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Review of non-lethal seal control options to limit seal predation on salmonids in rivers and at finfish farms

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D. Thompson, A.J. Coram, R.N. Harris and C.E. Sparling

Sea Mammal Research Unit, University of St Andrews, St Andrews, Fife, KY11 9LB

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D Thompson, AJ Coram, RN Harris and CE Sparling

Sea Mammal Research Unit, University of St Andrews,
St Andrews, Fife, KY11 9LB

Executive Summary

This paper reviews measures that have been adopted in the UK and overseas that could assist in developing non-lethal strategies to control seal predation on salmon in rivers, and to prevent seals from depredating at marine finfish farms. It then presents a number of assessments and recommendations for use of, or further development of, specific measures.

While the report addresses the river and fish farm problems separately, some of the methods are similar so there is some inevitable overlap.

Salmon Rivers
It is clear from the available literature that there is no single, effective non-lethal solution to address the problem of seal depredation in salmon rivers. There are however a range of methods that have been shown to have some success or have the potential to reduce predation.

Globally, the most widely employed methods are simple, low tech attempts to disrupt predation activity and to drive seals and sea lions away from parts of rivers where predation is concentrated. In general, harassment methods have not solved the predation problems, but are still widely used in the large salmon rivers in the United States of America (USA) to disrupt pinniped foraging behaviour and where non-lethal measures must be attempted before lethal removal is permitted.

In Scottish rivers, attempts to actively move seals away from predation sites have involved relatively mild forms of harassment (e.g. shouting, hitting the water) compared to the methods routinely used in the USA. However, some of the methods employed in the USA such as cracker shells, aerial screamers and small hand-thrown pyrotechnics are widely used in the UK as bird scarers and therefore could potentially be used to increase the intensity of negative stimuli to move seals away from sensitive locations.

If all, or a proportion of the seals, can be prevented from swimming upriver, the problem would be reduced. A range of seal exclusion methods have been attempted or suggested which include:

- Physical barriers may provide a solution where they can be installed and maintained.
- Arrays of acoustic deterrent devices (ADDs) to produce acoustic barriers have shown promise in preventing seals entering or moving up rivers and may be the only option for preventing seals moving through the estuaries and lower reaches of larger salmon rivers
- Electric field barriers may prevent passage of seals, but results have been equivocal and additional testing would be needed before deploying a system.

If deterrence and exclusion methods have not worked or are not a practical option at a site, one possible solution would be to catch and remove the seals. Translocating harbour seals (*Phoca vitulina*) and other pinniped species has been attempted in the USA and Australia but has not been successful. An alternative approach may be to catch seals and hold them in temporary captivity to remove the predation threat during important periods of the year e.g. during the peaks of the salmon runs or until the end of the fishing season.

Finfish farms

There is a continuing problem of seal depredation at Scottish finfish farms. Defence against such depredation is essentially a matter of dissuading seals from approaching and attacking the cages or of making the cages seal-proof.

Measures to reduce the incentive for seals to attack cages include routine husbandry such as regular removal of dead fish and modification of the cage floor to include a seal blind. These are widely practiced in Scotland.

Measures to make seal attacks less successful rely on a combination of factors including:

- Maintaining the correct tension on nets to stop deformation in tidal currents and prevent folds and loose net that allow seals to access fish.
- Changing to new stronger and stiffer net types. The gradual uptake of new net materials is already having a significant effect in reducing the number of seals being shot at sites using them.
- Using anti-predator nets (APNs). The use of APNs is reportedly increasing in Scotland.

The primary method used to deter seals from attacking cages is the use of acoustic deterrent devices (ADDs). A separate Scottish Government study has examined available information on the extent and usage of ADDs at Scottish finfish farms in order to improve understanding of their use and effectiveness (Coram et al., in prep).

Where ADDs are used, there are a number of potential methods to reduce the levels of noise input into the inshore marine environment and reduce potential impacts on non-target species (NTS), including European Protected Species (EPS) such as harbour porpoises (*Phocoena phocoena*), bottlenose dolphins (*Tursiops truncatus*), minke whales (*Balaenoptera acutorostrata*) and killer whales (*Orcinus orca*) which are the most commonly encountered cetacean species in areas surrounding Scottish finfish farms.

Several ADD systems have been developed to reduce noise output at the frequencies most likely to disturb porpoises and dolphins. Other potential methods to reduce noise output involve reducing source levels and duty cycles, attempting to attenuate the ADD signals, restricting transmissions to times when seals are present and blocking transmissions whenever porpoises or dolphins are in the vicinity of finfish farms. These options necessitate the development of a sensitive seal detection system, and sensitive porpoise and dolphin detectors.

In addition to direct deterrence using sound, this report also addresses aversion methods including an electrified fish model that delivers a painful but not damaging electric shock and conditioned taste aversion methods.

Seal detection systems

Active deterrence and seal capture methods, both in rivers and at finfish farms, either rely on or will be made more efficient by the timely detection of seals. Minimising the use of deterrents and targeting them only at times when seals are actively involved in predation or when they are at particular, sensitive locations, should reduce the likelihood of seals habituating to the deterrents and reduce the frequency and duration of disturbance to non-target species. The importance of effective detection components within such detect and deter systems cannot be overstated.

Video systems designed for monitoring seals in rivers and at finfish farms are currently undergoing field trials and sonar systems have already been used to automatically monitor marine mammal activity around tidal turbines. Modification and further development of such systems, particularly the development and testing of detection algorithms should provide useful detection capabilities for both rivers and finfish farms.

1. **Introduction**

River fisheries for Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta*) are an important component of the Scottish rural economy. The economic benefits of Scotland's wild fisheries are significant despite declines in the number of returning salmon in recent decades. A recent Scotland-wide economic impact assessment of wild fisheries indicates around £135m of angler expenditure, 4,300 full-time equivalent jobs and £79.9m Gross Value Added (GVA) in 2014 (Marine Scotland, 2017).

In Scotland some individual grey seals (*Halichoerus grypus*) and harbour seals move into the estuaries of salmon rivers, and in some cases travel up-river, where they feed on salmon and sea trout (Graham et al*.,* 2011). This results in the loss of a proportion of the fish through predation, as well as injuries or damage caused by unsuccessful attacks. Such injuries may lead to mortality but will also reduce the value of the fish. In river fisheries there is an additional loss of revenue as recreational anglers prefer not to fish areas frequented by seals due to a perception that seal presence may reduce the catchability of fish. This could directly impact the local economy and may increase fishery costs associated with mitigating seal predation (Butler et al*.,* 2008; 2009; 2011). There are also concerns about the stress imposed on fish by the presence of seals, which may adversely affect spawning through reducing energy reserves used for gonad production or displacement of fish from redds (nests). These concerns are particularly acute where the numbers of returning fish are in decline as is the case in most salmon rivers in Scotland (Fisheries Management Scotland, 2020).

Salmon aquaculture is one of Scotland's most important rural industries, with production of 203,000 tonnes in 2019 (Marine Scotland, 2020a). Scottish farmed salmon is Scotland's largest food export, and in 2019 a record 94,300 tonnes was exported to 54 countries, with 25,000 tonnes worth an estimated £179 million exported to the USA alone (SSPO, 2020). The industry directly employs approximately 1600 people in production and supports substantially more jobs in the wider economy (Marine Scotland, 2020a). Between 2013 and 2017, aquaculture GVA increased by 58% to £354 million (Moffat et al*.,* 2020). Finfish aquaculture cages often attract grey and harbour seals, and depredation has been recognised as a major problem since the 1980s. Northridge (2010) estimated that 72% of finfish farms in Scotland experienced problematic levels of seal depredation. Marine aquaculture in Scotland is primarily concerned with production of salmon and to a lesser extent trout, so for simplicity the term finfish farm will be used throughout the report for any marine aquaculture site.

Several reviews, workshops and questionnaire-based documents have addressed the issue of pinniped depredation in fisheries and at aquaculture sites, with most summarising existing research which might have relevance to a particular area or fishery (e.g., Northridge et al*.,* 2010; Coram et al*.,* 2014). This contrasts with the limited amount of empirical research into novel mitigation techniques (e.g., Kastelein et al*.,* 2010; Milne et al., 2010; Götz & Janik, 2011).

All active deterrence systems will either rely on or be made more efficient by timely detection of seals moving into sensitive parts of a river system or approaching cages in a marine finfish farm. To date, a range of detection methods have been either proposed or attempted. These will not all be appropriate to each situation, but a selection or combination of systems will be required depending on local conditions.

Reviews of potential solutions to pinniped-fisheries interactions were conducted in 2014 with an emphasis on aquaculture (Coram et al*.,* 2014) and in 2019 with an emphasis on river salmon fisheries (Coram et al., 2019). The current review aims to expand on these reports, adding recent research findings where appropriate. This will then be followed by an assessment of the available approaches and any associated recommendations for future progress with Scottish river fisheries and finfish farms in mind. Much of the information is derived from non-peer reviewed technical reports and in some cases appears only in press reports and on industry bodies' web sites or in manufacturers' publicity materials. These have been included where necessary to provide the relevant information to assess the effectiveness of methods and to provide as comprehensive a view as possible of the current state of knowledge.

Although it is recognised that there are significant overlaps and interactions between categories, for the purposes of this review, methods will be divided in to the following six main categories:

- Hazing and tactile harassment
- Acoustic deterrence
- Physical exclusion
- Electric field barriers
- Conditioned taste aversion
- Trapping and removal

1.1 Structure of the report

The report is divided into five inter-related sections. After a general introduction in Section 1, Sections 2 and 3 present the available information describing the current state of knowledge and practice in efforts to control seal predation on salmonids: Section 2 covers predation control methods in rivers; Section 3 covers predation control methods at marine finfish farms. Some of the methods will be relevant to both river fisheries and finfish farms, but the physical and operational differences mean that applications will generally differ. This has inevitably led to some duplication, but this has been kept to a minimum.

Many of the deterrence methods described in Sections 2 and 3 will either depend on or will be better targeted and more efficient when paired with effective seal detection systems. As similar methods will be applicable to seal detection in rivers and at finfish farms, Section 4 presents a summary of information on available methods for the detection of seals in both situations.

Section 5 then uses the information in the preceding sections to provide a series of recommendations for the application and further development of those methods deemed most suitable for preventing seal predation in rivers and finfish farms.

2. Deterring Seal Predation in Rivers

The numbers of grey and harbour seals involved in predation on salmonids in rivers in Scotland is small, but the impacts of these individuals on depleted salmonid populations and on river fisheries may be large, particularly in the context of ongoing conservation concerns for wild salmon (Fisheries Management Scotland, 2020). There is a widely-held belief and some scientific evidence that the seals in rivers, often referred to as rogue seals, are specialist predators of salmonids (Graham et al*,* 2011). Deterring these individuals from preying on salmon in rivers or from entering or moving up rivers would potentially solve the problem. Many of the methods described are targeted on disrupting the behaviour of individual seals in rivers and/or preventing them from accessing predation locations.

2.1 Harassment, Deterrence and Exclusion

Where predation problems exist and one or more predatory seals have been identified and located, the simplest solution would be to drive them away from the site. Several simple, low tech methods have been used in attempts to deter pinnipeds or to drive them away from areas where they prey on commercially important and/or endangered fish stocks. To be useful such methods must persuade seals to leave the area and stay away. However, to date the effectiveness of these methods have not been tested rigorously. Here we provide brief descriptions of simple visual and in-air acoustic disturbance, underwater percussive noise devices, physical contact devices and herding or driving methods that have been used in attempts to move seals away from specific sites.

Most information on seal harassment methods comes from a small number of sites in the USA and Canada where large numbers of seals and sea lions are involved in predation on salmonids and where intensive efforts to reduce the predation have been recorded (e.g., NMFS & ODFW, 1997; NMFS, 1996a). One important caveat, when interpreting these observations with respect to their potential for use in Scottish rivers, is that much of the information on the effects of active hazing and tactile harassment is based on the responses of sea lions, mainly California sea lions (*Zalophus californianus*). Although there have been no direct tests of differences in sensitivity to disturbance between species groups it is generally accepted that there are species specific differences in responses to human activity, and sea lions are generally more robust than phocid seals in their interactions with humans. For example, several species of sea lion have been shown to regularly overcome their fear of humans and in some cases become a problem in harbours, marinas, and in commercial and recreational fisheries. It is therefore important to consider that a lack of response to a deterrent by sea lions does not necessarily mean that grey or harbour seals will not respond.

In addition, the scale and intensity of pinniped predation on salmonids may be much greater in large American salmon rivers. The scale of the runs of Pacific salmonid species and the numbers of pinnipeds involved in the predation events is often much larger than in Scottish salmon rivers. The scale and intensity of active control measures required to effectively remove the problem will likely be commensurately large and intense. In some situations, it is possible that the presence of persistent salmonid predators encourages others and may therefore render mitigation measures less effective. That is not the typical situation in Scottish salmon rivers where predatory seals are often solitary individuals. The fact that the predation control in the USA rivers is usually in much wider and deeper bodies of water may allow seals more options to evade the control measures than would be the case in the smaller, shallower rivers in Scotland.

The extensive use of, and demand for simple methods to move seals and sea lions away from specific sites led the US National Marine Fisheries Service (NMFS) to publish an information note in 2018 on acceptable methods for harassing seals and sea lions (NOAA, 2018). For information these recommendations are summarised in TEXT BOX 1.

It should be noted that at the time of writing NMFS have issued a draft revised set of guidelines for deterring marine mammals (NOAA, 2020a) that were subject to a consultation process.

TEXT BOX 1. Recommended methods of seal deterrence in the USA.

In the USA, the Marine Mammal Protection Act (MMPA) prohibits the harassment, hunting, capturing, or killing of marine mammals, but does make exceptions under which NOAA can authorize certain individuals to deter marine mammals from damaging fishing gear and catch, and to protect private property. The latter being a particular issue where sea lions haulout on man-made structures such as floating decks and moored boats.

Any such actions in the USA must avoid killing or seriously injuring an animal. NOAA advise that in order to reduce the risk of causing "serious injury" to an animal, deterrence methods should be chosen that avoid penetration or tearing of skin, damage to eyes, and blunt force trauma that could cause broken bones or internal injuries. NOAA therefore advise against the use of firearms including BB guns and anything firing metallic, sharp or glass projectiles. They do however provide a list of potential methods, that are considered to be acceptable for use as deterrents for pinnipeds under section 101(a) of the MMPA.

Guidelines for non-lethal measures that the public may use to deter pinnipeds include:

- Noise Makers such as horns, whistles, bells, music, loud banging of pots, pans, drums etc.; electronic acoustic devices (Acoustic Harassment Devices); starter pistols and pyrotechnics (e.g., bird screamers, bangers, firecrackers, propane canons)
- Visual Repellents, such as flashing lights or strobes and human attendants/monitors
- Physical Contact, such as high-pressure water hoses; sprinklers, and various projectiles including non-toxic and water-soluble paint ball or air soft guns (no metallic/glass/sharp projectiles) and slingshots (no metallic/glass/sharp projectiles)

Specifically for moving seals off terrestrial sites and/or floating structures, the use of crowder boards (usually known as pig boards in the UK) and blunt tipped bull poles or brooms to push animals away are recommended. The use of chemical irritants (e.g., non-toxic pepper spray, mace) and cattle prods (electric shock devices for handling livestock) that were included have now specifically excluded from the proposed revised recommendations.

Additional potential methods are suggested for use by fishermen, including boat hazing, circling, pounding on hull, using horns, bells, whistles and firing off pyrotechnics (e.g., bird screamers, bangers, underwater firecrackers (seal bombs) and cracker shells). They also identify additional physical contact methods including using slingshots (no metallic/glass/sharp projectiles), non-toxic and water-soluble paint ball guns and non-lethal ammunition (e.g., rubber bullets). The proposed revised recommendations do not include rubber bullets/baton rounds and prohibit the targeting of the head region.

2.1.1 Chasing or hazing

Vessels have been used in attempts to scare or chase pinnipeds, usually in combination with additional methods such as banging on the boat, seal bombs, cracker shells etc. Attempts at Ballard Locks in Seattle and at Bonneville Dam, on the Columbia River, USA, and in various gillnet fisheries have not proven totally effective, as pinnipeds in many cases simply swam under the boat and resisted leaving the area. Aggressive boat manoeuvring combined with use of underwater firecrackers was initially effective at the Ballard Locks, but became less effective as California sea lions learned to avoid the boat or temporarily move downstream before quickly returning to the Locks (Pfeifer et al., 1989). Fishermen have also used their vessels to chase seals and sea lions from their salmon netting operations in the Columbia River, but such efforts were usually unsuccessful (Beach et al., 1985, referenced in Burger, 2010).

There are no documented studies of the effects of boat hazing on phocid seals in UK waters, although it has been used in some instances to move seals from a particular area. For example, attempts to drive or herd seals towards nets during seal catching for research projects, have been successful on some occasions, but results are erratic and have not involved moving seals from favoured foraging sites (SMRU unpublished).

In Scotland, attempts have been made to drive seals downriver to avoid interaction with river fisheries, with mixed success. In some cases, seals have been successfully moved many kilometres downstream using ADDs suspended from small boats, including in both the River Dee and the Kyle of Sutherland (SMRU unpublished data). However, in other cases, (e.g., an attempt to drive a juvenile harbour seal from the River Ness), the ADD was apparently ineffective with the seal remaining in very shallow water close to the bank, appearing reluctant to go downriver and as the boat attempted to move from the deeper central channel the seal bolted up river. Difficulty with manoeuvring small row boats in fast currents means that seals escaping upstream of the device cannot be recovered, and the presence of islands in the river means that multiple boats and deterrents are needed to ensure that seals do not simply by-pass the driving boat and move back upstream. Individual river characteristics may lend themselves more than others to this type of mitigation. Operators on the River Dee suggested that although an ADD was used, there was also a great deal of human activity and disturbance associated with this activity and, where seals did move downstream it was not clear if the disturbance or the ADD was the main factor.

If these methods are to be practical, then an ability to reliably follow the seal would allow monitoring of their effectiveness. Seals can be difficult targets to follow by observers sitting in watercraft. Ideally this could involve animal borne telemetry devices with near real time localisation capability allowing seals to both be relocated should they pass upriver of the driving boat, for further attempts as well as allowing an accurate assessment of efficacy in the longer term.

2.1.2 Firecrackers/seal bombs

Underwater firecrackers (called "seal bombs") are pyrotechnic devices that have been used in attempts to deter pinnipeds in a number of different scenarios. Seal bombs (sometimes also referred to as Seal Control Devices) that are commercially available in the USA (e.g. Seal Cracker Device manufactured by Stoneco Energetics Systems LLC, Arizona, USA) consist of a cardboard tube containing approximately 36 grains (2.3 g) of potassium perchlorate and pyro-aluminium flash powder with an 8-second waterproof fuse. Tubes are weighted with sand, and sink before exploding underwater (Scordino, 2010). They produced a flash and a loud bang. Awbrey and Thomas (1986) estimated that seal bombs generated sound pressures of approximately 190 dB re 1 µPa @ 1 m (RMS) (root mean square), with most of the sound energy below 1 kHz, which is below the range of maximum hearing sensitivity for sea lions (Reichmuth & Southall, 2012).

