, then an increase in threshold of 6 dB would equate to a halving of detection range (Mohl, 1981). If acoustic sound sources (e.g. prey items) are distributed randomly in 3-dimensional space then this halving in detection range is equivalent to an 8 times (2^3) reduction in the number of prey items that are within detection range. Thus, if the detection of quiet signals is biologically important, the effect of even a small shift in threshold could be very substantial. A small degree of hearing damage can also degrade frequency discrimination, and thereby reduce the ability to classify sounds (Götz and Janik, 2013).

When the fatiguing noise has a restricted frequency band, TTS appears to be most pronounced over a frequency range centred at about half an octave above that of the fatiguing noise. Thus, the effect on detection range will be greatest for signals at these frequencies. For a species such as the harbour porpoise, which produces signals in a narrow frequency band, the effects of changes in detection of these signals, on the efficiency of echolocation or communication for example, may be limited to only those threshold shifts affecting hearing sensitivity in that narrow band.

7.2.7 Commercial Significance of Hearing Damage

Hearing damage is not solely a concern from an animal welfare perspective, but also because it is likely to reduce the effectiveness of ADDs themselves as the depredating animals become decreasingly sensitive within the targeted hearing range (Götz and Janik, 2013). Seals rely to some extent on passive acoustic detection of prey items and loss or reduction of the ability to discriminate frequencies and classify sounds could lead to increased reliance on predictable and ‘low cost’ prey, including farmed fish (Götz and Janik, 2013).

7.2.8 Likelihood of ADDs Causing Hearing Damage

Gordon and Northridge (2002) attempted to assess risks of hearing damage to marine mammals from ADDs by extrapolating from human damage risk criteria. However, we suggest that the process outlined in Southall *et al*. (2007) and new data on threshold shifts in marine mammals that have been published since then (see section 7.2.5), should supersede those efforts.

Lepper *et al*. (In Review) provides an exhaustive analysis of the source levels of ADDs used at Scottish salmon farms and the propagation losses (especially within 500m) predicted by appropriate propagation models for a range of typical Scottish salmon farm sites. They compared the “sound fields” that would be expected from these with the thresholds for auditory damage sound exposure from Southall *et al*. (2007) and from the more recent findings of Lucke *et al*. (2009).

As discussed above, Southall *et al*. (2007) proposed two sets of thresholds beyond which they predicted the onset of permanent threshold shift: one for the maximum instantaneous exposure to un-weighted peak pressure levels and a second based on cumulated sound exposure levels (SEL) to sound after appropriate species specific frequency weighting filters had been applied.

Assessing the likelihood of exceeding the first of these, the sound pressure level threshold, is straight forward because it is an instantaneous measure. The threshold provided by Southall *et al*., for seals, is 218 dB re 1µPa while Lepper *et al.*’s interpretation of Lucke *et al*. (2009)’s findings in this context suggested a threshold for porpoise of 206 dB re 1 µPa. Published source levels for ADDs are usually provided as root mean square (RMS) levels and peak levels may be somewhat higher than this. Even so it is unlikely that any ADD peak levels would ever reach these thresholds. Thus, even at 1m range, accepted instantaneous injury (PTS) exposure thresholds are unlikely to be reached.

Assessing the likelihood of exceeding the SEL based thresholds, however, is more complex. This is because SEL is a measure of cumulative exposure over a period of many hours and is therefore a function of the sound field around the device, its duty cycle (which are fairly easy to predict for ADDs that are activated continuously) and also the animals' movements within this field over this time period. Such movements could of course be highly variable and, unfortunately, this key information has never been measured. There are observations, however, supporting instances of the two extremes. For example, seals have been repeatedly sighted within *ca*. 50m of fish farms with operating devices over periods of days (Northridge *et al*., 2013), while porpoises have been observed moving quickly away from ADDs as soon as they are activated (Brandt *et al*., 2012b; Johnston, 2002).

Lepper *et al*. (In Review) considered the simplest scenario, that of an animal remaining stationary at a particular range and calculated the time to reach threshold for injury to such an animal at different ranges out to 500 m. They repeated these scenarios for both seals and porpoises for the Airmar, Ace Aquatec and Terecos devices. Their results are summarised in Table 5.

For the Airmar device, a seal at 100 m was predicted exceed threshold after 3.3 hours for a single transducer but within 1.6 or 1.1 hours if two or three devices were deployed (as is often the case at Scottish aquaculture sites). For a porpoise exposed to a single Airmar, threshold for injury would be exceeded at 200 m in 2.8 hours while for a site with three Airmar devices the time to exceed threshold at 300 m would be *ca*. 1 hour.

For a Terecos device, exposure to a seal would exceed the threshold if it remained at 100 m for around 9 hours or spent 24 hours at 200 m. For porpoise the exposure threshold at 100 m was exceeded after 2.5 hours while the safe range for 24 hour exposure was beyond 500 m.

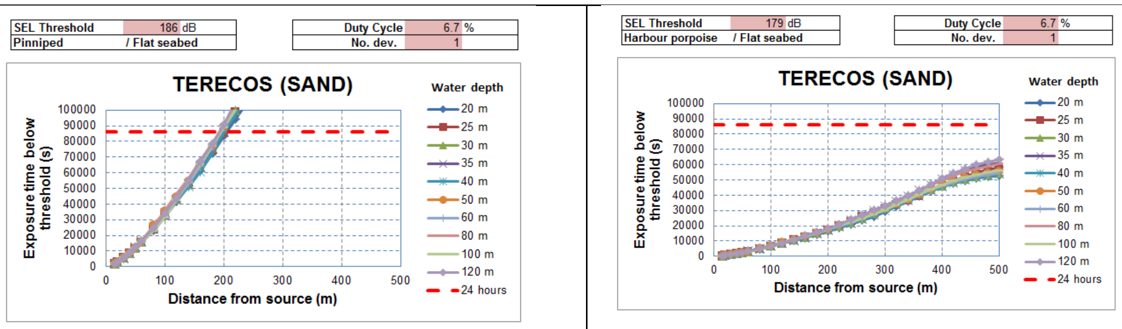
With an Ace Aquatec ADD, a seal at 100 m would receive a dose exceeding the threshold after 3 hours and the threshold range for a 24 hour exposure would be 350 m.

As expected, harbour porpoises are substantially more vulnerable to damage than seals and farms which utilise several Airmar units at the same time seem to pose the greatest theoretical risk. However, seals are known to spend extended periods close to fish farms and, presumably, seals that are attempting to get close to nets to attack salmon must be exposed to much higher levels than these simulations with static animals allow.

Clearly, the “movement model” employed here is an unrealistic one. Data on the movement of animals in the vicinity of fish farms or other sites with operating ADDs remain the largest source of uncertainty. Better data on this would certainly allow more complex and realistic modelling but, if movement patterns are highly variable between individuals, new data on movements from a few individuals may do little to clarify the real risks. What is evident, however, is that there does seems to be a real danger that the hearing of marine mammals can be permanently damaged by ADDs and that seals, which appear to be motivated to spend extended periods close to fish farms, even when ADDs are active, may be particularly vulnerable. Whether or not there may be similar motivations for seals or cetaceans to remain near to operational ADDs in other circumstances, for example around construction or turbine sites, remains to be determined.

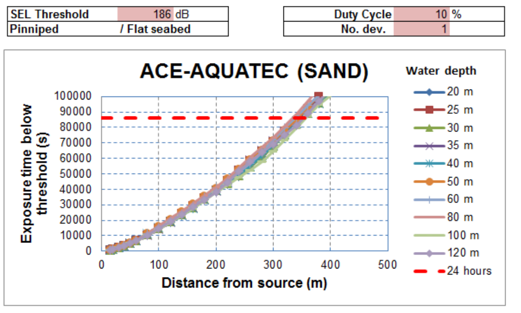
KG No.	**Knowledge Gap**
52	Realistic movement models for animals (particularly porpoises and seals) in the vicinity of ADDs.
53	Hearing damage caused by ADDs on wild populations of seals in particular seems possible, but has not yet been proven.

Table 5 Plots of time to exceed thresholds for injury based on Southall *et al*., (2007) for seals and porpoise with three different ADD devices. Propagation conditions assume a sandy bottom with a range of water depths from 20 to 120m. The red line indicates 24 hours.