Seal bombs were used in early attempts to reduce California sea lion predation on salmonids at the Ballard Locks. Initial results were promising, but in subsequent years some sea lions appeared to become habituated to the noise and continued preying on salmonids at the Locks (Pfeifer et al*.,* 1989). Although sea lions were initially frightened away by the explosions, the effects were transient, with sea lions either returning within a few hours or moving to different sites where they continued to prey on steelhead trout (*Oncorhyncus mykiss*) (Scordino, 2010). They also appeared to learn to evade seal bombs by diving and surfacing in unpredictable patterns (Pfeifer et al*.,* 1989). Use of firecrackers to deter California sea lions at Bonneville Dam also seems to have had limited success in keeping sea lions away from salmon predation areas near the dam (Brown et al*.,* 2008).

Geiger and Jeffries (1987) used salmon damage and catch rates to compare the effectiveness of seal bombs, cracker shells and an early ADD model on rates of seal damage by harbour seals foraging at nets in the Columbia River, USA. The percentage of damaged Chinook salmon (*Oncorhynchus tshawytscha*) in the catches where seal bombs were used during net set (20.5%) was not significantly different to net sets with no harassment (24.3%). The results are difficult to interpret because of differences in catch rates and the fact that fishermen were free to determine the location, frequency and timing of seal bomb use. It is however clear that seal bomb use did not prevent seal predation at the nets.

Seal bombs and firecrackers have long been used in the USA and have usually been assumed to be harmless. For example, known individual sea lions that were exposed to repeated use of firecrackers at the Ballard Locks from 1986 to 1988 were observed in subsequent years and showed no ill effects from the exposure (NMFS and WDFW, 1995). These same sea lions were reported to have continued to react to noise stimuli indicating they had not been deafened by their exposure to firecrackers. However, no details of the follow-up sounds were reported, so hearing damage in particular frequency bands cannot be ruled out.

However, recent reports from California suggest that seal bombs may pose a greater threat of injury than previously thought (Kerr and Scorse, 2018; Simonis et al*.,* 2020). Wiggins et al. (2019) estimated that a seal bomb with 2.3 g of flash powder is louder than previously reported, with an estimated source sound exposure level (SEL) of 203 dB re 1 μPa^{2}s @ 1 m when integrated over a 100 ms time window, which approximates the integration time of mammalian ears. The assumption that the energy is concentrated below the sea lion peak hearing sensitivity is also under question. Although most energy is below 2 kHz, broadband energy is reported above 10 kHz (Awbrey and Thomas, 1986; Ryan et al*.,* 2016; Meyer-Loebbecke et al*.,* 2017). There are concerns that seal bombs may cause physical injuries at close ranges of less than 4 m (Myrick et al*.,* 1990), and auditory injuries at longer ranges (Finneran, 2015; Wiggins et al*.,* 2019). Traumatic injuries to California sea lions, apparently resulting from intra-oral explosions have been documented (Kerr and Scorse, 2018).

In the UK small explosive devices are sold as bird scarers often as part of a multiple banger device with bangers set at intervals along a slow burning fuse. These devices are sold as fireworks and as such are available to be purchased by anyone over the age of 18, without the need for any specific permit. Although the bird scarers available in the UK are not designed for use in water, the inclusion of a waterproof/water-resistant fuse means that they may operate effectively without modification. A simple series of tests under controlled conditions would be needed, in collaboration with a manufacturer to assess their effectiveness as underwater bangers.

2.1.3 Cracker shells

Cracker shells are pyrotechnic devices fired from a 12-bore shotgun. The shells contain a flash powder explosive charge (same as a seal bomb) that is designed to explode in air or on the surface of the water at a distance of 75 m to 100 m from the point of discharge. There are therefore two loud bangs associated with each cracker shell, the firing of the shotgun and the explosion of the shell. The likelihood of auditory injury to the seal is reduced as the shell explodes above or at the surface so there is relatively little sound transmission through the water.

Cracker shells were used to deter California sea lions from salmon forage areas near the Bonneville Dam with limited success (Brown et al*.,* 2008). Cracker shells have also been used in fishery interaction situations with harbour seals with limited effectiveness because the seals learned to avoid or ignore the noise (Beach et al*.,* 1985).

Cracker shells are favoured over seal bombs when deterring seals at greater distances is necessary. However, their use is restricted or precluded in some jurisdictions because they require the use of a firearm.

At present devices equivalent to the cracker shells used as deterrents in the USA are supplied in the UK for scaring birds. They are widely used at airports and on farms, and although not specifically designed to explode on or close to the water surface they are functionally the same as cracker shells and can be targeted to detonate close to the water. A range of 12-bore cartridges are available from specialist suppliers in the UK, (e.g. Birdscaring by Primetake). The cartridges are fired either from a modified signal pistol (e.g. Very Pistol) or from an unchoked 12-bore shotgun. Variants that detonate after 1.3 to 4.0 s are available as are variants that produce a high-pitched scream before detonation. Firearms specifically designed for firing cracker shells, and modified signalling pistols, will usually require a firearms or shotgun certificate.

2.1.4 Effects of explosives on non-target species

In addition to being effective in preventing predation, a deterrent must not adversely affect the behaviour of non-target species, including migrating salmonids and other protected species.

2.1.4.1 Salmon.

To date there do not appear to have been any direct experimental studies of the effects of seal bombs or firecrackers on behaviour of migrating salmonids.

Attempts have been made to assess their effects using catch statistics from drift net sets. Beach et al*.,* (1985) and Geiger and Jeffries (1987) tested the effectiveness of seal bombs and gun-launched firecrackers in preventing predation on chinook salmon in gill nets in the Columbia River. They found reduced catch rates and increased proportions of the catch with seal damage when seal bombs or firecrackers were used compared to control sets with no harassment or when an early design of ADD was used. Although the sample sizes were small, Geiger and Jeffries (1987) concluded that reduced catch indicated that seal bombs caused fish to move away from the nets.

Sverdrup et al*.* (1994) subjected Atlantic salmon to sequences of explosions with pressure amplitudes of ≈ 2 MPa, to simulate powerful, close range seismic airguns. Fish reactions to each explosion were described as cessation of swimming and failure to express a flight reaction. No mortality occurred but levels of the stress hormones adrenalin and cortisol increased before returning to normal physiological levels within 72 hrs of exposure. Some vascular damage was observed that returned to normal after a week. However, these explosions exceeded noise levels likely to be experienced as a result of firecrackers in rivers (Wiggins et al., 2019).

Casper et al., (2012) exposed juvenile chinook salmon to sequences of 960 pile driving sounds producing cumulative SEL (SEL_{cum}) of 217 or 210 dB re 1 μPa^2s ; single strike SEL (SEL_{SS}) of 187 or 180 dB re 1 μPa^2s respectively. Barotrauma injuries occurred in at least 66% of fish that experienced the lower sound exposure level. Damage in the high exposure group was more extensive and comprised mainly bruising of organs with some haemorrhaging of various tissues. No fish died and all continued to take and digest food pellets and displayed normal behaviour. This study confirmed an earlier estimate (Halvorsen et al*.,* 2012) for the threshold level for physical damage of 210 dB re 1 μPa^2s SEL_{cum} and showed that juvenile chinook salmon recover from any injuries incurred at sound levels 17 dB SEL higher than their hearing threshold.

Although the signals are different, the apparent behavioural insensitivity of salmon to pile driving noise may suggest that adult salmon are unlikely to respond strongly to noise from seal bombs. Harding et al*.* (2016) exposed captive adult Atlantic salmon to recordings of piling noise and concluded that they did not show startle responses to playback of individual hammer strikes and that piling noise did not significantly alter their behaviour during an hour of noise exposure. Neither brown trout (*Salmo trutta*) (Nedwell et al*.,* 2006), nor juvenile coho salmon (*Oncorhynchus kisutch*) (Ruggerone et al*.,* 2008) showed avoidance behaviour when exposed to high sound levels from real piling events. There is therefore little direct evidence of any effects of small explosions and percussive sounds on the behaviour of salmonids. It is likely that salmonids will hear seal bombs that explode in close proximity, but the only recorded response of captive salmonids to any form of percussive noise was a temporary cessation of swimming. The evidence from airgun and pile driving noise suggests that salmonids are relatively insensitive in comparison to pinnipeds, but in the absence of direct observation this is conjecture and such devices should be used with caution until there is more concrete information on their effects.

2.1.4.2 Otters and beavers

Both the European otter (*Lutra lutra*) and the Eurasian beaver (*Castor fiber*) are listed as EPS under the EU Habitats Directive and under Schedule Two of the Conservation (Natural Habitats & c.) Regulations 1994 (as amended). Activity that has the potential to disturb, injure or kill individuals of an EPS can only be done under licence, if it can meet certain criteria. NatureScot is responsible for issuing licences to permit actions that might disturb or injure European otters or Eurasian beavers in Scotland.

The physical effects on otters and beavers have not been investigated but are likely to be similar to the effects on pinnipeds. The use of such devices would need to be carefully considered and managed to minimise disturbance and potential injury to other wildlife.

2.1.5 In-air deterrents

There are a few options available to create in-air acoustic emissions that could potentially drive seals away from a river. These may be useful in situations where seals avoid exposure to underwater stimulus by keeping their heads above the surface. These options are reviewed below.

2.1.5.1 Aerial pyrotechnics

Aerial pyrotechnics (e.g., screamer rockets, poppers, banger rockets) have been widely used to scare birds away from crops and airports. Screamers are fired from a handheld launcher (similar to a .22 starter pistol) and fly through the air, emitting a loud whistling sound (screamers) that ends with a “bang” similar to a firecracker. Noise from screamer and banger rockets are generally less intense than cracker shells but are still intended to cause animals to flee. The units have been used at Bonneville Dam to reduce avian predation on juvenile salmonids, and their use was extended to keep sea lions away from the fish ladder at Bonneville (NMFS, 2008a). As with firecrackers and seal bombs, sea lions initially responded by moving away, but either continued to forage elsewhere in the river or rapidly returned to foraging in the vicinity.

Aerial screamer variants of the 12-bore cracker shells are available in the UK for bird scaring. They are launched from the same modified signal pistols or un-choked shotguns and have the same legal requirements as cracker shells.

2.1.5.2 Long range acoustic devices

Long Range Acoustic Devices (LRAD) were initially developed as a long-range acoustic communication system to alert individuals and then transmit spoken warnings at ranges up to 3.5 km. The most widely used LRAD systems sold by Genasys Inc. (San Diego, California) transmit noise in air, in the range 1-5 kHz. LRAD systems in combination with automated radar detection, are already used to deter wildlife from airport runways, wind and solar farms and various industrial plants. The system initially detects approaching birds (usually geese and ducks) and transmits predator calls. If birds continue to approach, the sound changes to a loud percussion noise similar to a shotgun blast before being finally replaced by bird alarm and distress calls.

We are not aware of LRAD systems being applied to deterring pinnipeds. Such loud noises will likely produce a response in seals, but there is no evidence to suggest whether or how far seals will move to avoid the noise, nor if they would habituate to the sounds. Such aerial sound devices are unlikely to be successful in preventing seals moving upstream unless they are used in conjunction with other deterrents, e.g. in combination with either underwater acoustic or electric field barriers where seals may avoid or minimise the barrier effects by swimming at the surface.

2.1.5.3 Bird scarers / propane canons

In some situations, bird scarer gas canons could provide a cheaper, low tech version of an LRAD. Usually powered by propane gas, these are relatively portable units that produce a loud explosive noise either on demand or at pre-set intervals. They are widely used in the UK for driving birds away from crops and airports. We are not aware of bird scarer gas canons being applied to deterring pinnipeds, and the same caveats identified for use of LRADs will apply to the use of bird scarers as seal deterrents.

2.1.5.4 Effects of in-air acoustic deterrents on non-target species.

Since the in-air hearing ranges of seals overlap with those of other wild mammals and birds as well as domestic animals and humans it is likely that an aerial noise capable of deterring seals will be clearly audible to, and cause some disturbance to non-target animals and people. All of the methods described above would be extremely disruptive in terms of the acoustic disturbance caused to other wildlife and human river users. As such their use would need to be carefully considered and managed to minimise disturbance to other river users and other wildlife.

LRAD noise is directional to some extent, but other devices such as gas canon bird scarers and aerial pyrotechnics are not. The only similar activities are the use of loud aerial noises to move birds away from airfields and from crop fields and orchards. The National Farmers Union provide guidance on the use of bird scarers (NFU, 2012) and recommend that their use should be minimised by using alternative scaring methods such as visual scarers, that they should not be used during night time, and operators should use appropriate baffling, even something as simple as straw bales, to make the sound more directional.

Both the European otter and the Eurasian beaver are listed as EPS and are likely to be as sensitive as seals are to these airborne noises and appropriate EPS disturbance licences may be required.

2.1.6 Tactile harassment / physical contact methods

A range of different direct contact methods have been used to deter seals and sea lions from the vicinity of fishing operations at sea, in rivers and around aquaculture sites.

2.1.6.1 Rubber Projectiles

Various forms of rubber or plastic projectiles have been developed to deliver a non-lethal impact, causing potential bruising but not penetrating the skin. They are widely used in law enforcement for riot control and to deter large mammals such as bears from interacting with human activities, particularly in the USA.

Several of these devices have been used in attempts to drive seals and sea lions away from areas of salmon predation in rivers in the USA. For example, shotgun-fired rubber buckshot and rubber bullets designed to repel bears were used on California sea lions at Willamette Falls, Oregon, USA and at Bonneville Dam, USA and rubber-tipped arrows shot from a crossbow were used on California sea lions at the Ballard Locks.

Some California sea lions showed avoidance behaviour after being hit by rubber tipped arrows, while others were not deterred. For example, one sea lion that was hit six times continued to enter the target zone and predated on steelhead trout while avoiding the area near the shooter (Pfeifer, 1989). In 1986, Oregon Department of Fish and Wildlife tested the use of rubber projectiles (rubber buckshot and batons) fired from a shotgun. In total four individually recognisable California sea lions were hit, with smaller sea lions immediately leaving the area when shot and not returning. Larger animals returned within 24 hours and although they were more wary (NMFS and ODFW, 1997), avoiding the location of the shooter, they continued to forage on salmonids at the site (Boatner, 2000). At Bonneville Dam, shotgun-dispatched rubber buckshot and batons have been used intensively on California sea lions. For example, between 2006 and 2008, over 3,000 rubber buckshot/baton rounds were used from boats with limited effectiveness in deterring sea lions (Brown et al*.,* 2008). The potential environmental implications of introducing large numbers of non-biodegradable projectiles into aquatic systems may be a consideration when considering the adoption of this method of deterrence.

Rubber projectiles can cause severe soft tissue damage and bruising and pose particular risks of facial injury and eye damage if targeted at the head. It is difficult to see how such munitions could be used safely on phocid seals in the water, where the head is usually the only available target, unless rounds are fired into the water.

Although the use of these non-lethal ammunitions are recommended in the current US guidance on deterring marine mammals (TEXT BOX 1), proposed revisions to the guidance do not include rubber bullets and expressly prohibit firing any projectiles towards the heads of pinnipeds (NOAA, 2020a).

2.1.6.2 Paintball guns

Paint ball guns (also referred to as paintball markers) use compressed gas, either CO_2 or compressed air to fire dye filled gel capsules (paint balls). Originally developed for forestry workers to mark trees, they are now widely used as recreational toys. The paintballs are ejected at around 90 ms^{-1} and designed to rupture on impact leaving a paint or dye patch on the target. Pellets can weigh approximately 3 g and in humans can cause bruising. The risk of severe soft tissue damage means that targeting the head poses risk of damage to eyes, although the energy involved is much lower than with the rubber/plastic projectiles described above.

Paint ball guns used at Willamette Falls had similar effects to rubber munitions, in that sea lions that were hit moved away from the shooter but continued foraging (Boatner, 2000). Attempts to disrupt predation on salmon and to move harbour and grey seals using paintballs have recently begun in one river in Scotland (Harris pers comm.). The paintballs are not aimed at the seal, but are fired into the water, close to it in the expectation that the seal will react to and avoid the noise of the impact. No results have been reported to date.

2.1.6.3 Bean bag rounds.

Bean bag rounds consist of a fabric pillow filled with lead shot that is fired from a modified 12-bore shotgun. The bag spreads during flight and delivers a severe blow without causing penetrating injury. Recent press reports in Australia (e.g. ABC, 2018) report the extensive use of bean bag rounds to deter Australian fur seals (*Arctocephalus pusillus*) around aquaculture and open sea fishing operations with 8770 bean bag rounds being used on fur seals between 2013 and 2018. There is no documented information on the effectiveness of these devices, but the effect is likely to be similar to that of other non-lethal projectiles, i.e. short-term disruption of foraging behaviour. The potential environmental implications of introducing non-biodegradable or potentially toxic materials into aquatic systems may be a consideration when considering the adoption of this method of deterrence.

Animal conservation and welfare groups including the World Wide Fund for Nature (WWF) and Royal Society for the Prevention of Cruelty to Animals (RSPCA) have expressed concern about the potential for severe injury to seals from impacts on the head. The Tasmanian Government's Department of Primary Industries, Parks, Water and Environment (DPIPWE) regulations stipulate beanbags cannot be used in a manner likely to cause injury to a seal and to minimise risk of injury cannot be fired towards the head of a seal. The protocols also state that no more than 20 crackers and five beanbag rounds can be used against a seal within a six-hour period. As harbour and grey seals usually only expose their heads when they surface it is difficult to see how this method can be used, unless rounds are fired into the water. The use of lead shot in bean bags would also cause a pollution hazard. However, as it is illegal in the UK to shoot lead shot over wetlands, an alternative to lead shot would be required.

2.1.6.4 Taser technology

TASERs are familiar, low current, high voltage electric stun guns. Classed as "less-lethal methods" they are widely used by police forces around the world, including the UK. They work by discharging a high voltage through two wires that are fired into the skin of the target. The target is incapacitated by uncontrollable muscle spasms, but generally stays alert during exposure. Although they have limited effective ranges of only around 10 m to 15 m due to the need for direct wire contact to the charging system, they have been regularly used as part of the hazing methods for deterring bears from foraging at particular garbage dumps to reduce human-bear interactions (ADFG, 2010). The limited range means that standard TASERs will not be useful in deterring seals.

However, TASER also produced a wireless, long range electric shock weapon. Effectively a cartridge containing a miniature, stand-alone shock device that could be fired from a 12-bore shotgun and had an effective range of 30 m to 90 m. The effect on the target was like that resulting from a standard TASER, with the effect supposedly lasting up to 20 s. The company stopped production of these devices in 2011 due to lack of demand.

2.1.7 Effectiveness of harassment methods

Hazing activities have been intensively pursued as part of the non-lethal deterrence efforts in the Columbia River and at Ballard Locks, as the levels of predation by California sea lion and latterly Steller sea lions (*Eumetopias jubatus*) have increased. For example, in 2013 approximately 11,000 shell crackers and 600 rubber projectiles were fired, and more than 8000 seal bombs were detonated during hazing activities at Willamette Falls alone (ODFW, 2017). Hazing efforts are labour intensive. For example, the efforts at Willamette Falls employed one land based operator firing crackers and seal bombs to move sea lions away from the fish ladder entrance and a team of three personnel in a boat to move the sea lions further downstream, again by using shell crackers and seal bombs.

While deterrent efforts had some short-term success in reducing predation at specific locations and times, they were unable to eliminate predation or reduce the sea lion presence in the area (Brown et al*.,* 2008; Scordino, 2010). A common outcome of hazing efforts in various locations, was that sea lions generally acclimatised to hazing efforts and often continued foraging or moved away temporarily before quickly resuming their typical foraging behaviours. Based on several years of deterrence efforts with California sea lions at the Ballard Locks, researchers concluded that non-lethal deterrence measures had to inflict physical pain in order to effectively deter the pinniped beyond the initial response, especially when the pinniped had previously foraged on salmonids at the site (NMFS, 1996; Scordino and Pfeifer, 1993).

In 2010 the Pinniped-Fishery Interaction Task Force for the Bonneville Dam Section 120 program was tasked by NMFS to assess if non-lethal hazing had been an effective aid in reducing sea lion predation on salmonids (NMFS, 2017). Their consensus view was that it had not, and they recommended removing non-lethal hazing as a precondition of the permit for lethal removal of sea lions. Given these conclusions and based on several years' experience of hazing Californian sea lions at Bonneville Dam, Willamette Falls, and other locations, ODFW did not propose to conduct any non-lethal hazing activities in association with a 2016 application for the lethal removal of pinnipeds under Section 120 of the MMPA.

Again, it is important to stress that these results relate almost exclusively to sea lions. However, where harbour seals have been subjected to such methods, they appear to show similar resilience, e.g. during attempts to drive harbour seals down-river using ADD signals in the Columbia river and attempts to use electric field barriers in Puntledge river, Canada (Harlan et al., 2009; Burger 2010). However, there have been very few documented instances involving harbour seals and it is possible that both they and grey seals may be more easily deterred/moved by such audio and tactile stimuli.

It is not clear to what extent the lack of effectiveness could be due to sea lions being more robust and less likely to be deterred than phocid seals. It is also unclear whether grey and harbour seals in the smaller Scottish salmon rivers would be likely to leave the river altogether in the face of such deterrent methods.

2.1.8 Excluding seals from rivers

Preventing seals from accessing foraging areas would be the most effective way of preventing predation on salmonids in rivers. In this section we describe methods that have or are being used to prevent seals gaining access to foraging sites in rivers.

2.1.9 Physical barriers

The most effective method to prevent seal depredation on salmonids in river systems would be to exclude seals from the river entirely. Barriers have been tried at several locations using various means, depending on the local environmental and practical constraints.

At the Dosewallips River, Washington, a barrier was placed across the river mouth to prevent harbour seals from entering a channel in the river where their presence was thought to be causing high faecal coliform counts in shellfish beds (NMFS, 1997). The fence type barrier was effective in excluding harbour seals from a haulout site and resulted in lowered faecal coliform counts at the shellfish beds. Flood conditions subsequently washed away the fence and it was not replaced (Scordino, 2010).

One of the earliest attempts to limit harbour seal predation at the Puntledge River, British Columbia, was to string a rope across the river with cork floats placed every 1 m (Yurk & Trites, 2000) with the aim of disrupting behaviour and preventing the seals from moving upstream. The rope and floats were deployed on two nights but monitoring suggested that seals quickly became familiar with the floats and showed no deterrence response.

The cork barrier was subsequently replaced with a specially constructed ‘seal-fence’ but it did not withstand debris moving downstream and high flow rates of the river. A stronger fence was constructed and operated from June to October 1998 (Brown et al*.,* 2003). This fence was made from five steel and aluminium sections and spanned the 80 m width of the river, including a gate for kayak/canoe access and a sinkable panel that could allow passage of larger boats. For the first half of the operation period (until August 1998) few seals attempting to pass the fence were successful, but by the end of the season nearly all attempts were successful. The failure of the fence to prevent seals moving upriver was attributed to three factors: smaller, juvenile seals were able to pass through sections of the fence; maintenance of the fence was difficult; and growth of marine algae caused some sections of the fence to sink. Later in the season there were more salmon upstream of the fence, presumably resulting in seals being more motivated to pass the barrier.

The fence was also found to impede the upstream movement of salmon, with observations suggesting Chinook salmon were held downstream for 80 minutes longer on average, resulting in them being targeted by seals. Similar results were also found at the Ballard Locks, Seattle, where a net barrier appeared to impede salmon migration, with sea lions able to exploit this behaviour (NMFS, 1997). Concrete blocks (triads) were installed along the shore at the Puntledge River barrier, to provide fish with refuges to escape predators, but these did not appear to be used by the salmon (Brown et al*.,* 2003).

Predator exclusion gates have been used with some success at the Bonneville Dam on the Columbia River, Washington. Steller sea lions and California sea lions target salmonids at the entrances to several fish ladders, with observations suggesting that 9,500 fish were taken from January to May 2016 (Madson et al*.,* 2017). This dam is a rare example of a site where predators can be completely excluded from travelling upstream as a result of the installation of sea lion exclusion devices (SLEDs). The devices consist of 4.5 x 10 m metal grates which, in conjunction with large floating barriers, allow fish passage through the fish ladder but exclude sea lions. These barriers were effective in preventing sea lion access to the fish ladders, but the number of sea lions using the area and the number of fish killed remained very high as a result of predation outside the barrier. This suggests that although sea lion predation was concentrated at the entrance to the fish ladder, they were clearly capable of preying on fish in the main river, implying that moving predatory seals from their preferred foraging sites does not necessarily reduce the problem, but may move the problem to another part of the river.

To date we are not aware of any structures specifically installed to prevent seals entering rivers in the UK. In the River Tees, UK, there has been an increase in the number of grey seals targeting salmon near a barrage installed across the river in 1995. A canoe course and narrow fish ladder allow fish to migrate past the barrage, but seals have learnt to exploit this restriction in order to target fish. A fish refuge was recommended for construction outside the outflow from the canoe course, allowing salmonids to shelter from predation by seals (Moore & Potter, 2014) although this has not been pursued.

Several temporary barriers have been used as fish counting weirs and/or as a method for directing upstream migrating fish into traps. It is feasible that similar methods could be used either to prevent seals moving upstream or to confine them to smaller sections of a river for detection and/or targeted deterrence or capture methods.

There are several designs of fish barrier, utilising specific bar spacing to divert the target species. The larger spacings that would be effective in excluding seals, would also allow for less build-up of river debris than those used for fish deflection. The appropriate design will depend on the width, depth and flow rates of the river as well as the requirements of other river users. Boat traffic may require bespoke design features to allow passage of small leisure craft and canoes or larger vessels. For example, there are floating weirs in which sections of the fence are hinged on the riverbed to allow for changes in river level. These designs allow boats/canoes etc. and debris to pass as they sink with the extra weight (e.g. Fishbio, 2020). Seals could easily climb over such a barrier, so additional freeboard would be required to stop seals. Such structures could be installed and removed as required to coincide with seal activity or salmon runs.

A simpler rigid weir comprising of vertical posts, spaced to provide gaps wide enough to allow fish passage, but small enough to prevent passage of seals may warrant investigation. However, such barriers may delay fish on their migrations (Brown et al*.,* 2003). Predators may learn to capitalise on such bottlenecks and, in some cases, potentially elevate predation rates of salmonids. Careful consideration would therefore be required to identify specific functions and locations for barriers. One example set-up may be as a partial barrier to divert seals (and fish if required) through a channel whose width and length would offer little impedance to fish or river traffic but would allow suitable detection systems (such as sonar) to monitor fish and seals more effectively. This reduction in channel size would enable larger rivers to be reduced to a more manageable size and allow deterrence methods such as ADDs and or electric field barriers to be co-located (considered in more detail in Section 2.1.10 and 2.1.11). There is also potential to introduce capture methods in such locations.

Physical exclusion remains a potentially useful measure, although there is a continuing effort to remove barriers to fish passage. Any such measure would therefore require investigation of the behavioural responses of migrating salmon to the presence of such a barrier.

2.1.10 Electric field barriers

Methods of excluding seals in freshwater have generally relied on acoustic deterrents, lethal removal or physical barriers. However, seals can also be excluded from some freshwater systems by the use of electric fields (Forrest et al*.,* 2009). Freshwater electric field deterrence systems have been developed and tested in the US and Canada with the aim of preventing upstream migration of invasive fish species and to deter fish from entering important areas such as water intake pipes. These Graduated Field Fish Barriers (GFFBs) use pulsed Direct Current (DC), which do not harm the fish, and are used at hydro-energy and river fishery sites across Europe and North America (O'Farrell et al*.,* 2011; Smith-Root, 2017). They have also shown potential for deterring marine mammal predators (harbour seals and California sea lions) from rivers.

To be effective, a non-lethal electric barrier system must reliably change seal behaviour and produce either a long lasting or repeatable avoidance response. As has been discussed above with physical barriers, it must also not impede movement of salmon or other non-target species.

Although the intended effect is different, the physical arrangements of electrodes and electrode arrays used in fish barriers illustrate the range of possible array designs for seal barriers, but also highlight the potential for unintended effects on salmonids and other non-target species.

The responses of harbour seals and California sea lions to pulsed DC electric fields have been tested in captivity in freshwater tanks in Canada and the USA. Two adult male harbour seals were tested in Vancouver Aquarium, where they were free to swim in an 8.5 m x 4.8 m x 2 m freshwater pool with haulout areas at both ends (Forrest et al*.,* 2009). A simple array of nine electrode cables suspended along 1.2 m sections of the pool wall on either side of the pool were used to generate a pulsed DC electric field of differing frequencies and intensities. Results from initial trials indicated that harbour seals displayed significant avoidance reactions to electric fields that produced voltage gradients of < 0.32 $V.cm^{-1}$ at the surface, when pulse durations exceeded 400 μs at a pulse frequency of 2.25 Hz. Both seals repeatedly approached the field but turned away without crossing it. Neither seal showed any negative effects of the trials and returned to normal behaviour and feeding activity immediately following trials. It should, however, be noted that these trials did not involve any positive reinforcement/stimulus to incentivise the seals to enter or cross the electric field.

The responses of California sea lions to pulsed DC electric fields have also been tested using captive animals in a similar experimental set up (Burger et al*.,* 2012). Trials were carried out using pulse durations of 80-440 μs at a frequency of 2 Hz and voltage gradients of 0.14 and 0.27 $V.cm^{-1}$. In the absence of food, three of the four animals tested (two adult males & one adult female) showed strong avoidance responses at short pulse durations of 80-110 µs at voltage gradient of 0.14 $V.cm^{-1}$. The other adult male apparently detected fields at 110-170 µs pulse duration but did not show avoidance at pulse durations of less than 320 µs. The thresholds for avoidance increased when food was presented on the other side of the field. The three sea lions tested were willing to cross fields with two to four times longer pulse durations than those that caused strong deterrence in the absence of food.

2.1.10.1 Field trials of electric barriers in freshwater

Following on from the captive harbour seals trials, a temporary electric field array was tested in the Puntledge River, British Colombia. Initial results from three days of testing suggested that the electric field (frequency 2 Hz; pulse width 200 µs to 1 ms; voltage gradient 0.14 to 0.28 $V.cm^{-1}$) produced immediate avoidance responses in harbour seals that moved seals away from their foraging site and/or prevented upstream movement through the field (Forrest et al*.,* 2009; Burger et al*.,* 2012). No seals were assessed to have been injured by exposure to the electric field, although no animals were closely examined, and seals returned to forage at the site after the trials ended.

In a follow up study, three different array configurations (a “3-cable perpendicular” array, a “17-element parallel” array and a “4-cable perpendicular” array) were tested in the lower Puntledge River in 2008 (Harlan et al*.,* 2009). The arrays were sited to exclude seals from a previously identified foraging hotspot where seals apparently used bridge lighting to silhouette and capture out-migrating salmon fry and smolts. The river is approximately 49 m wide and between 2.5 m and 3 m deep across most of its width at that point. However, water depth varied significantly during trials with different flow rates and particularly with tide height. The tidal range is not presented, but quoted tide heights ranged up to 5.1 m. Seal and fish behaviour were monitored using DIDSON acoustic cameras and by visual observers at the array site. Pulse width was gradually increased during trials from 1 to 5 ms. At the lower pulse width settings (1-2 ms), seals successfully passed through the array and showed no indications of being harmed. Seals exposed to 3 ms pulses showed what were interpreted as behavioural responses indicating avoidance of short-term discomfort or pain. At higher pulse width settings (4-5 ms) seals exhibited clear physiological responses including involuntary muscle contractions. The 4-cable perpendicular array seemed to be the most effective at deterring seals from moving upstream. When operated at the 3 ms pulse width setting 79% of the seals that approached the array from downstream turned away and did not progress upstream.

Harlan et al*.* (2009) noted that there were gaps in the electric fields produced by the 3-cable perpendicular array and the 17-element parallel array that may have been caused by the presence of metal objects on the riverbed. These gaps may have allowed seals to move upstream. Despite these problems the 17-element array operating at maximum 5 ms pulse width setting, turned 68% of seals that were seen approaching from downstream.

In some cases, seals continued upstream through the electric field even when apparently demonstrating strong physiological responses. This may simply indicate that the incentive to move through the field was stronger than the negative effect of the electric field. Alternatively, the authors suggested that gradual increase in field strength that occurred during the trials may have trained seals to tolerate the negative effects and enabled them to push through the electric field barrier. Individual seals were not identified so it is not known if the same individuals repeatedly challenged and tolerated the field. Only the electric field at or close to the surface was measured. This indicated that there were gaps in the field and that the strength of the field declined with increasing water depth. Seals "were often observed passing through the array during high tides" and were thought to be using gaps in the field even at low water levels. It is possible that the underwater electric field also varied.

2.1.10.2 Effects of electric barriers on salmonids

As part of the development and testing of electric fields barriers in Canada and the USA, several structured and ad hoc tests were carried out to assess the responses by salmonids. The results of these trials were equivocal in terms of effects of electric field barriers on salmonid behaviour. In captive trials, adult hatchery-reared steelhead trout did not show avoidance responses to pulsed electric fields higher (i.e. 0.6 $V.cm^{-1}$, 2 Hz and 400 µs pulse width) than those shown to cause avoidance in captive harbour seals (0.32 $V.cm^{-1}$, 2.25 Hz and 400 µs pulse width) and captive California sea lions (0.14 $V.cm^{-1}$, 2 Hz and 80-440 µs pulse width) (Mesa and Copeland 2009; Burger, 2010). Even at higher applied voltage gradients ranging from 0.8 to 1.1 $V.cm^{-1}$ (with pulse frequency and pulse width held at 2 Hz and 400 µs) the majority (67-87%) of steelhead successfully passed the array. Further increasing either pulse rates (3 Hz) or pulse length (10 or 20 ms) induced avoidance responses and prevented steelhead from passing the array.

Adult steelhead therefore successfully passed through electric fields that caused clear avoidance reactions in sea lions. Furthermore, fish were apparently unaffected by the higher field strengths that deterred harbour seals and California sea lions from passing through the electric field when incentivised by food rewards (Burger, 2010).

In contrast to the lack of responses of steelhead trout in captive trials, adult spring Chinook salmon migrating upstream were apparently deterred from entering an electric field generated by a scaled model of a proposed sea lion deterrence array, installed in the upstream migrant tunnel of a fish pass in the Bonneville Dam (on the Columbia River, Washington) (Mesa and Dixon 2010). Three electric gradient levels were tested: 0.14, 0.32 and 0.6 $V.cm^{-1}$. Eighty-three percent of fish successfully transited through the array during control periods, i.e. when the electric field was off. In contrast, only 4 to 5% of fish passed through the array when it was operational and "stronger directional reversals" were observed at higher electric field gradients.

These voltage gradients were lower than those which captive steelhead had passed (Mesa and Copeland, 2009).

In field trials in the Puntledge River, short duration pulses (<3 ms) had no adverse effect on out-migrating juvenile Chinook salmon passing through the array, but as with the Bonneville Dam trials, upstream migrating adult Chinook salmon appeared to have been obstructed during operation of the 4-cable array at the 3 ms pulse width setting (Burger, 2010; Harlan et al*.,* 2009).

Forrest et al*.* (2009) integrated an electrode array into a salmon gill net to determine if a pulsed electric field would deter harbour seals from taking pink salmon (*Oncorhynchus gorbuscha*) and sockeye salmon (*Oncorhynchus nerka*) out of experimental gill nets in the Fraser River, British Columbia. Half of the net was electrified on each of 67 net sets, each set lasted 20 minutes. The position of the attending boat and which section of the net was electrified were randomnly allocated. The catch in the electrified section of net was four times higher than the non-electrified section. This, combined with observations of seals turning away from the electric field, indicated that seal depredation was significantly reduced and that the electric field did not prevent salmon from swimming actively into the net.

The discrepancy between results of different captive and wild fish studies has not been resolved. The behaviour of captive steelhead trout and wild pink salmon, and of sockeye salmon in the Fraser River trials, was apparently unaffected by electric field strengths that deterred harbour seals and some sea lions. Wild Chinook salmon at both Bonneville Dam and in Puntledge River were prevented from moving upstream through the arrays by similar electric fields. This may indicate that Chinook salmon are more sensitive to electric fields, or that the field strengths encountered by the fish were higher than indicated by the surface voltage gradient measurements. In the Bonneville trials the pulsed electric field was constantly on for much longer periods (30 or 120 minutes) than were envisaged for actual seal or sea lion deterrence. Short periods of targeted activation in order to deter passage of individual pinnipeds would be less likely to cause major disruption to upstream migration.

The conclusion from these field studies is that low intensity electric fields capable of deterring seals and sea lions may also adversely affect passage of adult salmonids. Additional work will be required to assess the responses of Atlantic salmon in individual rivers and at specific locations before such systems could be deployed in Scotland without an automatic seal detection system which would enable targeted activation when seals are present to minimise any effect on salmon.

2.1.10.3 Effects of electric fields on other non-target wildlife

With some correction for species-specific differences, the effects of electric fields are proportional to the size of a fish (Dolan & Miranda, 2003). The voltage across or along a body in an electric field is directly proportional to its length, so a larger fish will experience a greater effect. As salmon are usually the largest fish in Scottish salmon rivers, any electric barrier that does not affect adult salmon is unlikely to adversely affect the behaviour of other freshwater fish.

Both the European otter and the Eurasian beaver are protected species under the EU Habitats Directive. Otters are widespread in Scottish salmon rivers and beaver populations are established and spreading in eastern and western Scotland. There appear to be no published data on the responses of otters or beavers to electric fields. However, systems to produce a water surface electric field barrier have recently been deployed in the USA to dissuade American beavers (*Castor canadensis*) from building dams in or close to culverts in order to prevent flooding of roads and agricultural land (Smith-Root, pers. comm. June 2020). It is therefore possible that beavers may be prevented from passing an operating electric barrier. There do not appear to be any published reports on the effects of electric fields on water birds. If swimming and diving birds are able to sense the field in the vicinity of an electric barrier, they may be deterred from swimming through it. However, such effects would be unlikely to significantly affect the movements and foraging behaviour of water birds which can simply by-pass such barriers by flying over them. Most pre-fledged water bird chicks are small enough that they are unlikely to detect the electric field, but if they are large enough to detect it, they may be deterred from swimming upstream through it. Downstream passage is unlikely to be interrupted as flow will carry them through the field.

2.1.11 Acoustic deterrent device barriers

Acoustic deterrent devices (or ‘seal scarers’) are used at marine finfish farms to address seal depredation, to reduce marine mammal bycatch in fisheries and to displace marine mammals from specific areas, and are discussed in more detail in the finfish farm section below (Section 3.1). There is some debate about their effectiveness, but the relative simplicity and low cost of operating ADDs makes them an attractive means of deterrence and they have been considered as a potential means of blocking seal movements in salmon rivers. Shortly after ADDs were first developed there were several attempts to establish acoustic barriers using arrays of ADDs, to prevent harbour seals moving upriver to prey on migrating salmonids in the USA in the early 1980s.