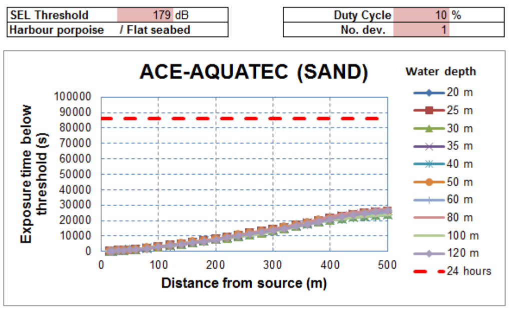


A. Terecos Seal

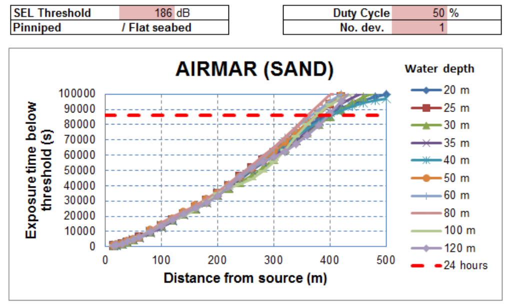
B. Terecos Porpoise



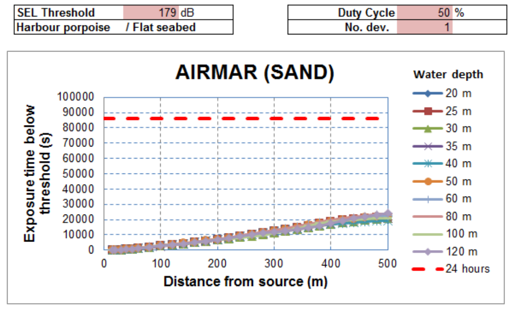
C. Ace-Aquatec Seal



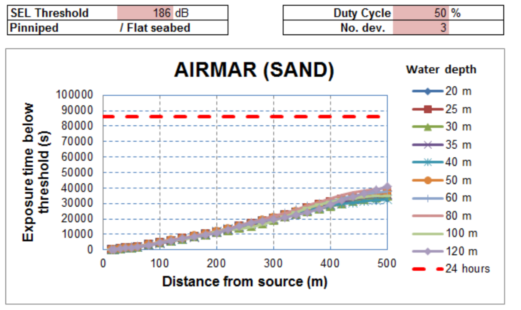
D. Ace Aquatec Porpoise



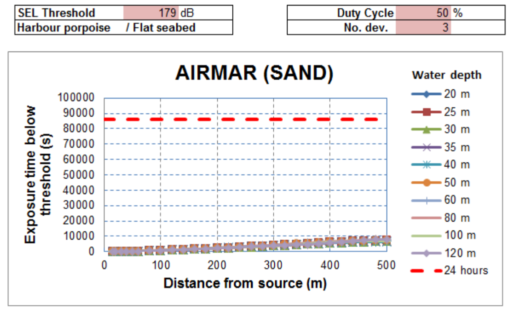
E. Airmar Seal



F. Airmar Porpoise



G. Three Airmar Devices Seal



H. Three Airmar Devices Porpoise

7.3 Disturbance, Exclusion and Behavioural Effects on Non-Target Species

Sound provides the principal modality for long range detection in marine mammals and these animals are known to respond to some acoustic signals at very low received levels. For example, gray whales responded negatively to playbacks of killer whale calls at just perceptible levels (Cummings and Thompson, 1971) and an aversive response might be expected where a signal is perceived by the receiver as having similar characteristics. Similar responses have been observed to other signals that might be associated with threats. For example, beluga whales were shown to respond negatively to ice breakers at very substantial ranges (25 - 50 km) and it is likely that the vessels were only just audible to these animals at these ranges (Cosens and Dueck, 1993; Finley, 1990; Richardson *et al*., 1995). Negative effects of disturbance of marine mammals include both disruption of biologically important behaviour and exclusion from habitat.

Acoustic deterrent devices used in the Scottish aquaculture industry are generally intended to have a strong behavioural effect on seals. However, they can also have unintended impacts on the behaviour of cetaceans, many of which have more sensitive hearing than pinnipeds. Here we review studies of the effects of the types of ADDs on the behaviour of non-target cetacean species.

7.3.1 Harbour Porpoises

One of the earliest, and still one of the most comprehensive investigations on the effects of ADDs on harbour porpoises was carried out in 1994 by the Department of Fisheries and Oceans, Canada, in British Colombia. Results were presented in both a research report (Olesiuk et al., 1995) and a peer reviewed paper (Olesiuk *et al*., 2002). The field site for this study was in the Broughton Archipelago, an area of sheltered and enclosed deep water, not unlike many fish farm sites on the west coast of Scotland. Olesiuk and colleagues used a floating platform to establish an observation position with a 6.4 m eye-height close to an existing salmon farm site. The study took place over an 18 week period (29th June to 31st October 1994) during which observers made systematic scans with the naked eye and binoculars and measured ranges to sighted porpoises using a combination of reticule binoculars and known land marks. An Airmar ADD array was established about 80m offshore from the observation station and could be turned on or off under the control of the research team. The study period was divided into three six week sampling periods. In each of these the first three week period was a control, with no ADD, while for the second three weeks the Airmar ADD was active. This design, with its repeated alternating trials, helped to control for seasonal changes in porpoise density and sighting conditions.

The results were clear and striking. As soon as the ADD was activated a substantial and significant decline in porpoise sighting rates was evident. The mean sightings per scan fell to between 1.7% and 3.7% of control values for scans with the naked eye and binoculars respectively. Porpoises were also visible for shorter periods with the number of sightings during the tracking of a porpoise pod falling from around 13 per track to around 1.5, suggesting that animals that were in the area were spending less time there. No porpoises were seen within 200 m of the device when it was active and the proportion seen at ranges of 200 to 399, 500 to 599 m, 600 to 2499 m and 2500, 3500 m were 0.2%, 1.4%, 2.5%, 3.3% and 8.1% respectively of those seen in the same zones during control periods. The local topography meant that 3500 m was the maximum range at which observations could be made and it is clear that this is unlikely to represent the full extent of these effects. There was no sign of habituation or a reduction in the size of effects over the three week duration of any of the trials. However, sighting rates recovered within a few days of the ADD being switched off.

Another study, conducted on the Canadian East Coast, from the island of Grand Manan in the Bay of Fundy, used a different approach that aimed to measure responses of individual animals. Johnston (2002) established a tracking station on an elevated location (eye-height *ca.* 30m) and used a theodolite to fix the position of porpoises and track their movements. An Airmar dB Plus II ADD was deployed from a boat about 450 m offshore. On each observation day, the ADD was either turned on or was left inactive. ADD state was determined randomly and the observation team ashore were not informed of the treatment. Experiments lasted for 2 hours and only one was conducted a day. Observations were restricted to days with good visibility and a sea state of one or less. Data were collected on 16 observation days: 9 days with the ADD active and 7 controls. The observation team searched with binoculars and recorded the locations of all sightings within 1500 m of the ADD using a theodolite and group movements were tracked as far as possible. There were substantial differences in detection rates between ADD active and inactive days. When ADDs were active the mean detection rate was reduced to 0.22 (SD 0.44) porpoise sightings per scan from a mean of 2.91 (SD 1.29) on control days. There was also evidence in the data of animals leaving the site soon after the ADD was activated. Porpoise sightings within 1500 m were lower in the 5 minutes after ADD activation but not significantly so. Low numbers were seen during the first 30 minutes of scanning and no sightings at all were made in the remaining 1.5 hours of experimental exposure.

Porpoise movements were tracked wherever possible, with a total of 69 tracks being recorded: 60 during control periods and 9 when the device was active. It was clear from these data that porpoises maintained a greater range from the ADD when it was active. The mean closest approach of tracked animals was 364 m (SD 261 m) on control days but 991 m (SD 302 m) on days when the ADD was active. No porpoises were observed within 645 m of the ADD when it was active. By applying an appropriate propagation model to measured source levels for their ADD, Johnston calculated that the received level at 645 m would have been 128 dB re 1 µPa.

Research in Scottish waters to explore the effects of ADDs on porpoise densities in fish farming areas was presented by Northridge *et al*. (2010). This work differed from the earlier Canadian studies in two respects. In the first place the study sites were close to operating fish farms with no or limited experimental control over when ADDs were active or inactive. Secondly, the data on porpoise presence and relative densities were collected acoustically, using both static passive acoustic devices (T-PODs and C-PODs, Chelonia Research Ltd) moored at different ranges from fish farms with ADD devices and with simple towed hydrophone arrays.