Hanan & Scholl (1987) used an unspecified ADD to drive harbour seals down the Klamath River in California. Although apparently successful, they only reported two days of deterrent activity. Geiger and Jeffries (1987) report a longer trial where harbour seals were driven down a section of the Columbia River and an array of unspecified ADDs was used to establish an acoustic barrier across Youngs Bay to prevent their return. They reported a slight, temporary reduction in damage rates after seals were swept downriver, but the acoustic barrier had a negligible effect on subsequent seal damage rates. Harvey et al. (1987) used a combination of ADDs (custom built devices, 12 kHz, 50 ms pulses, 2 pulses per second, source level 189 dB re 1 µPa @ 1 m), seal bombs and aerial pyrotechnics to drive harbour seals out of Netarts Bay, Oregon and established an acoustic barrier using five ADDs (all the same type) spaced approximately 50 m apart, to prevent their return. Seal numbers at haulout sites in the bay dropped to zero immediately after the drive, but gradually increased to 100 over the following week of ADD operation. These three initial trials suggested that ADDs were not likely to provide an effective long-term barrier to harbour seal movements up salmon rivers when deployed in wide estuaries and bays.

However, later trials by Yurk and Trites (2000) using an Airmar ADD (see McGarry et al., 2020 for the specifications and acoustic characteristics of different devices) were successful in preventing harbour seals moving up the smaller (~50 m wide) Puntledge River to an important/preferred foraging site under a road bridge. The authors suggest that the effect was likely to be temporary as seals can avoid underwater sound by swimming at the surface with their heads clear of the water and that pinnipeds have a great ability to habituate to such stimuli. However, they do not present information to show that harbour seals in their study avoided the sound in that way nor any evidence of habituation. NMFS (1996a) reported that an Airmar ADD installed at Chittenden Locks, Seattle, USA was effective at deterring naïve California sea lions, but was ineffective with individuals that had already established a salmon predation pattern.

Graham et al. (2009) tested the effectiveness of a modern, high power ADD as an acoustic barrier in salmon rivers. They installed Lofitech ADDs (see McGarry et al, 2020 for device details) in shallow water sites in two Scottish salmon rivers (the North Esk and the Conon) to prevent seals from moving upstream to predate salmon. They concluded that although the absolute abundance of seals in the river downstream of the ADD did not change after the introduction of the ADD, the number of seals upstream of the seal scarer was significantly reduced (by around 50%). These results were further supported by a longer scientific control trial in a third Scottish river (the Kyle of Sutherland) where seal occurrence was significantly lower upriver of ADDs compared to periods when the devices were switched off (Harris, 2011). Lofitech ADDs were also installed in 2013 in the river Dee by the Dee Salmon Fishery Board with support from SMRU. Both harbour seal and grey seal sightings were reported upstream of the ADDs during the period of operation. Difficulties in creating an effective barrier due to too few transducers and in maintaining an adequate power supply through most of 2013 likely influenced their effectiveness (Harris and Northridge, 2015).

The results in the Puntledge River and Scottish salmon rivers are encouraging and Graham et al. (2009) suggested that some of the observed movement of seals may have been due to inconsistency in the output/operation of the ADDs, suggesting that with better management the barrier could have been more effective. Harris (2011) using photo-identification showed that some individual seals in Scottish rivers were prepared to pass ADDs while others were not, and that those individual differences appeared to remain consistent over the three years of the study. It is not clear why the results of later studies of the ‘acoustic barrier’ technique are different from the results of earlier studies which concluded that ADD barriers were not effective (Geiger & Jeffries, 1987; Hanan & Scholl, 1987), but possibilities include fewer seals and the smaller rivers increasing the efficacy of the ADD and/or the motivation of the seals, which may have been lower at these sites than elsewhere. Nevertheless, it does seem that an acoustic barrier based on a high power ADD design may provide an effective means of reducing seal activity in rivers, and their long-term effectiveness and the influence of individual river characteristics should be investigated further.

To date there have been no attempts to block movements of seals in salmon rivers using any of the more recently developed acoustic deterrents designed to minimise impacts on non-target species described for use in aquaculture (Section 3.1). The reported lack of habituation could increase the long-term effectiveness of an acoustic barrier.

2.1.11.1 Effects of acoustic barriers on non-target species

Scottish salmon rivers hold significant numbers of European otters and Eurasian beavers which may occur throughout the river system and may be affected by acoustic barriers. Barriers at or close to the mouths of the larger rivers may also affect bottlenose dolphins and harbour porpoises.

In relation to otter depredation, Harrington et al. (2013) describe an “opportunistic” test of a Lofitech ADD in a carp pond. They recorded a reduction in rate of otter visits during the trial but concluded that there was insufficient evidence of an effect because of the lack of a control site. In additional trials with captive otters using a broadband (10-25 kHz) chirp signal, they found no effect on animals habituated to human activity but recorded a small reduction in time spent in the pool for un-habituated otters. Otters have been observed using stretches of Scottish rivers where ADD trials were taking place (SMRU unpublished data); in one case an otter was observed swimming with its head out of the water past an active Lofitech ADD in shallow water. These results are inconclusive, and further investigation of responses of otters to ADD signals will be required to assess the risk of disturbance.

There are no published reports of the effects of underwater sounds on beavers. Beavers use tail slaps as an alarm signal. The slap produces a sharp underwater sound described as like a gun shot. It is therefore likely that beavers will be sensitive to similar low to medium frequency pulsed sounds. It is unclear if they would react to ADD signals. However, beaver range is limited in Scotland and they are generally absent from the lower reaches of rivers where ADD barriers would be more likely to be situated.

Crowell et al. (2015) measured in-air hearing in ten aquatic bird species; eight ducks, a diver and a gannet. In all species the peak hearing sensitivity was in the 1 to 3 kHz range. Larsen et al. (2020) measured in-air and underwater hearing in great cormorants (*Phalocrocorax carbo sinensis*) and found peak sensitivity was around 1 kHz in both environments. Swimming and diving birds that occur in Scottish rivers and estuaries are therefore likely to be able to hear some low frequency ADD signals.

Species such as cormorants, shags (*Phalacrocorax aristotelis*), long-tailed ducks (*Clangula hyemalis*) and little grebe (*Tachybaptus ruficollis*) have been noted by observers during ADD trials in Scottish rivers and at coastal net fishery sites engaging in diving behaviour as they passed through areas with Lofitech ADDs (SMRU unpublished data). For example, a female long-tailed duck regularly appeared, over several days, to forage within five meters of an active Lofitech ADD (Harris, 2011). In areas where the presence of protected aquatic bird species is a concern, an assessment of the potential effect of ADDs on such species may be required.

2.2 Aversion methods.

A frequently suggested solution to predation problems is to make the predators averse to some aspect of the predation activity, usually either making the prey unpalatable or making the action of predation unpleasant or painful for the predator. The electric field barriers and acoustic deterrents discussed above work on the same principle, i.e. making it too unpleasant or too painful for a seal to pass through an electric or acoustic field to prevent predation at some point upstream. For many species, repeated disturbance is used to produce an aversion to a location or activity and several of the direct acoustic or tactile deterrent methods described above are effectively attempts to produce aversion to predation activity or foraging sites in rivers. There is little evidence that these methods cause a lasting aversion. While disturbance can cause grey and harbour seals to abandon haulout sites there is little evidence of seals or sea lions abandoning favoured foraging sites, even when subjected to intense and repeated acoustic disturbance.

2.2.1 Conditioned taste aversion

Several predator species have been shown to avoid specific food types after becoming sick, suggesting that this learning process could be reproduced by the use of certain tasteless emetic agents alongside an otherwise harmless food. This phenomenon known as Conditioned Taste Aversion (CTA) is widely used in human addiction therapies and has been used in attempts to control predation by terrestrial carnivores, including prevention of coyote and wolf predation on sheep (Quick et al., 1985).

CTA is more likely to be effective in the context of seal attacks on finfish farms, and is discussed further in Section 3.3, but here we present a brief summary of the background and current state of knowledge on CTA in pinnipeds and attempts to use it in the context of predation on salmonids in rivers.

CTA has been demonstrated in one pinniped species in captivity. Four California sea lions were fed an alternating diet of herring and mackerel (Kuljis, 1986) for 21 days, at a slightly lower than normal ration to increase feeding motivation. Two of them were then fed mackerel laced with lithium chloride (LiCl) which caused them to immediately begin vomiting. They returned to normal behaviour after one hour and did not appear to be adversely affected. The control animals were fed untreated mackerel. In subsequent sessions all animals consumed herring as normal, but the two treated animals refused to eat mackerel. One individual continued to refuse mackerel for 19 days, while continuing to eat herring as normal. The other began eating mackerel after three days, but after a second treatment it refused mackerel for the remainder of the trial. The two control animals continued feeding as normal. The CTA treatment had no noticeable impact on the sea lions beyond modifying feeding behaviour.

To date no experimental tests of CTA have been performed with either grey or harbour seals, but CTA is documented in such a wide range of mammal species that it is likely that phocid seals would also demonstrate CTA.

Gearin et al*.* (1988; the same study is described in NMFS, 1997) documented attempts to induce CTA in wild California sea lions that were actively preying on salmonids at Chittenden Locks. Freshly killed steelhead were laced with capsules of LiCl and tethered by monofilament lines so that they trailed in the current below the Locks. Five sea lions were seen eating the baited fish. Two were subsequently seen behaving unusually and one vomited. Both returned to the foraging areas within two hours and were seen to catch at least one fish each. Predation by both sea lions was lower for the four days after treatment, with both reported to have resumed active/normal predation five days after the initial treatment.

Subsequent attempts to feed LiCl laced fish to these sea lions were unsuccessful, with the sea lions inspecting but ignoring the tethered fish. These results clearly indicate that sea lions were able to associate the CTA effect with feeding on dead/tethered fish and differentiate that from predation on live/untethered fish.

In light of these results, NMFS concluded that CTA was not a feasible method for protecting salmonids from sea lion predation in the Columbia River. They identified the difficulty of ensuring target animals are treated, low likelihood that an animal can be re-treated and possible effects on non-target species if uneaten, laced fish become available to other wildlife (NMFS & WDFW, 1995).

The context of CTA trials appears to be critical in determining their effectiveness as a deterrent. CTA is only likely to be an effective deterrent tool if the target animals strongly associate the laced food item that caused vomiting with the prey or food items that are to be protected. Although trials with coyotes and wolves have shown that they associate carrion with the live animal (Quick et al., 1985) and avoid that prey item, it is not certain that seals, which do not routinely feed on carrion, would make such an association. The limited data from Gearin et al. (1988) supports the suggestion that it is essential that seals associate the emesis effect with wild free-swimming salmonids, for use in salmon rivers. It is not known if the CTA response of phocid seals would be like that of sea lions or if phocid seals would be able to differentiate between emesis effects from eating dead fish and eating live-caught fish of the same species. This problem could be circumvented if methods for presenting laced fish to seals in rivers could be developed that were as close as possible to live prey capture from the seals' perspective.

The most widely used emetic in animal CTA studies is lithium chloride. In terrestrial animal studies this poses the problem of having a salty taste that may alert predators to the presence of the agent. This should not be a problem in marine situations but may present some problems in freshwater.

Coram et al. (2014) suggested that if "problem" animals (i.e. those that had been identified as responsible for depredation attacks) could be caught and held temporarily, they could be trained in captivity and then released once a CTA to salmon had been established. It is unlikely that such a method could be applied in the context of seals preying on salmon in Scottish rivers. Catching specific individuals is difficult and time consuming, and the training would require significant resources. As described above, it is unclear that grey or harbour seals would associate the CTA induced by eating dead salmonids with predation on live, free-swimming salmonids. Under current UK regulations, the Animals (Scientific Procedures) Act 1986, it is not possible to feed live fish to captive seals for the purposes of research.

It should be noted that at the time of writing the US National Marine Fisheries Service have issued a draft of a revised set of guidelines for deterring marine mammals (NOAA, 2020a). These draft guidelines specifically prohibit "Using any chemical irritants, corrosive chemicals, and other taste deterrents (including taste aversion) to deter marine mammals".

2.3 Non-lethal removal

2.3.1 Translocation

A non-lethal solution to seal predation could be to move the problem seal(s) to another location. However, catching seals is difficult and there is limited evidence to suggest that moving a seal to a different location would solve the problem.

To provide long-term relief, translocated seals would need to permanently stay away from their capture site. There is no published information on the effects of relocation of grey or harbour seals in the UK and it is not clear that moving seals to a new location would prevent them from returning to the capture site. There is one anecdotal report from the early 1980s of a translocation of one harbour seal from a site 50 km up the River Ouse, North Yorkshire to a release site in The Wash, Lincolnshire. However, the seal was observed back in the river close to the capture site less than a week later (M. Fedak (SMRU) pers. comm.). There are very brief reports of attempts to relocate harbour seals seen feeding on salmonids at Ballard Locks, in Seattle. Seals were caught and transported to release sites in Hood Canal more than 50 km away. The programme was apparently abandoned because seals returned to the capture site (NMFS, 1997). Oliver et al*.* (1998) reported that harbour seals had been recorded returning to capture sites from release sites between 21 and 421 km distant on the west coast of North America.

Capture and relocation have also been attempted for California sea lions and both Australian and New Zealand (*Arctocephalus forsteri*) fur seals. In the USA, sea lion relocation attempts were deemed unsuccessful due to some animals rapidly returning to their capture sites. California sea lions are still caught in the Columbia River in Oregon and Washington to remove the threat of predation on endangered populations of steelhead trout. However, after it became apparent that translocation was ineffective, captive sea lions were no-longer released back into the wild. Any sea lions that were removed from rivers were moved to animal holding facilities such as aquaria and zoos, but their holding capacity was quickly exceeded. Captured sea lions are now marked and put on a list of designated predatory sea lions and released. If any animals on the list are recaptured, they are euthanised. In 2016 this resulted in the removal and euthanasia of 59 California sea lions (Brown et al*.,* 2016). In 2020 the NMFS issued permits for the lethal removal of up to 540 California sea lions and up to 176 Steller sea lions from the Columbia River and its tributaries over a five-year period (NOAA, 2020b; WDFW, 2020).

In Tasmania, more than 4500 fur seal relocations were undertaken between 1990 and 2005 to reduce predation at finfish farms (Robinson et al., 2008a). Of the 4500 fur seals relocated, 56 % were recaptured seals, with 3 % of these seals trapped more than 20 times. Recapture intervals were highly variable, ranging from days to years and, within the same year, ranging from 4 to 258 days (mean 36 days). In a further study, 18 fur seals were moved between 140 and 470 km and satellite tagged before release (Robinson et al*.,* 2008b). All 18 seals returned rapidly to their capture sites at speeds of approximately 40 to 50 km per day.

Translocation has now been abandoned in Tasmania. Fur seals are still trapped to remove them from within marine farm lease areas to limit loss of fish and to minimise risks to farm workers. However, trapped seals can only be released within the marine farming lease site at which they were caught, either immediately or after being held for a period at an approved shore-based facility (DPIPWE, 2018). Relocation of fur seals to other parts of the state was abandoned because of the perceived risk of impacts on local commercial and recreational fisheries.

The available evidence from attempts to translocate harbour seals, California sea lions and fur seals suggests that catching and relocating pinnipeds is not effective at removing predation problems. Consequently, translocation is no longer practiced in the USA or in Tasmania.

In the case of seals in Scottish salmon rivers, if relocation was effective in preventing a proportion of captured seals returning to their capture sites, they could potentially pose a similar problem at another location. It is unknown whether individual seals caught in one river would be likely to swim up rivers close to their release sites.

Although this is a review of non-lethal management options, it may be informative to consider the effectiveness of the long-running lethal removal programme carried out on the Columbia River (NMFS, 2017). NOAA's Bonneville Pinniped-Fishery Interaction Task Force concluded that the long-term control programme at Bonneville Dam has not eliminated the problem interaction. They concluded that while killing an individual California sea lion eliminates that individual's impact on salmonids, new sea lions continue to arrive at Bonneville and prey upon salmonids and overall sea lion abundance and percentage of the salmonid run seen eaten in 2016 was higher than in the past. If lethal removal is ineffective in the long-term, temporary removal is unlikely to be effective. However, the numbers of seals involved in predation in Scottish salmon rivers is much smaller than in the Columbia River, so the replacement rate is likely to be much lower.

2.3.2 Temporary captivity

Although the limited information suggests that relocating seals is unlikely to solve predation problems in rivers, the act of removing a problem seal from a salmon river, similar to the process adopted at fish farms in Tasmania, would provide at least temporary relief until that seal either returned or was replaced by another.

Removing specific individual seals from rivers for periods of the salmon fishing season could dramatically reduce predation and direct interactions with fisheries and could have direct benefits in terms of salmon conservation by increasing escapement at important times of the year. Captivity could be either short term if the problem is concentrated in specific sensitive periods when predation problems are most acute, or long-term for seals known to be persistent salmon predators throughout the year. The practicalities of temporarily holding grey and harbour seals are discussed further in Section 2.3.2.

One potential advantage of temporary captivity would be the potential for establishing conditioned taste aversion to salmon in known predators. Although there is a potential problem of the CTA being associated with captivity and feeding on dead fish, there is the possibility that a firmly established taste aversion may transfer to consumption of wild salmonids, but this would be difficult to test.

2.3.3 Catching seals in rivers.

The capture of seals in the wild is important for a range of scientific and management goals. Any relocation or temporary captivity programme for 'problem' individuals will rely on effective and efficient seal catching methods. While successful techniques have been developed for capturing seals at a variety of coastal haulout locations, methods for catching free swimming seals and in particular those in swift flowing river environments are less well developed.

The capture and removal programmes for California sea lions and harbour seals at sites in rivers along the west coast of the USA involve routine capture and recapture of individual pinnipeds using experienced personnel. At those sites the catching process is apparently relatively simple, with sea lions in particular hauling out within trapdoor cage traps, and repeatedly returning to those same sites after capture (Wright et al*.,* 2010). However, attempts to catch harbour and grey seals in UK rivers have met with low success rates, highlighting the difficulty in catching seals that are not known to routinely haul out upriver.

Methods have been developed to capture free swimming seals in rivers where flow rates are typically low or where seals are known to actively hunt close to riverbanks (Graham & Harris, 2010). However, success relied on first gathering considerable behavioural knowledge about specific individuals. That study highlighted the difficulty of, and level of manpower resources required, to catch a small number of seals in relatively benign conditions of small, slow flowing rivers.

Catching free swimming seals in larger, faster flowing rivers such as the River Dee represents a more challenging environment for which new methods needed to be investigated. Harris & Northridge (2018a) explored new approaches for capturing seals in larger rivers including capture at one of the few in-river haulout sites, developing a floating baited cage trap and testing various sweep netting and tangle netting options. The initial work shows that the methods have potential but have not been tested sufficiently to assess their effectiveness. Potential methods are listed in section 5.1.5.

It must be emphasised that catching and handling seals in nets is potentially hazardous to both the seals and the personnel involved. Any activities involving seal capture will require highly trained, specialised catching teams. Seal catching in Scotland will require a licence issued by Marine Scotland and catching in or close to Special Areas of Conservation will require a licence from NatureScot.

2.4 Summary - river fisheries

It is clear from the available literature that to-date there is no single, effective non-lethal solution to address the problem of predation by seals on salmonids in rivers in Scotland. This situation is most clearly demonstrated in some of the larger river systems in the north west of the USA, where despite many years of intensive efforts to prevent seals and sea lions from preying on endangered populations of salmonids, that predation continues. There are however a range of methods that have been shown to have some success or have potential in reducing predation, albeit usually only temporarily.

Hazing and tactile harassment: Although these are generally low-tech methods with relatively low capital and running costs, the total staff time involved is often large.

In general, attempts to move seals away from predation sites in Scottish rivers have involved relatively mild forms of harassment (e.g. shouting, hitting the water) compared to the methods routinely used in the USA (e.g., cracker shells, seal bombs), which may not be appropriate on Scottish rivers. Furthermore, where the effectiveness of hazing and tactile harassment have been assessed, they have not been effective in reducing the number of pinnipeds actively hunting salmon in rivers. However, these methods are still widely used to disrupt foraging behaviour and are pre-requisites for permitted lethal removals of sea lions in the USA.

At present there is little or no information on the likely effects of such deterrents on the small numbers of seals in confined and relatively shallow Scottish salmon rivers. Attempts to move seals with some of these methods and a structured monitoring programme to record the intensity and duration of responses may prove useful.

Excluding seals from rivers: If all, or a proportion of, the seals attempting to swim upriver can be prevented from doing so, the problem would be solved or the intensity reduced. A range of seal exclusion methods have been attempted or suggested, each of which has potential but also problems.

Attempts to use ADDs or arrays of ADDs as acoustic barriers have been shown to be relatively successful, but their success appears to have been limited by technical problems and difficulties of maintaining the barrier. Acoustic barriers may be the only option for preventing seals moving through the estuaries and lower reaches of larger salmon rivers where electric fields cannot be maintained and physical barriers are impractical. Additional trials with carefully designed barriers would be needed to assess their effectiveness and to identify additional measures that could make barriers more effective such as inclusion of in-air visual or acoustic deterrents to prevent seals from avoiding the ADD signals.

Physical barriers may provide a solution where they can be installed and maintained. Promising laboratory results and initial field trials suggest that electric field barriers might also provide a workable solution in small to moderate sized rivers, or locations where seals are constrained to pass through a narrow channel. As with ADDs, the failure of electric field barriers to stop some seals in field trials was apparently related to operational difficulties rather than fundamental problems with the method. Questions about the potential effects on salmonids still need to be addressed and additional trials would allow a more realistic assessment of the potential.

Non-lethal removal: If deterrence and exclusion methods are not effective, one possible solution would be to catch and remove problem seals. However, attempts to translocate harbour seals and several other pinniped species have been unsuccessful, with most seals rapidly returning to the vicinity of their capture sites.

An alternative to translocation would be to catch seals and hold them in temporary captivity to remove the predation threat during important periods of the year e.g. during the peak of the salmon runs or until the end of the fishing season. This would be a major undertaking and would need to be administered or operated by a competent authority, but there are relatively inexpensive captive facility options available such as use of modified salmon cages as holding pens.

Experience with long-term lethal removal programmes in the Columbia River, USA, suggest that even permanently removing problem seals may not solve the overall problem of pinniped predation on salmonids in rivers (NMFS, 2017). If lethal removal is ineffective, temporary removal is even less likely to be a long-term solution and should be seen as a short-term mitigation measure. The efficacy in any particular river will be governed by the replacement rate which is thought to be far lower for Scottish rivers than for American rivers with larger runs of salmonids and larger populations of pinnipeds.

3. Deterring Seal Predation at Finfish Farms.

The interactions between seals and finfish farms in Scotland involve both UK seal species; grey and harbour seals. The physical characteristics of aquaculture installations mean that these interactions are different to those in rivers in several important respects. The principal differences can be summarised as:

- A large proportion of the cages at finfish farms contain salmon which are visible to seals and therefore represent a powerful incentive to seals to attack the cages to gain access to the resource.
- Finfish farms are situated in coastal waters that are inhabited by both grey and harbour seals. As a result, a larger number of seals are exposed to finfish farms than is the case in river fisheries where the presence of seals is unusual and only seals specialising in predation on salmonids are likely to be encountered.
- The spatial extent of the average finfish farm makes monitoring and detection of seals above and below the water surface difficult. This is compounded by the fact that there is often no surface indication that a seal is attacking a fish cage and, conversely, surface observations of seals in the vicinity of cages do not necessarily indicate a seal attack.
- The presence of sensitive NTS (e.g. cetaceans) is far more likely to be a concern at finfish farms compared to river systems.

One common means of deterring seals has been the use of ADDs, but there are concerns about the potential impact of these devices on non-target species, including cetaceans which are sensitive to noise sources, and are often distributed in the waters around finfish farms.

Methods of direct harassment, such as those used in rivers (described in Section 2.1) are not generally used to deter seals from finfish farms. It is unclear exactly why, but it is unlikely that such methods would be successful due to the more open sea environment of the finfish farm setting (compared to rivers) and the inability to drive seals away in a given direction. It is also possible that the presence of salmon cages provides a stronger motivation to return.

3.1 Acoustic deterrent devices

Sounds have been used in attempts to deter marine mammals from interaction with fisheries since the 1970s. For example, Fish and Vania (1971) used broadcasts of killer whale calls in a successful attempt to prevent beluga whales (*Delphinapterus leucas*) moving up the Kvichak River in Alaska to prey on sockeye salmon smolts.

Acoustic deterrent devices were first introduced to the Scottish aquaculture industry in the mid-1980s, and while there have been improvements in efficiency and reliability, and flexibility in signal transmission patterns, available ADDs were until recently based exclusively on early device concepts. A recent review by the Joint Nature Conservation Committee (JNCC) on ADDs for offshore pile-driving mitigation contains a useful appendix with system specifications for all currently used ADDs (McGarry et al*.,* 2020).

A Scottish Government study has collated and examined operational records from Scottish finfish farms to determine the extent of their use and the effectiveness of ADDs in practice (Coram et al., in prep). Furthermore, the development, use and effectiveness of acoustic deterrent devices (ADDs) was extensively reviewed by Coram et al. (2014). This review concluded that there was little firm evidence for the long-term effectiveness of ADDs in reducing depredation at finfish farms and there have been no studies published since then that challenge that view. There have however been some studies on the effectiveness of ADDs in other contexts, such as in controlled exposure experiments and in sea fisheries which are described in the following section. It is important to note, however, that much of this more recent work has involved the Lofitech ADD device, a device which is not currently used in an aquaculture context in Scotland (Marine Scotland, 2020b).

ADD use is now considered widespread in aquaculture and ADD signals have been detected throughout the inshore waters of western Scotland (Findlay et al., 2018). This has raised concerns about the potential for effects on non-target species such as cetaceans and has led to attempts to produce more tailored, species-specific ADD signals to minimise effects on non-target species. These will be reviewed separately, and such systems are described in Section 3.1.5.

3.1.1 Controlled exposure experiments with ADDs

Mikkelsen et al. (2017) monitored the responses of harbour seals in Denmark to a simulated version of a Lofitech ADD, but with a substantially reduced source level, far below normal operational levels. Positions of harbour seals were visually monitored from shore with a theodolite, for 20-minute silent control periods followed by 20-minute periods of exposure to the simulated ADD sound. They found that seals generally surfaced closer to the loudspeaker during playback, compared to the controls. During playbacks, seals were observed most often in the range of 100 – 150 m from the device. Sighting rate of seals also increased during playback, possibly indicating orienting behaviour (or curiosity) when seals detected the sound.

Gordon et al. (2019) obtained very different results when they conducted a series of controlled-exposure experiments (CEE) to measure the responses of individual free ranging harbour seals to signals from a standard/full power version of the same Lofitech ADD. Harbour seals fitted with Global Positioning System (GPS) radio transmitters were tracked before, during and after CEEs allowing accurate estimation of test distances and received sound levels. During 71 CEEs seals responded to all playbacks at ranges < 1 km (predicted received level (PRL): 134 dB re 1 μPa (RMS)) and the maximum response range was 3.1 km (PRL: 111 dB re 1 μPa (RMS)). Responses did not always involve movements directly away from the source, especially for seals travelling at the time of the exposures. Results suggested that signals from Lofitech ADDs are aversive to harbour seals and could be used to move seals away from the vicinity of potentially harmful activities such as pile-driving and underwater explosions. By extension, such devices might be expected to act as effective deterrents at finfish farm sites. However, as these trials were conducted in the open sea, additional work is needed to assess their effectiveness in moving seals away from large and presumably attractive prey resources such as finfish cages.

The differences between the results of the two studies are most likely due to the amplitude of the signals used. Gordon et al. (2019) measured the device output and estimated a mean source level of 193 dB re 1 µPa @ 1 m (RMS) (S.D. = 1.9). To avoid potential hearing damage to target seals the source level in the trials of Mikkelsen et al. (2017) was fixed at 165 dB re 1 µPa (peak-peak), which was substantially lower than the nominal output of a real Lofitech ADD (advertised as 189 dB re 1 µPa (RMS)). Peak-peak and RMS source levels cannot be directly compared, but it is likely that the signal used by Mikkelsen et al. (2017) was significantly lower than the full scale Lofitech ADD used by Gordon et al. (2019). A difference in the source level of 30 dB could mean that a seal at 50 m range in the Mikkelsen trial would have been exposed to similar sound levels as seals more than 4 km from a real device.

3.1.2 Trials of ADDs in coastal fisheries

Harris et al. (2014) monitored the effectiveness of a Lofitech ADD at reducing grey and harbour seal depredation at coastal fixed salmon nets in Scotland. During randomly assigned periods of acoustic deterrence, the number of seal sightings was reduced significantly compared to when the device was off, and the catch of fish increased by approximately 33%. In the first year of operation no seals were seen within 80 m of the device, but in the second year there were six sightings within this area, suggesting possible habituation in certain individuals.

3.1.3 Effects of ADDs on non-target species

The widespread use of ADDs at finfish farms means that their signals could be audible to marine mammals in large parts of the coastal waters around Scotland (Findlay et al., 2018; Todd et al., 2019), which raises concerns about possible disturbance impacts on non-target species such as harbour porpoise and other cetaceans (Benjamins et al., 2018), all of which are listed as European Protected Species (EPS). The cetacean species of primary concern in Scottish waters are harbour porpoise, bottlenose dolphin, minke whale and killer whale. Several studies have extensively reviewed the deterrence effects of commonly used ADDs on cetacean species (e.g., Coram et al., 2013; Sparling et al., 2015; McGarry et al., 2020), so only a brief summary is provided here for cetacean species regularly sighted in Scottish coastal waters.

3.1.3.1 Harbour porpoise

Several studies have indicated the potential for Airmar ADDs to cause displacement of harbour porpoises (Olesiuk et al., 2002; Johnston, 2002; Northridge et al., 2010) out to ranges in excess of 3 km. Evidence for another device, a Terecos ADD, was more equivocal with Northridge et al. (2013) finding no significant difference in detection rates when the ADD was active or inactive. The apparent difference between the devices in terms of effects on porpoises, is likely due to the lower source level of the Terecos ADD compared to the Airmar ADD (Lepper et al., 2004).

A number of studies have demonstrated displacement effects of the Lofitech device on harbour porpoises (Brandt et al., 2012a and b). Porpoise acoustic activity at an offshore site in the North Sea declined by 96% out to 7.5 km, where received levels were estimated to be 115 dB re 1 μPa (RMS). The effect range must therefore have been greater than 7.5 km. However, at a shallow-water Baltic Sea site, porpoise did not show any response at either 2.1 km or 3.3 km ranges, probably as a consequence of the greater propagation losses at the shallow Baltic site. However, as noted above, the Lofitech device is not used in Scottish aquaculture (Marine Scotland, 2020b).

ADDs can emit signals loud enough to raise concerns about potential damage to porpoise hearing. Schaffeld et al. (2019) demonstrated a Temporary Threshold Shift (TTS) in hearing after exposure to an artificial ADD signal with a peak frequency of 14 kHz, at received SPL of 152.9 dB re 1 μPa (peak-peak). The authors recommended that signals for mitigation of pile driving noise should use a gradual increase in amplitude when activated, and that source levels of ADDs should be downregulated to match the desired deterrence range to minimise potential for injury.

Evidence from these studies and previous reviews, indicate that ADD models currently in use at finfish farms in Scotland could result in disturbance to harbour porpoises. The nature and extent of disturbance to cetaceans as a result of current ADD use in Scotland is not well known. Similarly, the consequences of any disturbance for cetaceans at an individual and population level are currently unknown.

3.1.3.2 Bottlenose dolphins

Bottlenose dolphins are frequently seen in inshore waters, but there appears to be only one published study of the responses of bottlenose dolphins to ADDs. López & Mariño (2011) monitored movements of bottlenose dolphins around a finfish farm on the coast of Sardinia to assess their reactions to signals from an ADD with source level of 194 dB re 1 μPa @ 1 m and peak frequency range from 6.2 to 9.8 kHz. They found no change in sightings rate, distance from the ADD, group size or time spent in the finfish farm area when the device was transmitting.

3.1.3.3 Minke whales

A controlled exposure experiment carried out off Iceland in 2016 tested the responses of minke whales to a Lofitech device (McGarry et al., 2017). Individual minke whales were visually tracked for at least 30 minutes before the ADD was deployed at distances of 0.5 or 1.0 km. The estimated source level in this study (based on in-situ measurements) was 198 dB re 1 µPa @ 1m (RMS) with a fundamental source frequency of 14.6 kHz. The behaviour of 15 focal animals was visually tracked during control, treatment, and post-treatment phases. All focal animals moved away from the ADD deployment site and increased swim speed, by an average of more than 2 $m.s^{-1}$. Individuals exposed to ADD signals at 0.5 km showed stronger reactions. Whales were tracked post-exposure, continuing to move away to distances of between 3-4 km before being lost to trackers. The outer extent of displacement was not established but was predicted to be more than 4 km.

3.1.3.4 Killer whales

Morton & Symonds (2002) used acoustic monitoring, visual surveys and long-term photo-identification data to show that killer whale activity around Broughton Archipelago in British Columbia decreased in areas where Airmar ADDs were transmitting. There was no evidence of habituation to the sounds over the five years but encounter rates returned to pre-ADD levels the year after the devices were removed.

Tixier et al. (2014) found that killer whales predating toothfish from longlines reacted to their first exposure to signals from an OrcaSaver AHD (Acoustic Harassment Device, another term for an ADD) by moving rapidly away from the sound source to distances of between 0.5-1 km, but did not apparently react to further exposure. The OrcaSaver source level (197 dB re 1 µPa @ 1 m, 6.5 kHz) was slightly higher than the Airmar devices that caused the long lasting changes to killer whale distribution reported by Morton & Symonds (2002). Tixier et al. (2014) suggested that the difference was likely due to the higher motivation levels of whales targeting easily accessible prey on longlines.

3.1.4 Methods to reduce impacts of ADDs on non-target species

Four basic approaches are available to reduce impacts of ADDs on non-target species: (1) avoiding the sensitive hearing ranges of non-target species, (2) reducing the source level, (3) reducing the number and duration of transmission sequences by transmitting signals only when seals are present, and (4) avoiding transmission when non-target species are in the vicinity.

Reducing potential for hearing damage to non-target species can be achieved by reducing the amount of ADD noise to which they are exposed. This could be achieved by altering the sound output, for example by reducing the amplitude of the signal from the ADD, or by reducing the duty cycle and therefore the average sound output of the device.

Another option to minimise the risk of hearing damage would be to gradually increase the signal amplitude to move animals away from the device before full power operation ("soft start"). However, if there is no displacement in response to chronic ADD sound exposure, this gradual ramping-up of signals may not reduce overall sound exposure and risk of injury. These methods would not necessarily reduce the overall duration or levels of disturbance

ADD output could be further reduced by only transmitting when a seal is in the vicinity of a finfish farm, i.e. triggering ADD signals on seal detection. This would still leave the possibility of sensitive, non-target species such as porpoises being too close to an ADD at the start of a transmission sequence. Such a situation could be avoided by blocking ADD signals in the presence of non-target species. It may also be possible to attenuate the ADD signal, for example by using strategically placed bubble curtains.

3.1.5 Species specific acoustic deterrents

Hearing sensitivity and vulnerability to loud sounds are frequency dependent, and where this differs between target and non-target species specifically tailored signals can be designed that will be louder for seals than for the NTS. Such signals may produce avoidance responses in seals at lower sound pressure levels than with a conventional ADD. A relatively narrow frequency range combined with lower source levels would greatly reduce the potential for impacts on non-target species with different hearing sensitivities

Four such devices were available at the time of writing that are described by their manufacturers as being developed specifically to reduce the effect on non-target species:

- **FaunaGuard Seal Module and Acoustic Seal Deterrent** is an acoustic deterrent that randomly emits a set of sounds tailored to the hearing range, peak hearing sensitivity and estimated behavioural response threshold levels for harbour seals (Van der Meij et al., 2015). Originally developed for Van Oord dredging and marine contractors, SEAMARCO build separate deterrents for porpoises, seals and fish that produce targeted deterrent sounds derived from tests with captive examples of the species groups. Based on the assumption that sounds with complicated spectra have a greater deterring effect than pure tones for almost all animals (e.g. Ruiz-Monachesia & Labrab, 2020), FaunaGuard is designed to emit a variety of complex sounds with harmonics, sweeps, and impulsive sounds in the frequency range 0.2 – 20 kHz. Sounds are centred on the range of best hearing to maximise the sensation level (number of dB above the hearing threshold for a particular frequency).

- **GenusWave SalmonSafe** is an acoustic deterrent that relies on eliciting the acoustic startle reflex that is triggered by sounds with a rapid onset/short rise time. Targeted Acoustic Startle Technology (TAST) achieves target-specificity by selecting a frequency band where the hearing sensitivity of the non-target species is much lower than the sensitivity of the target species (in this case seals). Differences in hearing sensitivities between species allow signals to be designed to specifically target one group of species while not affecting others. The startle signal developed for seals has a peak frequency of 1 kHz, with a 2 to 3 octave bandwidth, in a frequency range where phocid seal hearing is more sensitive than hearing in non-target species such as harbour porpoise and bottlenose dolphin. The startle response can be elicited by brief (0.2 s), isolated sound signals at relatively low source level and as a result, the duty cycle can be lower (GenusWave's TAST is ~1%) (Götz & Janik, 2015; 2016b). Götz & Janik (2015) conclude that there is no risk of hearing damage in target and non-target species.

- **Ace Aquatec RT1** is an ADD with a low frequency range, 1-2 kHz, specifically designed to be loud and aversive to seals but to be less audible to porpoises and dolphins, user selectable transmission rates of 12-144 signals per hour and a resulting duty cycle of 0.7 to 8% (McGarry et al*.,* 2020).

- **OTAQ SealFence 4** –According to McGarry et al. (2020) the device has two modes: a Protect mode with a source level of 189 dB re 1 μPa @1 m (RMS), frequency range of 9-11 kHz, and 3 second transmissions with random pulse gaps of between 3 and 10 s, and a "Patrol" mode with the same frequency range but a lower source level of 165 dB re 1 μPa @1 m (RMS), and 2 s transmissions with 20 s gap between pulses.

The FaunaGuard and GenusWave-TAST systems have similar power output with source levels around 180 – 182 dB re 1 μPa (RMS) and, along with the OTAQ Sealfence in 'Patrol mode', therefore have much lower source levels than typical ADDs. However, in the UK the FaunaGuard marketed for mitigation at pile driving sites has an optional high-power setting with a source level of 195 dB re 1 μPa (RMS). The FaunaGuard also incorporates a soft start whereby the source level automatically slowly increases after it is switched on which is intended to allow animals to move away before the max level is reached.

The RT1 device is a high power ADD with an average volume within a transmission of 183-185 dB re 1 uPa (Ace Aquatec, *pers. comm.* 2021), but when used with the proprietary control system it has a built-in noise reduction protocol where source level and duty cycle decline after a pre-determined period of transmission at maximum output.