PODs were used to collect data at two different salmon farm sites, both using Airmar ADDs on the west coast of Scotland; one was at Fiunary in the Sound of Mull and the other at Laga Bay in Loch Sunart. At Fiunary, PODs were deployed at monitoring stations with similar water depths and distance from the shore at ranges of 200, 500, 1000, 1500 and 3000 m from the fish farm site. PODs were deployed nearly continuously for over five months. For the last two months of monitoring the fish farm had been harvested and no ADD was present. At the Laga Bay site PODs were deployed at monitoring stations at distances of 240, 1100, 1700, 3000 and 8000 m from the cages with ADDs. Here the PODS were deployed for 23 days while ADDs were active. After this the ADD was turned off and after three weeks of ADD inactivity the PODs were redeployed for seven weeks. The trial then had to be abandoned because seal activity at the site resulted in the farm manager wishing to resume use of the ADDs.

The number of porpoise click train detection positive minutes (DPM) per day was used as an index of porpoise density. Changes in detection rate with distance from active farm sites were less clear cut than the changes in sighting rates reported by Olesiuk *et al.* (2002) and Johnston (2002). Complete exclusion was not evident even at the closest monitoring sites and substantial inter-site differences in detection rates, which were likely due to habitat factors, tended to obscure effects of range to ADDs. Indeed at one farm location the POD which was closest to the ADD had the highest detection rate overall, probably because it was adjacent to deeper water. However, significant increases in detection rates were evident in the data after the ADDs had been turned off. At the Laga Bay site DPMs per day increased by factors of 7, 4 and 9 times at monitoring stations at distances of 200, 1100 and 4000 m respectively. The PODs at the other stations at this site were either lost or malfunctioned. Sound levels in the ADDs main frequency band (*ca*. 10 kHz) measured at ranges of 240, 1100 and 8000 m were 146, 128 and 105 dB re 1 µPa.

The use of static acoustic loggers for this work allowed monitoring to extend over several months and to continue 24 hours a day where previous studies had been limited to daylight hours. While the data show an effect of ADDs with no sign of it being reduced at a range of 4000 m, these results seem less dramatic than those reported by Olesiuk *et al*. (2002) and Johnston (2002). The more opportunistic approach adopted, which involved collecting data around real operating farm sites, provided a messier, less controlled dataset, but had the advantage of being more representative of real-world situations. Porpoises in this area are exposed to ADDs from a range of fish farm sites throughout their home range and it is likely that animals will not have been naïve to these signals. It is possible that this resulted in a degree of reduced responsiveness. It is notable, however, that even considering this level of long-term exposure, full habituation had not occurred.

Northridge *et al*. (2010), like the earlier Canadian studies, investigated responses to just one type of ADD, the Airmar dB II. However, at least four different makes of ADDs are used by the Scottish salmon farming industry and, according to Northridge *et al*. (2010), nearly half (42%) of sites were using Terecos devices. Northridge *et al*. (2013) used PODs in a similar manner to the studies described above, to investigate porpoise responses to a Terecos device deployed at a fish farm site in Loch Hourn. Nine PODs were deployed at matched monitoring sites at ranges between 300 and 4500 m. PODs collected data for 65 days during which time the Terecos ADD was alternately either active or inactive following an approximate seven day cycle. Overall, there was no significant difference in detection rate when the ADD was active. Detection rates were reduced, though not significantly, at the four closest sites, which were all within 1000 m. Terecos ADDs are known to have a lower acoustic power output than the Airmar dB Plus II (Lepper *et al*., 2004), see Table 2. The Airmar system at Laga Bay was measured with a calibrated hydrophone to be 185 dB 1 µPa, higher than the previously reported Terecos SPL of 179 dB re 1 µPa (RMS). These source level differences may go some way to explaining the lack of a pronounced response to the Terecos. As far as we are aware, this is the only trial of the effects of Terecos devices on harbour porpoises. The work should be repeated with a more complete set of trials, but if this finding proves to be robust, there would be a strong case for preferring the Terecos to some other ADD types on the grounds that its effects on harbour porpoise densities seems to be minor or non-existent.

KG No.	**Knowledge Gap**
54	Is the Terecos device consistently less aversive to harbour porpoises than other ADDs?

Work to develop an ADD which would be effective in deterring seals while having a minimal effect on harbour porpoises and other cetaceans is described by Götz (2008) and also summarised in section 1.3 of this report. To make the device aversive to seals, psycho-physiological research was reviewed and these findings were used to design a signal which would induce a startle reflex in seals (Gotz and Janik, 2010). In order to minimise the effects of these sounds on odontocetes, signals were used of relatively low frequency, to which seals were more sensitive than porpoises and dolphins. Götz (2008) reported field trials to test porpoise responses to a prototype system. Observations were made, and animals were tracked, from the shore using a similar approach to that of Johnston (2002). Porpoise sighting rates were not significantly lower when the candidate ADD signal was being broadcast and neither were ranges of closest approach any greater. In fact, porpoises were observed as close as 8m from the speaker broadcasting the signal at full level. Commercial ADDs using the same signal type are now under development. If porpoises and other small cetaceans show the same minimal level of reaction to signals from these devices as they did to the experimental playbacks described above, it would provide a strong basis for the use of these new ADDs at Scottish salmon farm sites, assuming they are seen to be at least as effective as more established devices in reducing depredation (something which itself is unquantified).

A project recently conducted in the Baltic and North Sea, designed to investigate how ADDs could be used as an aversive signal for mitigating potentially dangerous activities such as pile driving and reported by Brandt *et al*. (2012b), is the most recent sizeable piece of research measuring the effects of ADD signals on harbour porpoise. As the intention of this work was to investigate ADDs for deterring porpoises from pile-driving operations, the methodology is described more fully in section 4.4.4.1 of this report. In this case, the ADD being tested was a Lofitech seal scarer and fieldwork was conducted in two contrasting locations - an offshore site in the North Sea and an inshore site in the Baltic close to an elevated onshore observation location. Acoustic detection rates, collected by an array of 16 PODs at the offshore site, were compared before, during and after active ADD deployments. There was a clear and dramatic reduction in detections when the ADD was active. Porpoise detections were almost completely absent at the zero range POD and even at 7500 m detection rates were around 96% lower during broadcast trials. Received sound levels from the ADD at 7500 m were estimated to be 115 dB re 1 µPa. A visual aerial survey of a 30x30 km survey block, centred on the playback location, was conducted before and during an ADD transmission trial. Results from this survey were compelling and also provide strong evidence that changes in POD detection rates were really indicative of porpoises leaving the area, rather than merely a change in acoustic behaviour. Sighting rates fell by 86% during transmission periods. In the pre-transmission survey, nine porpoises were sighted within 7500 m of the device location while during transmission there was only one sighting in this area, at a range of 6300 m. This was the closest observed approach during transmission.

The experiments conducted in the Baltic (reported in Brandt *et al*., 2013) complimented the offshore trials and were useful in revealing the behaviour of individual animals in an inshore region. They showed that porpoises responded as soon as transmissions commenced and that, even though the experimental protocols meant that porpoise groups were usually being tracked at the time transmissions started, the animals typically “disappeared” during transmissions which was taken as an indication of a very pronounced disturbance effect. During a series of six trials designed to measure responses of animals at ranges of greater than 1500 m there was no obvious avoidance response at ranges of 2100 to 3300 m. Propagation loss at this site was found to be much greater at this inshore location than at the North Sea site. Brandt *et al*. (2012b) suggested that the Lofitech device has a significant disturbance effect at sound levels above 119 dB re 1µPa (RMS), and that near complete deterrence occurred at received levels of greater than 132dB re 1µPa (RMS).

Brandt *et al.*’s studies provide the first data on the effects of Lofitech devices on harbour porpoises of which we are aware. The range, in the offshore area, over which such dramatic responses are evident, is striking. There was a 96% reduction in detection rate at a range of 7.5 km and no indication that this was the maximum range at which effects would be evident in offshore conditions. The Lofitech produces a narrow band high frequency signal rather similar to that of the Airmar (see Figure 3). It is perhaps to be expected, therefore, that it would also cause a high level of disturbance, seemingly over even greater ranges than has been reported for the Airmar (Olesiuk *et al*., 2002).

Another relevant piece of work that might be mentioned is a study of harbour porpoise presence at aquaculture sites reported by Haarr *et al*. (2009). They monitored for the presence of harbour porpoises at salmon farm sites in the Canadian Bay of Fundy over two summer seasons using both shore based visual observation and static acoustic monitoring devices (T-PODs). ADDs were not in use at these sites at this time. However, the occurrence of other forms of disturbance such as large and small boat traffic and net cleaning were noted. It was clear that for most of the time, porpoises were not avoiding the farm sites. Mothers and calves in particular seemed to prefer to be among the cages at these sites and it was suggested the cages might provide some shelter and protection. POD data indicated that there were more detections at night than during the day. Vessel traffic and activities such as cage cleaning caused short-term disturbance leading to lower densities within the immediate area. These results suggest that, in the absence of ADDs, porpoises will make full use of fish farm sites; there were even indications that some components of the population might prefer them because they offered some protection and possibly feeding opportunities.

7.3.2 Killer Whales

Salmon farms sites in British Colombia are located within the home range of one of the world’s best known populations of resident killer whales. Nearly every whale encountered in this area can be individually recognised and the life histories of most individual whales have been followed since the 1970s. Several research groups are continuously engaged in studying and monitoring the population here. Morton and Symonds (2002) reported on changes in killer whale detection rates and residence patterns at two locations: the Broughton Archipelago, a salmon farming area, and the mouth of Johnstone Strait, some 25km away, over a period of 15 years between 1985 and 2000. Airmar ADDs were introduced at four farm sites in the Broughton Archipelago in 1993 and remained active there until 1999. At Johnstone Strait, by contrast, no ADDs were active. Both sites were very intensively monitored using a combination of cabled hydrophone systems, which allowed constant real time shore-side monitoring, a system of VHF communication with experienced observers and water users, and a combination of both land-based and boat-based searches. Killer whale pods in this area can be identified reliably by their call types so the acoustic monitoring provided a particularly complete information set. The authors believed that it would be unlikely that whales would pass through either site without being detected. Morton and Symonds (2002) reported that while whale presence (the proportion of days in which killer whales were detected in the area) remained stable in the Johnstone Strait location, their presence in the Broughton Archipelago fell substantially (by a factor of over 3) and significantly during the five years when ADDs were active there. Whale occurrence, however, returned to levels that were not significantly different to pre-exposure values once the ADD had been removed. This pattern was particularly clear when the occurrence of just the resident (salmon eating) killer whale pods was analysed independently of the presence of mammal eating “transient” whales. Analysis of photo-identification data showed that the same pods were using the area throughout the study, so these changes in density were unlikely to be due to any larger scale population changes. There were also no indications of changes in food (salmon) availability when killer whale occurrence was low. Indeed the high level of escapement from some farms led to a rise in salmon availability in the Broughton Archipelago area at that time.

Several aspects of this study are worth commenting on. In the first place it is intriguing to find that killer whales should be so strongly affected by ADDs. Research summarised above (section 7.3.1), has shown the harbour porpoise to be particularly vulnerable to disturbance. For many researchers this is not unexpected. Harbour porpoises are known to be shy animals and easily scared, and are described as neophobic (for example, they rarely interact with boats). They are predated upon by killer whales and also attacked by bottlenose dolphins (Ross and Wilson, 1996) and crypsis and avoidance of novel sounds may well be their anti-predator strategies. Killer whales, by contrast, are large robust animals with no known predators, which are not afraid of vessels and often approach them. Another interesting finding from this research is the extended period, some six years, over which avoidance and partial exclusion was demonstrated. This indicates an absence of significant accommodation or habituation over that period by individuals, in a population of known resident animals. Morton and Symonds (2002) collected photo-ID data that showed the same animals were repeatedly observed in the area, throughout the period of ADD activity. They would therefore have been repeatedly exposed to ADD signals and some degree of habituation might thus have been expected, but was not observed.

7.3.3 Pacific White-Sided Dolphins

Morton (2000) reported on the occurrence of Pacific white-sided dolphins (*Lagenorhyncus obliquidens*) in the waters around the Broughton Archipelago between October 1984 and December 1989. This was the same study area as for the study on killer whales (Morton and Symonds, 2002) reported above, and the two studies also overlapped in time. During the first years of this study measures of occurrence of dolphins increased dramatically, increasing from being present on only 0.4% of days in 1984 to being recorded on 19% of days in 1994. Morton (2000) suggested that rising water temperature and increases in prey abundance may have led to these changes. In 1994, ADDs were introduced at the local fish farm sites and dolphin occurrence subsequently fell, with dolphins being present on only 2% of days in 1998. Data after 1998, when ADDs were removed from the fish farms in the area, were not included by Morton (2000). However, Alexandra Morton reported, as a *pers. comm.* in Gordon and Northridge (2002), that rates of occurrence increased in the first two years after ADDs were removed. In 2001, however, sightings of white sided dolphins and several other species were reduced, which might have been attributable to unusual oceanographic conditions in that year.

This study, like that of Morton and Symonds (2002), was an opportunistic one. There are indications that ADDs may have had an effect on the frequency of white-sided dolphin sightings. The fact that the population distribution appeared to be quite dynamic (for other reasons), as well as the limited time series available for analysis and the lack of a control area, all combine to make the case less clear than that made for killer whales and porpoises.

7.3.4 Baleen Whales

There have been no dedicated studies investigating the effects of aquaculture ADDs on baleen whales. However, a reduction in the number of sightings of humpback, gray and minke whales in the Broughton Archipelago over the period when salmon farms in the area were using Airmar ADD devices, followed by a substantial recovery in sighting rates after ADD use was halted in 1999, was reported by Morton (1997). Sightings rates were very also low in 1999 but this seems to be attributable to oceanographic conditions that provided exceptionally good feeding conditions in another nearby location (Morton, *pers. comm*.).

Other opportunistic observations suggesting that humpback whales vacated areas where high intensity ADDs were in operation were provided by Lien *et al*. (1995).

The minke whale is the only baleen whale routinely encountered in Scottish inshore waters and is likely to come within range of aquaculture ADDs. In the winter of 1993 a minke whale “took up residence” for at least ten weeks in Loch Grimshader on the Island of Lewis. This small sea loch had a shallow entrance and it was not clear whether this animal had become embayed or was choosing to stay there to feed on dense fish schools which were present in the loch at the time. A team from the Mull-based Sea Life Surveys research group collected behavioural data from this animal to assess its well-being. A fish farm within the Loch was equipped with an Airmar dB plus II ADD. This had not been active when the whale entered the loch. However, because the farm felt they might need to use the device in the near future it was decided to turn it on for a 24 hour trial during which time the animal’s behaviour would be monitored allowing any responses to be assessed. When the ADD was turned on the animal changed from a ‘resting’ to a ‘feeding’ mode of behaviour but continued to make full use of the loch. In fact, at one stage it seemed to be actually investigating the device (Fairbairns *et al*., 1994; Gordon and Northridge, 2002). The indications from this very short trial are that the whale could detect the device but that its behaviour did not change in any manner that was an immediate cause for concern.

Götz and Janik (2013) recommend the use of lower frequency signals than are currently employed by ADDs in order to minimise impacts on odontocetes (1 – 2 kHz). They stress, however, that impacts on baleen whales (and hearing specialist fish species) should be investigated before such devices be used commercially.

KG No.	**Knowledge Gap**
55	Responses of baleen whales (and several other less studied species) to ADDs in Scotland are not clear at present.

7.3.5 Non-Target Species Discussion

Much of the evidence for displacement of non-target marine mammals by ADDs is drawn from one area (the Broughton Archipelago in Canada) and involved a single type of ADD. We do not know whether animals in different areas with different motivations would necessarily be affected in the same way, nor do we fully understand the likely different responses to different devices. Recent experiments with Lofitech ADDs, for example, suggest an even greater degree of displacement of porpoises with these devices (Brandt *et al*., 2012c), whereas another experiment using a Terecos device seemed to induce little if any response beyond in Loch Hourn (Northridge *et al*., 2013). Our lack of understanding or ability to predict the behavioural responses of a range of species to different devices in a range of contexts is another significant knowledge deficiency.