3.1.5.1 Effects of tailored signal ADDs on seals

Kastelein et al. (2017a) reported a series of controlled exposure trials with two captive harbour seals to assess their responses to signals from FaunaGuard's Seal Module. Seals were exposed to a random sequence of 16 different sounds at frequencies between 200 Hz and 20 kHz, with random sound intervals of 3-10 s and at two different background noise levels designed to simulate noise equivalent to Beaufort sea states 0 and 4.

Seals showed clear avoidance responses to the signals, including hauling out, swimming with their head above the surface and repeated jumping. Behavioural response thresholds were estimated to be between 136 and 148 dB re 1 µPa. Background noise levels had no effect, probably because they were both low relative to the test signal levels in the experimental pool. Based on simple 15log R and 20log R spreading loss models, the authors estimated harbour seal behavioural response ranges of between 100 m and 500 m for the FaunaGuard Seal Module system. FaunaGuard has been deployed to mitigate the potentially damaging effects of pile driving noise on seals and porpoises in the North Sea but has not so far been marketed as a stand-alone finfish farm protection method (Ace Aquatec, 2020, pers. comm).

GenusWave's TAST device was developed after trials with captive grey seals showed that repeated exposure to startle sounds caused sensitisation rather than habituation and that the startle reflex led to avoidance responses, interruption of foraging behaviour and flight responses (Götz & Janik 2011; 2015). The GenusWave TAST has been tested at marine finfish farms in Scotland. Götz & Janik (2015) reported a significant reduction in the number of seal tracks within 250 m of the device, while seal distribution was not affected at greater distances from the farm. In further trials conducted over 19 months at one Scottish fish farm there was a significant reduction in depredation (Götz & Janik, 2016a), with analysis suggesting that predation losses decreased by 91% when the device was active compared to pre- and post-activation periods and by 97% when compared with nearby control sites. The sighting rate of seals within 100 m was only slightly affected by the device, suggesting that the startle response was only activated at close range or that seals approached more closely while swimming on the surface.

There are no published reports of trials of either the RT1 or the SealFence 4 to assess their effects on seal behaviour.

3.1.5.2 Effects on non-target species

There are no reports of any tests into the effect of the FaunaGuard Seal Module on non-target species such as harbour porpoises or bottlenose dolphins. The FaunaGuard system also includes a porpoise module that is designed to act as an acoustic deterrent specifically for harbour porpoises and has a frequency range of

60 kHz to 150 kHz (Kastelein et al., 2017b), approximately 40 kHz above the upper limit of the seal module (0.2 – 20 kHz). Bottlenose dolphins and harbour porpoise have better hearing sensitivities than harbour and grey seals at frequencies between 10 and 20 kHz (Kastelein et al., 2002; 2009; Götz & Janik, 2013). The higher frequency sounds from the seal module would therefore be more audible to harbour porpoises and bottlenose dolphins than to harbour seals.

Götz et al. (2020) tested the startle responses of bottlenose dolphins to rapid onset sound signals, at a range of frequencies from 1 to 32 kHz. Startle responses were detected at all frequencies tested, but the startle thresholds were frequency dependent, increasing from 131 dB re 1 μPa at 32 kHz to 153 dB re 1 μPa at 1 kHz. Intensity of the startle response increased exponentially with increasing received levels. The response at startle threshold consisted of a minor muscle flinch detectable with an accelerometer, with the bottlenose dolphins in the trials not showing any form of avoidance behaviour. The source level of the TAST system in the 1/3 octave band at 1 kHz is ~176 dB re 1 μPa. Sound propagation of the TAST signal around a finfish farm was found to be ~18 log(distance) (Götz & Janik, 2015). The bottlenose dolphin startle response threshold would therefore be reached at a range of approximately 18 m in such conditions.

Harbour porpoises were recorded during field trials of the GenusWave device at Scottish finfish farms. Götz & Janik (2015) reported no change in the number of porpoise tracks in any of the distance bins as a result of sound exposure during a series of controlled exposure trials and recorded sightings within 250 m of the device during sound exposure. A similar result was obtained during the long-term trial of the GenusWave (Götz & Janik, 2016a) where the median numbers of harbour porpoise sightings were similar during control and sound exposure periods, indicating that porpoises did not avoid the signals. The observed seal depredation rates and porpoise densities during these trials were typical of many sites in Scotland, but the interactions may not have involved large numbers of seals or porpoises. Trites & Spitz (2016) suggested that these encouraging results should be confirmed by conducting tests at sites with higher depredation rates and porpoise densities.

There are no published reports on the effects of the Ace Aquatec RT1 device on non-target species. However, although it has not been formally tested in controlled experiments, at the published frequency range of 1-2 kHz, harbour and grey seals are approximately 20 dB more sensitive than harbour porpoises and 10 dB more sensitive than botttlenose dolphins (Kastelein et al., 2002; 2009; Götz & Janik, 2013). Porpoises and dolphins should therefore be less likely to be harmed or disturbed than by a higher frequency signal from most commercially available ADDs. However, Benjamins et al. (2019) tested the effectiveness of reducing the frequency of acoustic signals by comparing porpoise activity in response to two artificial sound signals: a high frequency signal (8-18 kHz) and a low frequency signal (1-2 kHz).

They found that porpoise activity was reduced in response to playbacks of both signals relative to control periods and therefore concluded that reducing the signal frequency of ADDs may not be effective in reducing impacts on porpoises.

Similarly, there have been no published reports of the effects of the OTAQ Seal Fence 4 on non-target species. In Patrol mode the reported source level is 15-17 dB lower than the FaunaGuard or GenusWave systems and therefore much less audible to NTS. However, in Protect mode the source level is approximately 6-8 dB higher than that of the FaunaGuard or GenusWave systems signals and will be audible at more than double the range of these systems.

3.1.6 Predator calls

Killer whales are the most significant natural predator of many marine mammal species, and prey on both harbour and grey seals in Scottish waters (Bolt et al., 2009; Deecke et al., 2011). They also produce loud characteristic vocalisations, so it has been suggested that playback of killer whale vocalisations may act as an effective acoustic deterrent to seals.

There have been several attempts to use transmission of killer whale vocalisations to frighten marine mammals in order to control their behaviour or distribution. For example, Anderson and Hawkins (1978) used killer whale vocalisations in an attempt to keep grey seals away from salmon nets in the River Tweed. These playbacks were not effective, possibly because they were carried out in a shallow river estuary where killer whales do not occur.

Trials have been carried out with harbour seals in British Columbia (Deecke et al., 2002) and Norway (VonGraven & Bisther, 2014). Killer whales are regular predators of seals in both areas and the results suggested that the seals' responses were context specific. Seals in open water appeared to react by immediately swimming away, whereas seals in shallow water close to shore were less likely to flee and instead appeared to be curious (VonGraven & Bisther, 2014). Deecke et al. (2002) also concluded that seals were able to distinguish and react appropriately to local fish-eating killer whales and transient marine mammal eating killer whales on the basis of their call characteristics.

Gordon et al. (2019) conducted controlled exposure experiments on harbour seals by using killer whale calls in the Moray Firth and the Sound of Sleat, to assess their effectiveness for aversive-sound mitigation. The observed responses were highly variable. Seals responded in 19 of the 26 playback trials, but range was not a good predictor of response; the maximum range at which a seal responded was more than 4 km and the minimum range at which a seal did not respond was approximately 200 m. The variation in responses may have been partly due to differences in previous experience with predators.

The results of exposing seals to killer whale sounds appear to be variable and context specific and they may not be a reliable deterrent. It is also likely that using the calls of killer whales that are known predators of small cetaceans might cause avoidance reactions and therefore disturbance to such non-target species. It is possible that seals may habituate to the deterrent signal, and then not react appropriately if exposed to a real killer whale call.

3.1.7 Attenuating ADD signals

In addition to changing the characteristics of ADD signals, it may be possible to further reduce the risk of hearing damage and the potential for behavioural disturbance to non-target species by attenuating ADD signals. This has the potential to decrease the environmental impact of sound pollution by reducing the volume of water insonified. To be effective, an attenuation measure would need to maintain the loud aversive signal close to and within the finfish farm but reduce sound exposure of any non-target species outside the finfish farm's perimeter.

Bubble curtains are widely used to reduce underwater pile driving noise to protect marine mammals from potentially damaging and disturbing sound levels (e.g. Würsig et al*.,* 2000; Dähne et al*.,* 2017). Lucke et al. (2011) used a simple air-bubble curtain to mitigate the effects of nearby (100-175 m distant) pile driving on captive harbour porpoises. The bubble curtain, generated from a 40 mm diameter plastic hose with 2 mm diameter holes every 100 mm, dramatically reduced sound transmission and stopped porpoises reacting to the piling noise. The recorded mean sound attenuation levels of 12 to 14 dB would reduce the effect range by a factor of four to six.

Bubble curtains have been deployed to surround finfish farm sites in Canada to protect them from algal blooms (CanadianPond.ca, 2020), and aeration systems are already widely used at Scottish finfish farms. We are not aware of any attempts to use bubble curtains to attenuate ADD signals.

At present ADDs are designed to produce a 360^{o} sound field to maximize the effectiveness of single devices in terms of coverage. It may however be possible to shield, or baffle ADD transducers to effectively attenuate signals in particular directions. Combined with careful positioning of ADDs around finfish farms it may be possible to reduce the amount of noise emanating from finfish farm sites.

3.2 Physical exclusion

Seals can only predate or cause direct physical damage to farmed fish if they can make contact with them. To do this they must either enter the cage or gain access to fish through the cage wall. Below we describe non-lethal measures currently available to prevent seals gaining access to and damaging farmed fish. This does not deal with the acute stress related effects of attempted predation events or of the chronic stress effects of seal presence in the vicinity of cages, both of which may have significant impacts on fish health and welfare.

In all cases (e.g., seal blinds, false bottoms, Anti Predator Nets, tensioning/novel weighting systems), the major hurdle to empirical assessment of efficacy is the availability of systematically collected data. Much of the available information is anecdotal or in the form of media reports but are included here for completeness.

3.2.1 Preventing seals from physically entering aquaculture cages

Seals may enter cages by climbing over the perimeter net wall, by breaking through the netting or by squeezing through gaps where net edges have worked loose. This was thought to be a rare occurrence but recent analyses from a concurrent study indicated that 23% (16 out of 69) of a subset of shooting incidents reported in 2019 and 2020 involved seals inside cages (Coram, unpublished data). It could therefore be a more significant problem than has previously been assumed.

There have been instances of seals entering cages in Scotland by climbing over the walkway and upper edge of the net. Similar problems occur at fish farms in Canada and at various sites along the Pacific seaboard where sea lions regularly haul out on floating structures such as fish farms, floating decks and moored boats. Railings and fences have been used to prevent sea lions from hauling out on docks and buoys in several areas. On land, grey and harbour seals are much less mobile than sea lions, so methods that are effective in preventing sea lions accessing cages by climbing over the walkway will be equally or more effective for phocid seals. Blocking entry can be achieved by maintaining a secure and seal proof fence around the walkway and by correct usage of a top-net or bird net.

Swimming grey and harbour seals are not capable of jumping over high barriers. Experience with captive seals in a research facility suggests that grey and harbour seals are reluctant to try to jump a vertical barrier of more than 50 cm to haul out (SMRU, unpublished observations). Harbour seals on land have been observed climbing fences up to 1.2 m high, using horizontal struts on the fence to pull themselves up (SMRU, unpublished). A barrier comprising a smooth fence made from vertical slats that rises 1.2 m above the walkway should be unclimbable for a phocid seal.

Where such fences or barriers have failed to prevent invasion by sea lions (e.g., at some fish farms and on floating docks), attempts to use electric fences and/or to electrify the decking itself have been successful. For example, a pulsed DC electric system produced by Smith-Root Inc. has been used to deter sea lions from hauling out on pontoons in marinas, where they cause a nuisance and damage equipment. Video observations showed that the device was highly effective as long as animals made contact with both of a pair of electrodes. The stimulus could not be felt by most humans (Burger et al*.,* 2012).

In the past seals have gained access to cages by ripping holes in the net wall. New High-Density Polyethylene (HDPE) and particularly stainless-steel core HDPE type netting materials, originally developed to prevent shark damage, have the potential to prevent seals from biting or tearing a hole large enough to allow entry. There have been anecdotal reports of harbour seals repeatedly chewing at one particular section of net wall over a sequence of dives, until they eventually manage to rip a hole in the net, however it is not clear if this would be possible with HDPE nets. New netting materials are discussed further in the next section.

3.2.2 Preventing predation through the net wall

Northridge et al*. (*2010) reported that finfish farm operators found that problems with seal depredation had improved over the preceding decade and that most respondents stated that this was likely due to improved containment and better husbandry. The perceived reduction in predator problems apparently coincided with a reduction in numbers of fish escapes through breaches in cages (Northridge et al*.,* 2013). However, the problem persists, and estimates of fish lost to seals through direct predation and escapes through seal damaged nets represent a major concern for the industry in Scotland (SSPO, 2020). There are two general approaches to reduce depredation through the netting; one is to make the contents of the cage less detectable/desirable and the other is to make the fish less accessible, i.e. make the net wall more resistant to attack.

3.2.2.1 Mort removals, seal blinds, false-bottomed cages

It has been suggested that most seal attacks occur at the base of nets, for example, Thistle Environmental Partnership (TEP, 2010a) suggested that “seal attack on the base of the net was twice as likely as on the wall of the net”. In most cases fish are bitten through the meshes of the net and Northridge et al*. (*2013) report that this is largely from underneath, again supporting the notion that a large proportion of attacks occur from the base. Although there is no published data, it has been suggested that dead fish (morts) lying at the bottom of the cage attract seals that then learn to take fish through nets this way.

The Code of Good Practice for Scottish Finfish Aquaculture (CoGP, 2014) recommends farmers to remove dead fish on a daily basis. All farms regularly remove dead fish as part of their routine husbandry, however, specific information on how often each farm does this is not available. TEP (2010a) suggested that if mortalities attract predation, the mandatory use of seal blinds (a 3 m to 5 m square of thicker material added to the base of the net to conceal dead fish from seals underneath) or the daily recovery of fish mortalities should be required.

Seal blinds are used on practically all sites where depredation occurs and their use is recommended in the Code of Good Practice (CoGP, 2014). They consist of a second layer of netting attached to the base of the net, usually surrounding the 'mort sock' – the lowest point of the net, where dead fish collect. The material used for the second layer may be the same as the main net or may be different (tougher and more resistant to seal attacks). In theory this second layer of netting stiffens the base of the net and makes it harder for a seal to chew fish carcasses lying in or around the mort sock. The extra net is also thought to occlude the inside of the net to a depredating seal, which gives rise to the name "seal blind".

A small number of sites in Scotland have taken the concept of seal blinds one step further, creating an entirely separate base to the net which hangs around one metre lower than the standard base. This creates a physical separation between a depredating seal and the mort sock.

Apart from the additional material and manufacture cost, seal blinds and false bottoms can reduce the water flow through the net base which may cause additional problems. Use of tarpaulin on the floor of the cage to act as a screen to completely obscure the mort sock has been tried and found to be impractical for the same reasons.

3.2.2.2 Anti-Predator Nets

The term "anti-predator netting" (APN) usually refers to a sheet of netting which is suspended from the outside of a finfish farm walkway to create a physical exclusion around the main net. The precise configuration can vary significantly from site to site and may depend on local conditions, suitability of existing infrastructure, and prioritisation of capital investment (sites experiencing severe depredation are likely to prioritise spending on anti-predator measures). The use of APNs at Scottish finfish farms has increased recently, from around 20% in 2016 to over 40% in 2020 (Marine Scotland, 2020b). However, it is not clear if this refers exclusively to APNs as there is a possibility that some stakeholders may also refer to HDPE cage nets as anti-predator nets.

Anti-predator nets used in Scotland often have no base, so they create a 'curtain' around the main net, with the lower edge of the curtain weighted with lead line and large weights. Where the water is relatively shallow, the lower edge may reach the seabed, creating a continuous sheet of net from seabed to surface. Otherwise the lower edge of the APN may hang above the seabed, leaving a gap through which predators can swim. The separation between the APN and the main net is determined by the width of the walkway at the surface, but the effect of current may change this distance below the surface, potentially pushing the nets together or pulling them apart. The APN is generally constructed from knotted HDPE material, and the mesh size is usually much larger than the inner fish net (around 150 mm diagonal).

One primary concern cited by farm managers in relation to the use of APNs (Northridge et al*.,* 2010) was entanglement and drowning of predators, particularly diving birds and seals. Possible solutions to this problem would be to either: a) increase the tension on the APN, for example with an additional weighting system (secondary to the main net weighting system) or by sharing the main net weight between the two nets, or b) reducing the mesh size of the APN. Both suggestions present practical challenges. For example, the use of smaller mesh nets can dramatically increase the drag caused by tidal movement, potentially necessitating uprated mooring infrastructure. Smaller meshes also reduce the flow-through of water, which is vitally important for maintaining a well oxygenated and clean environment, and increase the build-up of algal growth, which will further reduce flow-through, increase drag and increase the need for net cleaning. Increasing the overall weight of the tensioning system may require an increase in positive buoyancy, which may not be practical in some cases due to environmental conditions or site licence constraints.

3.2.2.3 Tensioning

Correct net tensioning is essential for maintaining shape and integrity in waves and tidal currents. If a net is not correctly tensioned it will likely distort more and make fish more accessible by allowing seals to push the net. It is also more likely to fold and thereby produce pockets that trap fish or at least restrict their movements and make them more accessible to seals. There is a clear view in the industry that correct tensioning can help to reduce predation problems (Northridge et al*.,* 2013). Marine Scotland’s Technical Standard for Scottish Finfish Aquaculture (Marine Scotland, 2015) states that down ropes must be attached to the netting in such a way that, when the weighting system is attached, the netting is sufficiently tensioned to deter potential predators.

However, correct tensioning to ensure the netting is taut, particularly of the base of a cage, is not straightforward, and TEP (2010b) reported that “there appears to be little information available to finfish farmers on the inability of weighting systems to effectively tension the base of a standard shaped net”, one of several factors they list as being crucial from a containment perspective. TEP (2012) recommended that research should be undertaken into the ways that nets behave in different current regimes with different weighting systems so that advice can be given to farmers on the optimal tension required and how this might be achieved. They further recommended that research should be directed at the best ways to tension the base of a net.

Although net tensioning is anecdotally reported as being important in minimising seal depredation, how seals use loose or distorted cage nets to access fish is poorly understood. It is assumed that seals can push and distort loose netting and that deformation of nets in currents may lead to predation opportunities in folds and pockets of netting, allowing seals to grab fish through the net. There is no published information on behaviour of wild seals to support this assumption.

To investigate this, Coram et al. (2016) studied the behaviour of captive grey and harbour seals in trials to test their ability to deform nylon cage nets, and to manipulate and eat fish through the net. Three grey and three harbour seals of different sizes were trained to push against a stretched piece of nylon finfish cage netting to establish how much force they would be able or willing to exert for a food reward. Results suggest a strong relationship between seal size (mass) and maximum force, and extrapolations suggest a large 300 kg grey seal can exert a force of over 800 newtons. The force measurements were used to estimate the maximal deformation of a typical bottom net panel from a 100 m diameter circular pen. An incursion of at least 30 cm would be expected from a medium sized seal of 100 kg. The ability of seals to significantly deform a correctly tensioned net suggests that they will be able to push much further into poorly tensioned nets and that might increase the likelihood of catching or at least contacting and damaging fish.