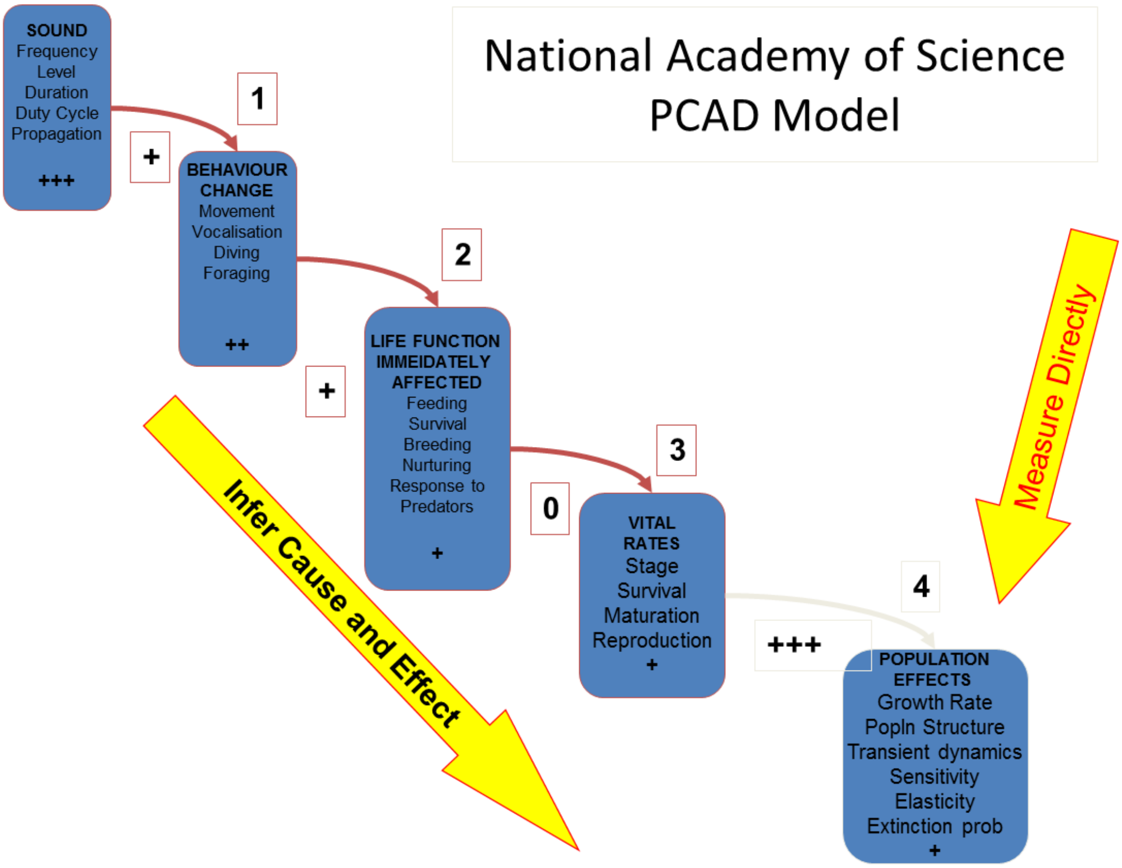
7.4 Summary

Most published reports have shown significant and long lasting behavioural responses from cetaceans to ADDs. Harbour porpoises seem to be particularly vulnerable, with good evidence that densities can be reduced substantially at ranges of many kilometres for at least two devices types in multiple locations. The majority of studies have investigated responses of animals to one particular type of ADD, the Airmar dB Plus II. Responses to other devices may be quite different. There are indications that harbour porpoises may respond even more strongly to the Lofitech seal scarer while the Terecos ADD may have much smaller impacts. From a Scottish perspective, there is an obvious requirement to measure responses to the range of devices available to Scottish salmon farms including the newly developed “cetacean friendly” ADD (Götz, 2008).

It is clear that some, if not all, of the ADDs currently being used on Scottish salmon farms have an effect on local densities of porpoises (and possibly some other species). This raises two questions: is this likely to be of any biological significance for local cetacean populations, and how should these devices be managed and permitted under existing regulations?

The biological significance of acoustic disturbance for marine mammals is a question that has attracted the attention of both scientists and regulators over the last decade. The US National Research Council held a series of workshops to explore this question which are summarised in two publications (National Research Council, 2003; National Research Council, 2005). One outcome from the latter of these was a model or conceptual framework for the population consequences of acoustic disturbance (PCADs), outlining the steps by which a sound might cause disturbance that could eventually result in biologically significant population consequences. This framework is outlined in Figure 14.

Figure 14 The National Academy of Science Population Consequences of Acoustic Disturbance Model (PCADS). The model considers the stages from a sound being produced, being detected and affecting an animal's behaviour and the potential consequences of this for individuals and populations. In each box the number of "+" signs indicates how easily the parameter can be measured while the number of "+" signs next to the arrows linking the boxes indicates how reliably one set of parameters can be inferred from the earlier ones.



It shows a fairly straight-forward cascade of events from a sound being produced, being affected by propagation loss, being received and perceived by an animal, resulting in a change in behaviour that could cause a change to a life process that might in turn result in a change in vital rates finally translating to changes at the population level. At each stage, the number of "+" signs within the box indicates how readily the required data type can be measured while the number of "+" signs next to the arrows linking the process show how reliably one type of data can be inferred from that proceeding it. It can be seen that, according to these authors at least, all of the parameter types can be measured directly, though with varying levels of ease. The "transfer functions" used to infer one set of parameters from those preceding them in the chain are particularly poorly known however, and, in the view of these authors at least one of these steps (inferring vital rates from changes in life functions) is not possible.

A pragmatic conclusion from this framework would be that the PCAD model provides a useful conceptual framework for the process but that it is very unlikely that one can use this as a practical tool for inferring the biological significance of a particular sound type. All of the steps in the process are amenable to being measured to some extent but it will also be important to establish cause and effect. While factors such as population size or viability might be the parameters of most interest, it will be very difficult to infer that observed changes at the population level were caused by any particular type of disturbance, especially in wide-ranging and long-lived species which will be affected by many factors in a complex environment. In addition, by the time any effects could be measured at this level it would be very late for taking useful management action. Measuring processes earlier in the chain in addition to population monitoring is thus essential for both establishing cause and effect and for allowing timely management to be put in place.

Having said this, some groups are actively exploring the extent to which population consequences can be predicted from short-term disturbance. It seems that, in the case of some of the best studied marine mammal populations in areas of high disturbance, it may be possible to infer consequences at the population level. In our opinion, no populations of Scottish cetaceans are sufficiently well studied to allow this.

A simpler perspective might be to regard displacement as exclusion and consider the areas from which animals have been displaced as representing a form of habitat loss. Plots such as figures 5 and 6 could be used to explore the extent of such ‘habitat loss’. This could, however, severely underestimate or overestimate the true biological significance of displacement. For example, if animals were displaced from an area, but there was a lot of ‘unused’ habitat outside that area in which they could feed and function just as efficiently as before, then the effects might be very minor and/or short-lived. This might occur, for example, if the population was being kept below carrying capacity by something other than overall food limitation. Alternatively, if animals are displaced into a habitat that is already ‘full’ then they would be competing for food and other resources with animals that were already established there. The resulting competition and disruption could lead to reduced foraging success for many more animals than just those (Gill et al., 2001; Gill and Sutherland, 2000), at least initially. Animals could, in this way, be indirectly affected by the noise causing disturbance, without having heard it themselves.

KG No.	**Knowledge Gap**
56	Likely total extent of exclusion and disturbance of ADDs on different species.
57	Population level significance of potential exclusion of cetaceans by ADDs.
58	Population level significance of potential disturbance of cetaceans by ADDs.

For coastal locations, such as most current aquaculture sites, another situation in which displacement might be particularly harmful would be if animals were excluded from ‘movement corridors’ required to access large areas of suitable habitat, for example exclusion from the mouth of a sea loch might exclude access to the whole of the loch itself. Similarly, disruption in channels or at headlands might make it difficult for animals to move between habitats at either side of them.

The Habitats Directive prohibits reckless disturbance of individuals of Annex II species (which includes all cetaceans). However, derogation can be granted provided this disturbance at the individual level does not affect the status of the species concerned, does not affect local populations and it can be shown that there are no feasible alternatives to the activity of concern.

8 Knowledge Gaps and Research Recommendations

8.1 Knowledge Gaps

Here we have used the term “knowledge gap” to refer to any topic arising within the report where uncertainties exist in the scientific understanding. Knowledge gaps have been highlighted throughout this text at appropriate points with the intention of clarifying the limitations of current understanding in each area. Table 6 collates these points, and reveals that a large amount of uncertainty exists in some of the areas addressed in this report. Where appropriate, these points have been expanded into recommendations for research below (section 8.2).