All the seals in the trials found it difficult to feed on fish presented to them in a model of a pen. When seals had access to fish over long periods, they recreated one type of damage often seen at finfish farms by chewing much of the flesh from the carcass, but leaving the spine, head and tail intact. The stereotyped gashes and abdominal bite-wounds sometimes seen in large numbers at finfish farms were not recreated in the experimental trials, and this may suggest that those wounds are indicative of seal attacks on live fish. Feeding live fish to seals is not allowed under the Animals (Scientific Procedures) Act 1986, so only dead fish could be fed as part of the captive experiments. The fact that seals could access dead fish through properly tensioned nets supports the suggestion that loose or poorly tensioned nets are likely to provide increased opportunities for seal predation.

3.2.2.4 New net materials

New netting materials, particularly high-density polyethylene are now widely used in cages in finfish farms around the globe (Cardia & Lovatelli, 2015), mainly because of their greater breaking load compared with other fibres of the same thickness (approximately 4x stronger than nylon), reduced elongation (3.5% at breaking load compared with up to 20% for nylon) and their resistance to water absorption. Consequently, net pens manufactured using HDPE can be both lighter and stronger and are more resistant to abrasion and tearing. They have been widely adopted for farming species that are prone to biting the net, e.g. cod (*Gadus morhua*) and gilthead seabream, (*Sparus aurata*). HDPE nets are expected to have a longer useful life than nylon nets but are also more expensive.

Coram et al. (2016) noted that HDPE netting materials being trialled at farm sites in Scotland were stronger and more rigid and therefore likely to make seal incursions more difficult. Marketed under trade names such as Sapphire and SealPro, these materials are often cited by environmental campaigners as the best or only ecologically responsible option to eliminate depredation of farmed fish. However, the mixed uptake of new style nets and the relatively low level of use of anti-predator nets in Scotland is indicative of a contrasting perspective from within the industry (Marine Scotland, 2020b).

At present, while there is significant experience and expertise within individual finfish farm companies, very little empirical information is available publicly to reliably compare different netting options. Where innovative materials or methods have been trialled (either within the Scottish aquaculture sector or abroad), the experience gained has generally remained within the individual company. In the past this may have been considered an understandable effect of competition within the sector but given the pressing need for industry-wide solutions to the problem of seal predation, there is a clear need for better dissemination of practical results from systematic trials.

Consequently, there is little published information on the extent of uptake of new HDPE nets and no peer reviewed information of their effectiveness at reducing predation problems. Although there are as yet no confirmed estimates of the numbers, it is currently thought that approximately 40% of farms are using HDPE netting (Marine Scotland, 2020b), and operators have reported a perceived benefit in reducing depredation. The size of this reduction has not been reliably quantified, and controlled tests of HDPE netting in the context of seal predation are required to provide reliable estimates of their effectiveness. However, early anecdotal results and reports in the media suggested that they were highly effective. For example:

- Cooke Aquaculture Scotland began installing new HDPE anti-predator nets at its sites in 2016. They reported that they had no issues with seals at the first 140 pens completed and planned to have installed them at all of their sites by the end of 2019 (Press, 2019a).
- Scottish Sea Farms (SSF) had installed new HDPE nets at 21 of its 45 farms by 2019, with plans for nine more to be equipped in 2019 and 2020 at the start of each new production cycle. SSF attributed a 30% reduction in the number of seals shot to the use of these nets. No seals were shot at the company’s seven farms in Orkney in the three years following installation of HDPE nets in 2016. SSF also reported that once netting has been installed at one farm seals apparently relocate to another farm without similar protection measures (Press, 2019b).
- Grieg Seafoods Shetland reported the use of HDPE anti-predator nets at some sites and regarded them as having been largely responsible for the fact that no seals were shot at their sites in 2018 (Press, 2019c).

More recently (winter 2019/20) there has been an increase in the reported levels of seal depredation at multiple sites fitted with HDPE nets (Coram et al*.,* in prep). It is currently unclear whether this is purely coincidental – for example due to changes in the behaviour of local seal populations, or if there is some systemic change in the properties of the net. Possible reasons for this apparent change could be a softening of the material caused by physical degradation and repeated washing cycles, shrinkage or stretching of the material causing poor fitting of the net to the walkways, or some other change in the physical properties of the nets. This observed reduction in effectiveness warrants investigation of the long-term effectiveness of HDPE nets.

Apart from the cost of upgrading to these HDPE nets, there are practical issues which have slowed down their adoption in Scotland. The net material is significantly 'rougher' than nylon, which is more likely to damage fish when nets are lifted to 'crowd' the fish for treatments or harvesting. Some brands also use knotted construction, which further increases how rough the nets are. One company in Scotland is currently using nylon net bases with HDPE net walls to address this problem, but it means that the base of the net (where a large amount of seal depredation is thought to occur) is not protected by the stiffer net. Where similar nets are used in Tasmania to reduce interactions with sea lions and sharks, companies are obliged to use divers to swim a net below the fish before they can be crowded for treatment. There are several considerations associated with the use of divers (e.g. health and safety and cost), but this is a good example of the kind of systemic change adopted in an industry required to adequately address the practical constraints of the current containment systems.

3.2.3 Removing seals from aquaculture cages

If a seal does gain access to a finfish farm cage it is likely to cause significant damage as well as causing stress to the farmed fish. It is therefore essential to remove the seal as quickly as possible. At present there are no established non-lethal measures specifically designed to, or currently used to, remove seals from finfish farm cages.

Providing an escape route would seem to be an appropriate method, however this may be operationally difficult and would probably require re-engineering of the containment system. Lowering a section of the barrier net to the surface level and providing an escape route is one option, although providing such an escape route for a seal that does not allow fish to escape would be difficult.

Once inside a cage, a seal has the potential to damage and kill a large number of fish rapidly. It is therefore imperative that whatever means are employed to remove the seal, they must be done quickly. Attempts to drive a seal towards an escape route may prove difficult as a stressed seal in a cage is unlikely to behave cooperatively and it may not recognise the escape route. Deploying an ADD may force a seal to search for and use an escape route, but care would be needed to avoid potentially harming the animal in the process, and there is no guarantee that a distressed animal would find or use an escape route. Simply leaving the seal alone to find and use an available escape route may work eventually, but such a passive approach would leave the seal free to attack and damage fish for long periods, and would therefore likely be unacceptable to farm operators due to concerns from a fish welfare perspective.

Catching a seal within a fish cage would be extremely difficult and potentially dangerous for both the seal and the farm operators. An apparently simple approach would be to attempt to dart and anaesthetise the seal in the water. This is a standard method for handling seals on land, using mixtures of either Tiletamine and Zolazepam or of Ketamine and Diazepam (Gates, 1989; Baker et al*.,* 1988). We are not aware of any successful attempts to anaesthetise free swimming grey and harbour seals. Due to the potential for a seal to respond to anaesthesia with apnoea and the added risk introduced by a dive reflex if the animal was anaesthetised while underwater, the risk of drowning is high. It is for this reason that darting unrestrained seals in the water is not recommended.

Two potential methods for safely and rapidly removing seals from cages have been identified, one using a floating cover and one using nets to confine seals to small areas at the surface where they would be accessible for anaesthesia and capture. These methods are described in Section 5.2.5. However, it is important to note that these methods have not been tested and therefore require development and testing.

3.2.4 Closed containment and recirculating aquaculture systems

The most obvious and, in theory, the most effective means of preventing predation problems would be to separate the fish production process from the wild/natural environment. Recent developments in marine closed containment systems (CCS) and semi-closed containment systems (S-CCS) and of land-based recirculating aquaculture systems (RAS) would appear to offer such predator proof finfish growing environments.

3.2.4.1 Closed and semi-closed containment systems

CCS and S-CCS systems were designed primarily to reduce the environmental impact of finfish cages and reduce sea lice issues but should also have significant benefits in terms of reducing seal predation. In most cases the CCS is effectively a modified cage system, with the net pen being replaced by a solid walled containment structure with a closed roof, so there is no direct contact between the fish and the surrounding sea water. Fresh, oxygenated seawater is drawn from depth and continuously pumped through the containment structure. Deeper water, below 25 m is not thought to support the infective stages of sea lice.

S-CCS are effectively the same as CCS underwater, but are open to the air, with solid perimeter walls high enough to prevent waves breaking into the pen. Assuming this perimeter wall is too high for seals to climb over, they should be effectively the same as CCS in terms of resilience to seal depredation. Stirling Aquaculture (2018) reviewed the technical and economic aspects of CCS and S-CCS and reported that three marine CCS were commercially available and ten were in advanced stages of development. Appendix 2 of their report provides a detailed description of all systems either in production or in the late stages of development.

In theory CCSs and S-CCSs can reduce escapes, avoid or reduce pathogens and parasite loads, and prevent predation. To date, efforts have been focused on producing post-smolt fish up to approximately 1 kg in weight, prior to transfer to traditional open sea cages for growth to marketable size. This would substantially reduce the total time fish spend in open sea cages. There seems to be no physical obstacle to using CCS to produce marketable size salmonids. However, they are more expensive than open sea cages and their performance and cost effectiveness is still under investigation, (e.g. Balseiro et al*.,* 2018; Global Aquaculture Advocate, 2018b). Stirling Aquaculture (2015) provide a financial model of the costs of producing 1 kg post-smolt salmon in CCS. They estimated that it would add between 8% and 13% to total production costs. However, the cost model makes assumptions about depreciation costs that the authors consider to be uncertain and assumes current stocking density limits will remain. Small changes in any of these assumptions can significantly change those costs.

Conversion to CCS or S-CCS would represent a major change in the operations and investment strategies of individual finfish farming companies. Seal predation would be only one of a wide range of considerations determining such a change, and those issues are out-with the remit of this project.

Trials of CCS for salmon are underway in Norway, but to date we are not aware of any marine closed containment systems in operation in the UK nor any empirical evidence of their resilience to seal depredation.

3.2.4.2 Recirculating Aquaculture Systems

Recent and continuing development of land based recirculating aquaculture systems (RAS) offers the advantage of removing the seal predation issues altogether. Such a shift would entail a profound change to the structure of the industry and a dramatic change in the methods, locations and investment strategies of individual finfish farming companies. As with closed containment systems, seal predation would be only one of a wide range of considerations determining such a change, and those issues are out-with the remit of this project.

However, it is worth noting that salmon production, particularly smolt production, in land-based RAS systems is increasing. For example, MOWI (formerly Marine

Harvest) is using large, land-based RAS facilities and is testing out floating, semi-closed containment systems for smolt and post-smolt production; Superior Fresh operate a land-based Atlantic salmon farm in the USA that combines fish production with a large scale hydroponics production system; Atlantic Sapphire's land-based, Atlantic salmon farms in Denmark began production in late 2013 and have recently begun production at a large RAS farm near Miami in Florida.

3.2.5 Electric field deterrents in saltwater

Graduated field electric barriers for seals or fish can only operate in freshwater, which has a low conductivity (25 to 250 µS/cm) compared to highly conductive seawater (45,000-60,000 µS/cm). Even in freshwater they require a substantial power supply. Replicating this technology in saline or brackish water would require prohibitively large amounts of electrical power to sustain an electric field with enough range to produce an exclusion zone around finfish farm cages.

However, while generating wide area electric field barriers in sea water is not possible, intense electric fields can be generated close to electrodes. It is therefore possible that a pulsed electric field could be used as a deterrent to prevent seals making and maintaining contact with the netting of finfish cages. Given the types of damage inflicted by seals they must maintain contact with the net for several seconds and probably much longer in order to manipulate and consume a salmon (Coram et al*.,* 2016).

The responses of seals to pulsed low voltage DC electric fields have been tested in seawater with captive seals in Scotland (Milne et al*.,* 2010). Seals were trained to take food from a small underwater window with electrodes on either side of the window. Voltages from 12 to 36 V, with increasing pulse durations from 10 to 1000 µs and pulse rates from 10 to 100 Hz were tested. Field strength was gradually increased in order to avoid any unnecessary exposure to painful stimuli, and the seals were always free to move away from the stimulus.

Seals did not respond to the electric field at the shortest pulse durations (< 50 µs), but aversive responses were evident in all seals at higher pulse durations. The intensity of response increased at higher voltages and higher pulse rates and all seals refused to enter the electric field to access the food reward. After refusal, seals were visibly more cautious when subsequently entering the feeding station, but all returned to feeding normally during control periods at end of each experimental session. There was no evidence of habituation or sensitisation to the stimulus. The deterrent effects were only apparent within a few centimetres of the electrodes. Even when the strongest electric field was applied, seals were not apparently affected at ranges of more than 30 cm from the electrodes.

These results led directly to the development of an electric field deterrence system by Ace-Aquatec which was trialled at a finfish farm site in Scotland (Whyte, 2015).

Their device covered the base of a fish cage in order to prevent seal attacks from below. Field trials were carried out, but the use of an electrified net on one cage was combined with use of ADDs on adjacent cages. When used in combination the electric net and ADDs significantly reduced predation at the farm overall, although there was no significant reduction in the number of seal-killed fish in the electrified cage. The results were confounded by the fact that both ADD and electric field deterrents were active, meaning that it was unclear how much of this effect was due to the electric field.

3.3 Conditioned Aversion

If methods to prevent seals gaining access to farmed fish are not successful, an alternative/next level of deterrence would be to remove the motivation to consume farmed fish. This could be difficult as finfish farm cages represent a powerful positive stimulus for a seal that recognises the farmed fish as a potential resource. There are however two clear potential methods for preventing naïve seals developing a taste for farmed fish and possibly even removing the motivation to eat farmed fish in experienced predators.

3.3.1 Conditioned taste aversion at finfish farms

The background to Condition Taste Aversion (CTA) in seals was presented in Section 2.3.1. The only published report of a trial of CTA with seals foraging at a finfish farm was an attempt to reduce depredation by Australian and New Zealand fur seals at a salmon farm in Tasmania (Pemberton & Shaughnessy, 1993). Twenty-six trials using lithium chloride laced salmon were conducted at a finfish farm experiencing predation, after a period in which unadulterated salmon were presented to predating fur seals. In 21 of these trials, animals were seen to take the bait, and on two occasions seals were seen convulsing and vomiting nearby (presumably having ingested the emetic). Two more seals were reported to leave the vicinity after taking the bait and vomiting. Although the authors considered the method to be potentially useful there is no evidence of it being developed any further.

Some very limited trials were conducted in Loch Sunart in Scotland in 1988, where wild grey seals were fed on salmon laced with chilli and curry powder (Coram et al*.,* 2014). Seals did not appear to be repelled, but predation on the nearby salmon farm was reported to have stopped during the trial. This case cannot be considered an example of CTA because the taste of the fish was modified, reducing the chance that animals would associate the effect with untreated salmon. Emetics were also tested on grey and harbour seals in Sweden with inconclusive results (Lunneryd, pers. comm. Reported in Westerberg*,* 2010). These trials were found to present both practical and ethical difficulties, with lack of control over dosage in field studies.

The taste, smell and flavour associated with the laced bait 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. If seals can be trained to associate particular visual or auditory signals with a CTA to salmon, it may help to generalise the CTA to other cages or other farms.

As with the use of CTA in rivers, the context of the presentation of the laced bait is likely to be critical. Presenting laced fish to seals at finfish farms should be relatively simple. The more similar the laced fish is to the normal prey, the more likely it is that the CTA will be effective in reducing predation. If as has been suggested, seals develop their predatory behaviour as a result of encountering and feeding on moribund fish (Northridge et al*.,* 2010) it may be relatively simple to lace dead fish and present them in the same way. If this is not possible it may be enough to present laced fish close to or attached to the outside of a cage. The brief trials with chilli laced salmon showed that wild Scottish seals will readily take whole dead salmon bait presented at a finfish farm (Coram et al*.,* 2014).

CTA seems to be most easily established if the food stuff is novel, but aversion can also be established for previously encountered foods (Kuljis, 1986). It may therefore be possible to develop CTA in seals that are already established as predators of farmed fish. If that proves difficult, it may still be helpful to dissuade naïve young seals from establishing a foraging strategy based on farmed finfish.

At present there is insufficient information to assess the potential for CTA to reduce predation by grey or harbour seals at finfish farms. Although the presentation of laced fish at a large number of farms would be relatively simple and inexpensive there would need to be an initial structured monitoring programme to identify the most appropriate emetic, to develop methods of delivering the baits and to evaluate the effects on both seal health and depredation rates.

Coram et al*.* (2014) suggested an alternative approach, using CTA on specific individual seals. The method would involve catching problem individuals at sites of conflict, maintaining them in a captive facility and establishing CTA to farmed salmon before release to the wild. However, capture of specific animals is difficult and even if successful, the cost and effort involved would mean that only a small number of seals could be trained in this way and it is not certain that CTA developed to fish in captivity would be transferred to live fish in an aquaculture cage. Evidence from attempts to develop CTA in free ranging sea lions in rivers shows the importance of the context of prey presentation (e.g. see Section 2.3.1 above).

3.3.2 Electric fish

Ace Aquatec have marketed an ‘electric salmon’ which is a moulded plastic shape similar in shape to an adult salmon, but with a number of protruding cables to act as electrodes. The device delivers an electric shock when a seal takes hold of it. It is unlikely that a seal would mistake the electric fish for a salmon, and the presence of the electrode cables further reduces its resemblance to a salmon. However, the recommended deployment is to place the electric fish in the bottom of the cage, among dead fish. The model will therefore be partially hidden and seals investigating or attempting to bite it or other nearby dead fish may come into contact with the electrodes and receive a shock.

The company report that several farms in Scotland have tried the device with some success. We are not aware of any controlled study of the responses of individual seals or of its effectiveness in reducing predation. The electric fish is currently used as part of a co-ordinated suite of measures including staggered use of medium and low frequency ADDs and is generally employed as an additional deterrence measure where a serious predation event is proving difficult to stop (Ace Aquatec pers. com).

As the electric fish is used in conjunction with a suite of other measures it is difficult to identify/quantify its specific effect. However, the manufacturer states that its inclusion in their suite of controls significantly enhances the overall effectiveness.

3.4 Summary - finfish farms

Mitigation of seal depredation at finfish farms is essentially a matter of dissuading or preventing seals from approaching and attacking the cages and/or of making the cages more resistant to attacks.

Acoustic deterrent devices
The primary non-lethal method of deterring seals from approaching and attacking cages is the use of acoustic deterrent devices. These are widely used despite little scientific evidence of their effectiveness. The widespread use of ADDs has also led to concerns about potential impacts on non-target species, particularly cetaceans. Several studies have shown that cetaceans (harbour porpoise in particular) are likely to be disturbed by ADD noise. It is therefore important that steps are taken where possible to reduce these impacts.

Four ADD systems are available that attempt to avoid the sensitive hearing ranges of non-target species and reduce the source level, although all would benefit from further scientific trials to demonstrate both their effectiveness in reducing depredation and the lack of impact on non-target species.

In addition to these newer ADDs, there are also potential methods for reducing the noise output of existing, widely used ADD designs, and to minimise or remove the risk of hearing damage and disturbance in non-target species. In particular, the number and duration of transmission sequences could be minimised by only triggering ADDs when seals are detected close to cages. Such a detect and deter strategy will require the development of an effective seal detection system to trigger the ADD when seals approach cages. The detection technologies that are available are reviewed in Section 4.