Table 6 Knowledge gaps as listed in the body of this report

Section	KG No.	Knowledge Gap
2.1.1	1	The extent and monetary cost of seal depredation at Scottish fish farms is unknown.
2.1.2.1	2	What effect do different netting materials have upon seal depredation of salmon?
2.1.2.2	3	Exactly what has been - and what should be - classified as seal predation mortality?
2.1.2.3	4	How are salmon growth rates affected by seal presence and depredation?
2.1.2.3	5	Is there a relationship between seals depredation and disease among farmed salmon?
2.1.2.4	6	Quantification of welfare concerns – to what extent do seals injure without killing fish?
2.1.3	7	What specific mechanisms do pinnipeds use to damage fish within nets?
2.2.1	8	Exact acoustic output of all devices and an appropriate metric (or suite of metrics) for comparison of different signal types.
2.2.1	9	Effect of fouling and voltage drop on signal output (under full range of operating conditions).
2.2.1.3	10	What is the relative efficacy of different ADD deployment

		‘strategies’, and how can they be appropriately compared?
2.2.2.1	11	How many sites have been denied approval for ADD use under planning regulations, and what criteria have been used to assess applications?
2.2.2.1	12	Total extent and distribution of ADD usage in Scotland is currently unknown.
2.2.2.2	13	Over what maximum range are cetaceans likely to be impacted by ADDs?
2.2.3.2	14	How can the effectiveness of ADDs be measured and compared, and what level of effectiveness is tolerable?
2.2.3.4	15	The effectiveness of ADDs in reducing seal depredation to stocked fish remains unclear. An experimental approach to address this fundamental uncertainty is difficult for economic and fish welfare reasons.
2.2.3.4	16	Effect of motivational state and context in mediating and modifying aversive response to ADDs.
2.3.1	17	How does stocking density influence seal behaviour and depredation rate?
2.3.1	18	Salmon behaviour within nets and in response to depredation is poorly documented, particularly at night.
2.3.1	19	How does net tensioning affect the ability of seals to remove fish?
2.3.1	20	How important are dead fish (morts), and their removal or concealment in motivating or preventing seal depredation?
2.3.1	21	How are anti-predator nets utilised internationally to avoid common problems experienced in Scotland?
2.3.2	22	The “rogue seal” hypothesis, and the rate at which removed seals are replaced is currently unclear.
2.3.2	23	How can recovery of seal carcasses be improved?
2.3.2	24	How can information about the demographic parameters of seals shot be improved?
2.3.2	25	It is unclear to what extent lethal removal is effective in minimising damage. No studies have looked at how depredation rate is affected by lethal removal.
2.3.3.3	26	Which emetics are most effective and what are the minimum doses required for CTA?
2.3.3.3	27	Are there any harmful physiological effects on seals treated with CTA, and if so, how can they be minimised. Is CTA sufficiently specific to salmon to leave the seals’ normal diet of wild fish unaffected?
2.3.3.3	28	Are there any environmental effects of CTA?
2.3.3.3	29	How can baits for CTA best be prepared and presented to wild seals at salmon farms?
2.3.3.3	30	What patterns of “treatment” are most effective? Should baits be presented routinely or only when problems become evident?
2.3.3.3	31	Are there seasonal difference in when and how CTA should be use? Should there be “closed seasons”?
2.3.4	32	Behavioural aspects of electrical deterrence: how will behaviour be modified by context and motivation?
2.3.4	33	Practical aspects of electrical deterrence: engineering solutions

		are lacking and will be required before deployment in real-world applications can be feasible.
2.3.5	34	What legal and ethical restrictions would affect the use of trapping for translocation, conditioning or lethal removal?
2.3.5	35	What would the monetary cost of implementing such a trapping system be?
3.2	36	Efficacy of devices designed to deter depredating odontocetes in capture fisheries is currently unknown.
3.2	37	Efficacy of low frequency devices for deterring baleen whales is unknown.
3.2	38	There is general lack of understanding of the response of marine mammal species to different signal-types and how these responses are modified or mediated by context.
3.3	39	What proportion of seals have naturally impaired hearing? How does this change with age?
4.2	40	Empirical measures of displacement movement rates are required in order to improve the TTS risk modelling approach. Appropriate movement models are the limiting factor in predicting risk of TTS.
4.3	41	It is unclear whether auditory preference/aversion is transferable between species.
4.3	42	Effects of absorption and reverberation on different signal types have not been shown, and could be prohibitive to long-range effectiveness of complex signals.
4.4.4.1	43	To what extent can a learnt response to a specific signal (e.g. non-response to aquaculture ADDs) be transferred to a different context?
5.2	44	The acoustic output of tidal energy devices in all states of operation is unknown.
5.3	45	At what range will tidal turbines be detectable above ambient/background noise?
5.3	46	To what extent can noise hotspots in tidal areas be predicted based on parameters such as benthic composition? How stable are they spatially and temporally?
5.3	47	A greater understanding of the response elicited by existing deterrent devices, how this varies between species and contexts, and how this is likely to change over time.
5.3	48	A greater understanding of how marine mammals currently utilise tidal environments, and how this is likely to be affected by new structures and activities and additional sound sources.
6	49	Signal types which can reliably elicit a predictable and useful response in reducing risk of ship-strikes are currently unavailable.
7.2.3	50	Reliable audiogram data (or equal loudness contours) are not available for several of the species found in Scottish waters (e.g. minke whale, white-beaked [*Lagenorhynchus albirostris*] and Atlantic white-sided [*Lagenorhynchus acutus*] dolphins).
7.2.5.3	51	Equal energy hypothesis for TTS does not seem to hold in all circumstances. A universal relationship between signal duration, intensity and hearing impact has not yet been described.
7.2.7	52	Realistic movement models for animals (particularly porpoises and

		seals) in the vicinity of ADDs.
7.2.7	53	Hearing damage caused by ADDs on wild populations of seals in particular seems possible, but has not yet been proven.
7.3.1	54	Is the Terecos device consistently less aversive to harbour porpoises than other ADDs?
7.3.4	55	Responses of baleen whales (and several other less studied species) to ADDs in Scotland are not clear at present.
7.4	56	Likely total extent of exclusion and disturbance of ADDs on different species.
7.4	57	Population level significance of potential exclusion of cetaceans by ADDs.
7.4	58	Population level significance of potential disturbance of cetaceans by ADDs.

8.2 Research Recommendations

The knowledge gaps identified in this review are summarised in Table 6. Below we outline a series of themed research recommendations to address these knowledge gaps and provide information necessary for a clearer understanding of the effectiveness of non-lethal measures. Each recommendation ('R') is accompanied by a suggested approach.

8.2.1 Aquaculture and Seals

8.2.1.1 Baseline Data

Recent work highlights that data collected by salmon farms, in general, does not collect all of the pertinent information, is insufficiently detailed and is often difficult to access for research. A priority should therefore be given to the collection of more appropriate data on seal-fish farm interactions by the industry (**R1**).

Research approaches: Work is required to define the data sources that could reasonably be collected to address key research questions. Key points to address include: what data are currently available to answer management questions (this would include assessment of reliable indicators of seal damage on fish), appropriate format for data collection, recommendations as to how data can be reliably collected (for example, can data fields be added to existing reporting requirements e.g. seal management reports, SEPA reporting), what mechanisms are required to ensure delivery of any additional data required. This is likely to require a close collaboration of researchers, industry practitioners and regulators.

8.2.1.2 Information on the Efficacy of Existing Management

Reliable information is lacking on the effectiveness of management measures currently being employed. This is particularly important for those activities which have unintended negative consequences. Useful progress should be made by analysis of data from an improved reporting scheme (R1) but directed research into the effects of site specific management regimes should also be undertaken (**R2**).

Research approaches: Where sufficient data exist, the efficacy of various existing management measures should be assessed by comparing predation rates at matched sites applying different management techniques. Key points to compare would include: net size and shape, net tensioning systems, locality of seal haulouts, stocking density, net cleaning regime, tidal flow rate etc. Experience has underlined that this will be an effective strategy only if industry partners are engaged and have a responsibility for delivering results.

Another potentially useful source of information is the large database of telemetry tracks which SMRU holds. These should be examined for instances where tagged seals seem to be spending time in the vicinity of fish farms and these could be compared with existing datasets on depredation.

8.2.1.3 Lethal Removal

Depredation events sometimes lead to the removal of individual seals by shooting. There is a very poor understanding of this method and whether and how it is effective. Knowledge gaps include the types of seals (for example, species, gender and age of animals) removed, their recent diet, how reliably marksmen identify and remove “problem seals”, how successfully and for how long does lethal removal provide relief from depredation. The success or otherwise of lethal removal needs further investigation (**R3**).

Research approaches: Implementation of a strict recording structure including: on-site observation prior to lethal removal, photo-identification of individual seals and carcass recovery to determine whether removed animals match photo-ID “culprits”, demographic characteristics (age, gender, health) of removed animals, stomach contents analysis (otoliths and DNA).

8.2.1.4 Efficacy of ADDs

There is a need for information on the extent to which ADDs of different makes and design provide relief from seal depredation and/or reduce the number of seals that the industry requires to remove lethally (**R4**).

Research approaches: Collection of improved data from salmon farms (above) may provide some insights. Information from sites where ADDs are not permitted to be used may be especially useful. Investigation of instances where ADDs cease to be effective, e.g. acoustic mapping of sound fields for comparison with effective ADDs.

A series of field trials could be conducted to address these issues. For example farms could be allocated existing ADD types according to a randomised controlled trial design once seal attacks start. This would allow unbiased comparisons to be made between the performance of currently available ADDs without leaving any farms “unprotected”. The experimental design might allow site managers to opt to switch to an alternative device (also allocated randomly) if the first device was shown to be ineffective. This would allow development of a formal index of relative effectiveness of different devices, but could only be achieved with commitment of industry.

8.2.1.5 Anti-Predator Nets

This project has highlighted that while anti-predator nets are rarely deployed in Scotland, they are routinely used in other salmon-producing countries. The reasons for this difference are not clear and should be investigated (**R5**).

Research approaches: Dialogue with salmon producers and researchers working with anti-predator nets (and related techniques) in other countries, for example, in Canada, Chile and Australia into the effectiveness of these nets. A critical comparison of anti-predator net structure used abroad with those (previously) used in Scotland, followed by controlled trials of any promising modifications or new devices at one or more appropriate sites in Scotland.

8.2.2 Unintended Environmental Consequences of ADD Use

8.2.2.1 Hearing Damage

The risk that individual animals may suffer hearing damage through exposure to ADDs is currently poorly understood. A potential risk has been identified through this review and it is most likely to affect seals that are motivated to remain close to fish farms with operating ADDs. Risk of hearing damage needs investigation (**R6**).

Research approaches: Risk of hearing damage could be assessed by combining maps of sound fields with photo-identification and range measurement data (movement patterns) for seals at fish farms and using these data to calculate cumulative sound exposure. Another potential approach would be to catch seals at farms and use telemetry devices, including acoustic dose meters, to measure movements and exposure simultaneously. Existing telemetry datasets held by SMRU could also be examined to approximate acoustic exposure. The hearing sensitivity of captured seals that have apparently “habituated” or become resistant to ADDs could also be assessed. The inner ears of seals shot at fish-farm sites could also be examined for evidence of hearing damage. Any assessments of hearing sensitivities and potential damage would need to be made in the context of an understanding of these parameters in the wider population.

8.2.2.2 Disturbance of Non-Target Species

Questions still remain about the extent of habitat exclusion and disturbance of non-target wildlife (e.g. cetaceans) from ADDs. At least four different ADDs are being used in Scottish waters. These are likely to differ substantially in their potential effects on wildlife but effects of only one type have been measured. Impacts of other devices on non-target species should be investigated (**R7**).

Research approaches: In Scotland, harbour porpoises can be used as a representative species because they are locally abundant. Well proven, effective passive acoustic monitoring methods exist to quantify their displacement due to ADDs. Research using a balanced experimental design can be used to quantify and compare the degree of habitat exclusion caused by the ADDs most commonly used in Scottish waters. This type of monitoring approach has been applied successfully several times at Scottish salmon farm sites so there is little technical risk. As with most research, close cooperation from the salmon farms involved will be essential. This work could provide a disturbance index for each ADD type which, in conjunction with data on the effectiveness of devices in reduction of seal depredations, could be used by regulators to make recommendations.

8.2.2.3 Ecological consequences of habitat exclusion

The first step towards understanding the population consequences of habitat exclusion caused by ADDs is to measure small cetacean densities in the regions around fish farm sites and at nearby control sites. For porpoises this can be done most efficiently using a combination of visual, towed hydrophone and static acoustic monitoring. Further work is needed to investigate the ecological consequences of habitat restrictions on small cetaceans (**R8**)

Research approaches: Quantification of porpoise densities year round in the wider vicinity of several representative farm sites including at times when ADDs are not being used. A combination of visual and towed acoustic surveys in conjunction with static monitoring at appropriate locations is likely to be most effective technique. These data, in conjunction with measures of disturbance, could be used to advise on appropriate ADD types for particular sites.

8.2.3 Development of New Management Approaches

If a combination of improved management and containment practices (including ADDs) are not able to reduce seal depredation to the point where levels of lethal removals are considered acceptable by regulators then new management options clearly need to be explored (**R9**). Two examples are given:

8.2.3.1 Electric field deterrents

Research supported by SARF is ongoing at SMRU. Where necessary, this should be extended and continued.

8.2.3.2 Conditioned taste aversion

This review has identified CTA as a particular area where research is warranted. Both captive and field studies are required as outlined in section 2.3.3.3.

8.2.4 Alternative Applications Using Sound for Management

8.2.4.1 Active Acoustic Mitigation of Risk from Pile Driving and Explosions

Given Scotland's ambitious plans for development of offshore wind farms and the ongoing removal of abandoned well heads and other offshore oil infrastructure the development of effective and affordable means for mitigating the risks of hearing damage from pile driving and explosives is urgently required.

A method that shows considerable promise is the use of aversive sounds to move animals out of areas where they would be at risk using aversive acoustic signals. Research is needed to show how animals move in response to different sound types and how such signals could be used to provide practical and predictable mitigation (**R10**). Potential research approaches for Scottish priority species are outlined below.

Research approaches. Different research approaches will be needed for different marine mammal groups:

- **Seals**

Recent work funded by Scottish Government has developed and demonstrated an approach combining a new detailed telemetry system with low-cost, at-sea playback, which can be used to provide the detailed information on animal movements in response to acoustic signals that is needed to develop aversive sound mitigation techniques for seals. This approach should be applied to both harbour and grey seals and conducted either within areas where mitigation techniques are required or within habitats that closely match those areas.

- **Harbour porpoises**

An approach combining the use of static acoustic monitoring devices with detailed observation of behavioural responses to controlled exposures has been shown to be effective with this species. Trials may need to be completed with a greater range of candidate acoustic signals. The development of live capture methods to enable telemetry would greatly assist such work.

- **Minke whales**

Controlled exposure of animals would be likely to be successful but methodological and equipment development (e.g. suction cup telemetry devices) may be required as precursor.

9 General Conclusion

It is clear that acoustic deterrent devices have the potential to play an important role in marine mammal conservation and welfare, and in the management of interactions with fisheries, aquaculture and in certain areas of marine engineering. Much of this review has focused on the specific application of reducing pinniped depredation at salmon farms as this is the main current use for acoustic deterrent in Scotland, and is clearly a significant source of profit reduction within an increasingly important industry. The potential application of acoustic deterrence, however, is a long way from being fully realised and conservation, welfare and economic benefits are being lost as a result. A poor understanding of how animals respond to acoustics signals and how sound affects them being the main contributory factor. We are beginning to obtain a much clearer picture about how some ADDs work and what their impacts are on marine mammals, but there are still large areas of uncertainty.

Despite being used to protect Scottish aquaculture sites since the mid-1980’s, it is striking that there is so little independent evidence of the effectiveness of ADDs in reducing seal depredation. What little research has been conducted overseas has shown little support for long-term, continuous use of ADDs, but the lack of formal evidence is critical. A paucity of research effort and regulation in this area has encouraged the development and widespread deployment of a number of devices without evidence of their effectiveness, some without any documentation of their acoustic characteristics.

Depredation at Scottish fish farms appears to have reduced over the last decade, but this is probably due to improvements in containment and husbandry practice rather than the widespread use of ADDs. Other methods for reduction of depredation, such as the use of anti-predator nets and lethal removal of seals, are not seen as ‘complete’ management strategies, but are worthy of increased research effort.

Acoustic deterrents have been found to be effective in reducing the bycatch rates of some species in capture fisheries, and this effect has not been seen to have decreased over time. The neophobic nature of some species, including harbour porpoise, is likely responsible for a substantial degree of this success.

Most sound sources can have negative as well as positive consequences and both must be understood in order to allow a balanced assessment of costs and benefits. A major concern is that powerful devices may have detrimental impacts on the auditory system, behaviour and ecology of both target and non-target species.

There is evidence to suggest that the criteria currently used to assess the likelihood of hearing damage may not be as precautionary as they were intended to be. In the case of aquaculture, for example, it seems entirely plausible that seals which spend extended period of time in the vicinity of fish farm ADDs may well be impacted by hearing impairment. More information to allow the development of realistic movement models for individual animals in the vicinity of devices is required before this risk can be assessed in finer detail. Similarly, there is considerable evidence that at least some of the devices being used may have significant impacts on the distribution and therefore the ecology of some cetaceans, notably harbour porpoises. Population level impacts of such displacement and hearing damage are very hard if not impossible to determine, but it is clear that if animals are highly dependent upon the detection of signals at or near their sensitivity threshold, then even small threshold shifts could have large impacts. The potential for hearing damage is a concern in respect to ADD effectiveness as well as animal welfare.

From a legislative perspective, deliberate disturbance of European Protected Species, such as cetaceans, contravenes the Habitats Directive (Conservation (Natural Habitats, &c.) Regulations 1994 as amended in Scotland). The question of whether and in what circumstances the use of ADDs will need to be licenced is still being deliberated by regulators such as Marine Scotland and SNH. If the use of ADD’s in particular circumstances requires a licence, it will be important to demonstrate the efficacy of ADDs. At present there is evidence that ADDs can work, at least for short periods of time, in deterring some seals from the proximity of river mouths and from salmon trap-net fisheries and that the use of ADDs at salmon trap net fisheries can reduce the amount of damage to fish that are caught, but these results cannot necessarily be extrapolated to infer anything about long-term use of such devices at salmon farm sites. There is anecdotal evidence to suggest that ADDs can reduce seal depredation at aquaculture sites but there has as yet been no independent and objective assessment of how effective ADDs are in managing seal depredation at Scottish aquaculture sites. Such information would greatly facilitate an objective assessment of the costs and benefits of ADD use.

Apart from aquaculture, aversive sound mitigation has the potential to reduce risks to marine mammals associated with construction and energy installations. Suitable mitigation ranges will depend greatly on the species, pile-diameter and environmental conditions. There is also the potential for unintended consequences such as the separation of groups including mothers and calves, strandings, and widespread exclusion. A more complete understanding of likely effects is therefore required before these techniques can be broadly adopted.

Finally we consider the original questions posed for this project.

- What types of ADD are currently employed, or are in development, which are used to deter marine mammals in different scenarios, for example at fish farms, netting stations, rivers, and in/around areas of development (e.g., oil and gas, renewables)?

The commercially available devices that are commonly used in Scotland are listed in Table 2. All of these devices have been used at fish farms to a greater or lesser extent. Netting stations and river fisheries have mostly used or tested Lofitech ADDs and more recently Airmar devices. A sixth device developed at the University of St. Andrews is currently under development (see section 2) but is not yet available for commercial purchase.

We have found no reliable sources of information on the types of acoustic deterrent devices used to keep marine mammals away from marine industrial development sites. Although the use of ADDs is part of the Joint Nature Conservation Committee (JNCC) protocol for minimising the risk of injury to marine mammals from piling noise, no co-ordinated records are maintained on which types of device have been used where. This is an area which will be examined in detail under phase one (of project four) of the Offshore Renewable Joint Industry Programme, with the intention of developing a protocol for ADD use at development sites. Detailed studies of the Lofitech device for this application suggest that it has successfully been used abroad to some extent.

- Are these devices fit for purpose and appropriate for deterring marine mammals in a range of scenarios and often at a very local scale? For example, are some commercial devices more applicable for deterring seals in more constrained salmon rivers, while others are more appropriate for deployment in coastal or offshore waters? Will some devices be more appropriate for long-term deployment as opposed to short-term?

Because so few trials have been conducted, and there is such a poor understanding of how and under what circumstances these devices actually achieve their apparent deterrent effect, it is impossible to determine the relative effectiveness of the currently available candidate devices. All have different acoustic characteristics and different logistical constraints (power supply, robustness) which on a practical level may make them more or less suitable for different applications. There is little objective evidence as yet to suggest the relative merits or superiority of any one device compared to the others for a specific context (see section 2.2.4). It is very likely, given the range of target and non-target species which will be encountered in different applications, that multiple signal types will be required, dependent on environmental context as well as industrial requirement. Work toward development of such signal types is currently in its infancy.

- Are certain devices more appropriate to a particular species? Are there different requirements for seals, toothed cetaceans, and baleen whales (dependent on the purpose of deterrence)?

A complete list of devices is provided in Table 1. Across the range of these acoustic deterrent devices, several different types of pinger, primarily used in set net fisheries, have proved effective in displacing porpoises. However, such devices remain unproven with respect to most other species, and may attract seals when used on fishing gear. Louder ADDs such as the seal scaring devices used at fish farms, are likely to be more effective for a wider range of species (see section 2.2.3.3), however, there are several contextual considerations that may constrain deployments. For example, it may be desirable in some cases to deter all marine mammals, whereas in other cases it may be preferable to deter only one group (such as seals). In other cases the use of a specific ADD or signal type, which may be associated with food in other circumstances, might attract rather than deter particular species. The species specificity of different devices remains poorly understood.

- What is the relative effectiveness of existing ADDs on marine mammals (considering seals and cetaceans separately)? For example, at what range do they exclude mammals? Do certain devices exclude seals and not cetaceans, and vice versa?

Given our current state of knowledge of the efficacy of the different devices it is not possible to make such a comparison.

Our understanding of the relative effectiveness of ADDs on seals is particularly limited. There are better data on deterrent/exclusion effects on porpoises and other odontocetes. It is known for example that Airmar and Lofitech ADDs are effective in deterring porpoises to several km from source (see section 2.2.3.3) though in many applications this is not a desired effect. Some studies have also tried to quantify the degree of exclusion of porpoises for various types of pingers. In part the range of effectiveness will be contextually driven, but will also likely relate to the amplitude and frequency characteristics of the devices. It is likely that devices could be targeted towards particular marine mammal groups by designing them to emit frequencies to which that group was more sensitive. Thus, devices which emit higher frequency sounds are more likely to be aversive to odontocete cetaceans whose high frequency hearing sensitivity is greater than that of seals. Baleen whales are more likely to be sensitive to low frequency sounds, but once again our understanding is limited by the paucity of relevant studies. Recent work at the University of St Andrews has used this approach in an attempt to develop an ADD that will be effective against seals but not disturb odontocetes. Preliminary results suggest that one of the ADD types used routinely at Scottish fish farm sites is much less disturbing to porpoises compared to others that have been tested.

- Are there efficiency improvements which could be made by best practice in using existing ADDs? For example, targeted activation of devices when marine mammals are located in the vicinity of the devices (as opposed to continuous use).

Targeted activation could make deterrent devices more <u>efficient</u>, in that power consumption could be reduced and acoustic output reduced. Whether or not such devices would be more <u>effective</u> in minimising seal depredation or in deterring marine mammals more generally remains to be determined. Less acoustic energy will be released into the environment and unwanted exclusion effects should be reduced. However, some argue that some hearing damage risks could be increased. Certain fish farms already employ different tactics in this respect (targeted or continuous activation). There is no clear evidence to suggest either tactic is preferable but insights might be derived by analysing data collected at fish farms.

- What are the ecological consequences of ADD's in terms of underwater noise?

The introduction of loud sounds into the environment is considered a form of pollution by some authorities and it is generally recognised that it should be avoided where possible. ADD signals have been shown to alter the distribution of some species, especially the more neophobic animals with greatest hearing sensitivity (e.g. porpoises). The extent to which such distributional changes are of ecological relevance remains unknown. The output characteristics of some ADDs are fairly well described see (section 2.2.1), but for others there is very little reliable information available. The extent to which different types of ADDs displace marine mammals can be measured relatively easily and is likely to be influenced by to source levels and spectral composition of ADD signals and how these relate to animal's hearing sensitivity. Displacement studies have only been reported for two of the devices routinely used. A measurement of displacement provides straight-forward metric, allowing regulators to judge one device against another.

- Beyond ADDs are there any other current or developing technologies for deterring marine mammals? When answering this question, consideration should be given to the reasons for deterrence (e.g., aquaculture, fisheries, mitigation for renewable development).

There are several other methods that are currently being used to limit seal depredation at fish farms including net tensioning, seal blinds and mort removal. Other methods of deterrence such as conditioned taste aversion and electric fields also show some promise, but require development and testing before they can be applied. Lethal removal to limit depredation at fish farms and nets is widely used but has not been adequately assessed as an effective management strategy, and may not be considered acceptable to the public or other stake holders (see 2.3.3). It also raises specific conservation concerns for harbour seals in some areas. For renewable energy developments and fisheries interactions, acoustic deterrents appear to be the only viable means of deterring or alerting marine mammals.

- Can baseline information be improved which would benefit developing marine industries?

There is still a dearth of information on several key issues. For fish farms, more standardised recording of anti-predator techniques and associated levels of damage, coupled with a commitment to analyse such data, should help in isolating and refining the most effective management measures. Lethal removal of seals yields sources of data (carcasses) that could be extremely insightful, but are currently only very rarely collected or analysed. For marine renewables, key areas of uncertainty include the density and distribution of marine mammals around development sites, the behavioural responses of different species to different acoustic stimuli, and how these may vary in different contexts and in different motivational states.

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