Even if ADD transmissions are triggered by seal presence, it is possible that non-target species will be in the vicinity of transmitting ADDs, particularly when transmissions start. It would therefore be sensible to develop an override system that prevents transmission if a cetacean is detected in the vicinity of the finfish farm. This will necessitate the development of a sensitive and reliable automated cetacean detector. Such detection systems based on passive acoustic monitoring of baleen whale vocalisations and porpoise/dolphin vocalisations and echolocations, have been developed as research and monitoring/survey tools and with modification should be capable of providing an automated detector to override the transmission trigger from a seal detector.

An alternative or complementary approach to reducing noise output is to attenuate the ADD signals which could be achieved through the through the use of strategically placed sound absorbing material or air-bubble curtains. The successful application of this method to protect captive porpoises from piling noise shows that it is likely to be effective at attenuating ADD signals. The practicality and feasibility of this solution needs further investigation.

Conditioned aversion
In addition to direct deterrence using sound, it may be possible to effectively train seals not to attack cages by making the prey less attractive through some form of aversion therapy. One such method is already used, an electrified fish model that is placed among dead fish on the floor of a cage and delivers a painful but not damaging electric shock if a seal touches it. A conditioned taste aversion method which is used to control other predator prey interaction has been tested successfully on captive pinnipeds but needs additional development before it could be used at finfish farms.

Improving resistance to seal attacks.
The ultimate aim is to make fish cages seal-proof and/or to remove or reduce the incentive for seals to attack. Measures to reduce the incentive for seals to attack cages are detailed in the industry Code of Good Practice for Scottish Finfish Aquaculture (CoGP, 2014). These include routine husbandry such as regular removal of dead fish, modification of the cage floor to include a seal blind to make dead fish in the mort sock less visible to seals, or additional of a false bottom to the cage. These are already widely practiced at Scottish finfish farms.

Measures to make seal attacks less successful rely on a combination of:

- Maintaining the correct tension on nets to stop deformation in tidal currents and prevent folds and loose net that allow seals to get access to fish.

- Changing to new stronger and stiffer net types. Anecdotal reports and media coverage suggest that this is already having an effect in reducing seal depredation.
- Using anti-predator nets. The use of APNs is gradually increasing in Scotland.

One particularly difficult issue is identifying an appropriate method for dealing with seals that gain access to a stocked cage but cannot or will not leave. These are relatively rare events, but when they occur, they need to be dealt with quickly and safely. At present there are no available safe non-lethal measures, but possible non-lethal trapping methods have been identified that may solve the issue and allow such animals to be removed quickly (see Section 5.2.5). These should be investigated further and if possible, tested in a realistic setting.

Taken together and applied effectively, the available methods and materials may reduce seal predation to manageable levels, but as with river fisheries there is no clear simple solution to the problem.

4. Detecting seals and cetaceans

All active deterrence (and possibly capture) methods will either rely on, or be made more efficient by, being triggered in response to the timely detection of seals. Minimising the use of deterrents and targeting them only at times when seals are actively involved in predation or when they are at particular sensitive locations, should reduce the likelihood of seals habituating to them and reduce the frequency and duration of disturbance to non-target species.

Acoustic deterrents at finfish farms are used either continuously or reactively in response to perceived threat of depredation. The ability to detect the threat of depredation in real-time would remove the need for continuous deterrent use, and development of automated systems would allow detection to be standardised and reliable. A reliable detection system could also increase the effectiveness of certain measures, for example, as a seal that responds to a negative stimulus is more likely to associate it with predation at a finfish farm if the deterrent only operated when it was actively attacking one.

The available methods for observation and detection may be applicable to several deterrence and seal capture methods and will therefore be addressed as a separate category of techniques. In this section we describe methods that are currently used, under development or potentially useful for detecting and monitoring seal presence. As the methods of detection and identification of seals will be similar in many cases for both river and finfish farm scenarios, the section will address both and highlight differences where appropriate.

4.1 Direct observation

4.1.1 Direct observation of seals in rivers

The most straightforward method for detecting seals is through visual observation. Dedicated observer programmes associated with active seal deterrence measures in rivers have been documented in the USA and Canada, at sites with high levels of pinniped activity and frequent incidences of predation. To date, these have been associated with specific locations such as dams and lock systems where the concentration of foraging effort by the pinnipeds and the large scale of the control programmes mean that sufficient manpower is available to ensure regular monitoring for the presence of predatory seals and sea lions (NMFS & ODFW, 1997; NMFS, 1996a). This maximises the likelihood of the predatory seals and sea lions being sighted prior to or soon after arrival at the sites and allows control effort to be targeted effectively. Such levels of dedicated observer effort are unlikely to be available for control measures in the much smaller scale river fisheries in the UK where seal presence may be sporadic and distributed along the course of a river.

To date there have been few attempts to monitor the presence of seals in rivers in the UK and as a consequence, there is little information on seal occurrence upstream of the tidal limits of most rivers. Structured monitoring programmes have been developed as part of ongoing research into seal predation in specific rivers in Scotland (e.g., Graham et al*.,* 2009; 2011; Harris & Northridge, 2017). Direct visual observation has been used in Scottish rivers to document seal presence and estimate numbers of animals involved (e.g. Harris & Northridge, 2017), to detect predation events and estimate total consumption of salmonids (Harris & Northridge, 2019) and to identify individual seals and track their presence and activity (e.g. Graham et al*.,* 2011). The data obtained from these studies suggest that seal activity reported by members of the public, fishermen and other observers, supplemented by direct visual monitoring by the staff responsible for control measures, can form the basis of useful seal detection programmes in Scottish rivers.

It should be possible to maximise the effectiveness of observation efforts by ensuring the reporting of any observations through coordinated networks of observers, and through public and angler awareness programmes. For example, an app-based reporting scheme that uses Survey123 for ArcGIS has been developed for the Dee Salmon Fishery Board[1]. Primarily designed for use by bailiffs and ghillies, the system has been rolled out on the Rivers Dee and Tweed. Real time collection and collation of observation data will allow managers to maximise the usefulness of incidental observations, thereby allowing more effective targeting of dedicated observer programmes at key locations and at key times of day/tide/season (where possible using staff assigned to apply deterrent methods).

[1] https://survey123.arcgis.com

However, in many Scottish rivers there are large sections with little or no human presence to provide reliable detection and reporting of the presence of seals. This is especially true outside the main tourist and fishing seasons. The general lack of observers is compounded by the difficulty of spotting seals. Even in shallow water seals may remain submerged for a significant proportion of the time, present a small visible signature when at the surface and can move rapidly between surfacings. Even when seals are present, sightings will be rare and fleeting, and easily missed. Furthermore, sightings effort will not be effective or even possible at night, or in periods of adverse weather conditions (e.g., low-lying fog, heavy rain, high winds, etc.).

Developing methods to provide continuous monitoring of seal activity in rivers is essential for triggering control measures and providing information to assess their effectiveness. In addition, such programmes will provide essential information on when seals are using rivers, allowing for a more targeted approach to applying control measures and research efforts. Several potential options exist, such as video and sonar and they are briefly described in Sections 4.2 and 4.3 respectively.

4.1.2 Direct observation of seals at finfish farms

The most straightforward method for detecting seals at finfish farms is also through visual observation. However, dedicated observer programmes associated with active seal deterrence measures are labour intensive and not conducive to normal farm operations. In addition, an unknown but significant proportion of depredation is thought to occur at night, when site staff are not present and visual observations would be restricted by lack of light. It is therefore highly likely that a large proportion of seals visiting finfish farms are not seen. A technological solution that allows automated detection of depredation is therefore essential for continuous targeted active control at finfish farms.

4.2 Video monitoring

CCTV camera systems are a familiar and widely used method for monitoring presence and activity of both human and non-human targets in many situations. These may rely on continuous human monitoring or post-processing of recorded images by observers. But in practice, most CCTV systems are not monitored in real time and footage is rarely stored unless an alarm is activated, or motion or infrared (IR) detection is triggered. It is possible to transfer this technology to monitor seal activity in rivers or at finfish farms, but to date there have been few documented attempts to assess its effectiveness.

4.2.1 CCTV in rivers

A CCTV surveillance system to detect the heads of surfacing seals, is being tested in a section of the River Dee, Aberdeenshire (Harris et al*.,* 2020). The system comprises four Mobotix S16 dualflex cameras, each with two black and white video sensors, and four infrared light sources, and was installed at a site 9 km up the River Dee, above the tidal reaches. An infrared lighting system was incorporated to provide a cost-effective night-vision capability. The system allowed surfacing seals to be detected at ranges in excess of 130 m both upstream and downstream during day light conditions. At night seals were harder to detect and often relied on eyeshine from the IR lights. Telemetry tracking data were used to estimate transit rates and to identify a site where seals travelling upstream were likely to surface at least once within the field of view.

A total of 181 discreet seal visits and 754 surfacing events were recorded during a 106 day preliminary study (Harris et al*.,* 2020). Observers viewing all eight channels simultaneously at 8X speed were able to document seal occurrence and behaviour, including observations of feeding events during both the day and night. Most seal events occurred during hours of darkness. Independently obtained photo-identification of seals using the area suggested that most sightings were probably due to one grey seal and one harbour seal that regularly used this stretch of river.

The study demonstrated the ability of a fixed video surveillance system to record relatively rare seal events in a river, during both the day and at night. Such systems will be useful for monitoring the level of seal activity and assessing the efficacy of mitigation measures. However, using such systems for triggering management actions requires real time detection and image classification. To be practically useful as a management tool such monitoring will need to be automated. The results of preliminary studies such as that on the River Dee will provide data training sets for machine learning approaches that are being developed for automation of seal detection (e.g. Conway et al*.,* in press).

4.2.2 CCTV at finfish farms

In terms of the operation of video systems, the main differences between finfish farms and rivers are:

- Area coverage. Detection systems in rivers need to cover relatively small, well defined areas so the number of cameras and the range at which seals need to be detected are both relatively small. At finfish farm sites the total area that needs to be monitored is much greater and the numbers of cameras required and the ranges at which seals will need to be identified will be much larger. A typical site with twelve circular nets, 100 m in circumference, will measure approximately 400 x 100 m. Assuming monitoring needs to cover a range of 100 m in all directions beyond this area, the total area to be monitored is approximately 180,000 m^2.

- Larger numbers of video streams would be required to monitor such a large area in real time, meaning that rapid processing will be very labour intensive.
- The likely need for remote real time operation necessitates transmission of video signals to a base station, either on the farm or ashore.
- Power requirements become critical as cameras and transmitters will be remote from continuous mains power. Many farms run generators through the day, and some also run them at night to power underwater lights and deterrent systems.

Aside from research trials in Scottish rivers, as far as we are aware, the only video monitoring system specifically designed for automatic seal detection capabilities has been developed by Ace Aquatec and Peacock Technology. This system incorporates a surface seal detector based on a combination of thermal imagery, a night vision camera (image intensifier) and HD video, and is designed to function as part of their Portal deterrent control system. Initial trials with HD video and night vision camera picked out seals on land and seal heads in the water (Ace Aquatec, 2020).

According to the manufacturer the final design for deployment on a farm pen incorporates a dual lens camera capable of detecting seals at 2 km range and utilises image processing software to track seal heads and distinguish from birds and other non-target animals. The system will incorporate a pan and tilt mount and automated seal recognition to provide a fully automated seek and find technology. In theory such an automated system could also detect and classify sensitive species, such as cetaceans, and stop the transmission of sound signals. This could reduce the potential disturbance or risk of damage of non-target species, although the systems still require testing and development. Porpoises in particular may be hard to detect due to their relatively short and inconspicuous surfacing behaviour.

4.2.3 Automatic video detection of seal heads

Basic CCTV systems require either continuous real time monitoring or the downloading and post processing of video recordings. While post processing may be useful for monitoring the level of seal activity and assessing the efficacy of mitigation measures, triggering management actions requires real time detection and target classification. To be practically useful as a management tool such monitoring will therefore need to be automated.

To date we are not aware of any automated real time, seal detection system that has been used to monitor seal activity from video images. However, automated real time processing of video images to detect and identify small objects is a rapidly developing field of study and is a major issue in search and rescue. Remote monitoring cameras and unmanned aerial vehicles (UAVs) are widely used to assist search and rescue operations in both marine and terrestrial environments. The constraints and requirements of such systems are similar to those for seal detection.

The large volumes of visual information generated often exceed the real time monitoring capacity of available observers and the target images are often small and transient.

Several groups are developing automated search methods to deal with large data streams from UAVs. For example, Yun et al. (2019) used UAVs and fixed surveillance cameras to build an automatic detection system for the US Coast Guard (USCG) to find small targets such as human heads in the water. In direct comparison trials the automated detection system identified targets within 8 s, whereas the human observers took approximately 25 s. Such automated detection algorithms clearly have potential for development as components of automated video seal detectors. Images from video recordings of seal activity in coastal salmon bag nets are being used to develop and test automated detection and behaviour classification methods for annotating video recordings (Conway et al*.,* in press). Both image-only and video models classified seal activity with high accuracy (90%) and all seal visits were detected by both models. Such image classifiers may also be suited to those images produced by active sonar allowing similar models to be used with both CCTV images and those from sonar.

4.2.4 Video monitoring underwater

Northridge et al. (2013) reported tests of three underwater video systems for monitoring seal activity in the vicinity of fish cages at a finfish farm in Orkney. They detected seals and obtained video images allowing identification to species level. However, the range of detection was highly variable, with turbidity and low light levels often reducing visual ranges. Such restricted detection range means that many cameras would be required to observe seal activity at individual cages and large numbers would be needed to observe an entire finfish farm. For example, a single net may need to be monitored by four cameras to achieve full coverage, mounted near the base and looking upwards. To completely monitor a typical farm of twelve pens would therefore require at least 48 cameras recording simultaneously.

Although single or small numbers of cameras can provide useful insights into the timing and nature of interactions (Northridge et al*.,* 2013), data from such small areas would be of limited value as the detection part of a detect and deter system. It is therefore unlikely that underwater video will provide a practical observation method for whole farm coverage in typical Scottish environmental conditions.

4.3 Active Sonar

At short ranges and in specific water conditions, in terms of depth and bottom topography, it is possible to detect, identify, and track submerged seals using sonar. Tracking small targets has been technologically challenging, but development of active sonar systems for the defence sector to detect, identify and track underwater targets such as divers has advanced rapidly in recent years (Hastie et al., 2014; Hastie et al., 2019a). Such systems have been widely used for fisheries research and management, and more recently have been developed for tracking marine mammals and monitoring avoidance or evasion behaviour of seals and harbour porpoises around tidal turbines (Hastie et al., 2014; 2019a).

Active sonar has been used extensively to study the underwater behaviour of marine mammals and to track the movements of individual animals in a range of different habitats (e.g., Benoit-Bird & Au, 2003a; Benoit-Bird et al., 2004; Doksæter et al., 2009; Gonzalez-Socoloske & Olivera-Gomez, 2012; Nøttestad et al., 2002; Pyć et al., 2016). Sonar is effective in turbid water with poor visibility where visual monitoring is ineffective, for example, sidescan sonar has been used to successfully monitor West Indian manatees (*Trichechus manatus*) in very turbid water (Gonzalez-Socoloske et al., 2009; Gonzalez-Socoloske & Olivera-Gomez, 2012). It can also be effective in fast flowing water, for example, Ridoux et al. (1997) successfully monitored bottlenose dolphin movements in high tidal flows using multibeam sonar, and Hastie et al. (2019b) and Cotter & Polagye (2018; 2020) used sonar to record three-dimensional movements of harbour seals in a high tidal current.

Although sonar has been used effectively for behavioural studies of marine mammals, this has usually relied on visual confirmation of targets by sonar operators, either in real time or during post processing (e.g. Benoit-Bird & Au, 2003a; 2003b). As with video monitoring systems described above, to be effective triggers for management actions, sonar systems will need to identify targets in near real time.

Hastie (2012) reviewed available systems and collated an inventory detailing more than 200 systems from 39 sonar manufacturers. These are designed for a wide range of use including swathe bathymetry, underwater navigation, fisheries research, and seabed profiling, with fundamental transmission frequencies ranging between 12 to 2,250 kHz. Of these systems, 24 incorporated automated target detection and tracking software, but most were designed for vessel or port security rather than for marine wildlife tracking. More recently, Hasselman et al. (2020) reviewed both passive and active sonar systems used for monitoring marine renewable energy devices and identified commonly used imaging sonars. The choice of device depends on the specific aims of the monitoring programme, but several of these high frequency (HF) devices (260 kHz to 900 kHz) have effective detection ranges of between 30 m and 150 m and fields of view of 120° x 10-20°. Several include some form of target triggering and have the potential to provide seal detection capabilities for both river and aquaculture settings.

Verfuss et al. (2018) reviewed sonar systems for detecting marine mammals during seismic surveys. The use of sonar as part of mitigation measures in seismic surveys demands long range target identification. The range of active sonar depends primarily on the frequency and source level. For example, HF systems such as the Gemini 720 (Tritech International Limited) with a frequency of 720 kHz have limited range, in that case a maximum range of 120 m, whereas lower frequency systems such as the Simrad SX90 (Kongsberg Maritime Subsea) with a frequency range of 20-30 kHz are reported to be capable of detecting seals at ranges of up to 2 km (Pyć et al., 2016).

4.3.1 Sonar seal detection in rivers

Field trials of a sonar system developed specifically for detecting pinnipeds in rivers to act as a trigger for an electric field barrier, were described by Burger (2010). A library of sea lion and fish "shapes and forms" was assembled from sonar deployments in Astoria and Newport, Oregon, USA, and Principal Components Analysis and "analytical training and testing protocols" were used to classify targets. In a series of trials, the system was able to accurately discriminate between sea lions, salmonids and sturgeon (Simpson, 2008, quoted in Burger, 2010). Based on 160 "test tracks" (representing thousands of echo data points for both high and low frequency broadband sonar), all 21 sea lions and all 139 fish were identified correctly. Burger (2010) concluded that their hydro-acoustic system was capable of accurately discriminating sea lions from large fish targets based on their swimming patterns and target strength. The sonar system thus provided a potential tool for detecting pinnipeds and could act as a cueing technology for triggering the operation of active seal deterrence methods. Although apparently successful there has been no further development of this system and as far as we can ascertain it has not been used since the preliminary tests.

Although not directly related to either salmon rivers or aquaculture, similar requirements have been identified for sonar systems to detect encounters between marine mammals and marine renewable energy developments, in particular for tidal turbines. For example, Hastie et al. (2019a) described a test of a HF (720 kHz) multibeam sonar (Tritech Gemini 720) to remotely collect high-resolution movement data for marine mammals. Sonar data of wild seals was used to quantify detection probability and assess how this varied with range from the sonar. Data on the movements of harbour seals were collected in a tidally energetic environment, with the sonar system fixed to a custom designed, seabed-mounted platform. Concurrent visual observations from a nearby, moored vessel provided visual validation of seals and other targets detected by the sonar. In total, 65 confirmed seals and 96 other unidentified targets were detected by the sonar. Movement and shape parameters associated with each target were extracted and used to develop a series of classification algorithms. The best-fit algorithm correctly classified all the confirmed seals but misclassified a small percentage of non-seal targets (~8%) as seals.

Hastie et al. (2019a) concluded that sonar is an effective method for detecting and tracking seals in high current, tidal environments, and the automated classification approach they developed provides a key tool that could be applied to collecting long-term behavioural data around anthropogenic activities and marine infrastructure, such as tidal turbines. Their high degree of target classification with no false negatives and only a small proportion of false positives suggests that their sonar system could be a potential seal detector and trigger for the operation of active seal deterrence methods.

In shallow rivers, surface reflections and clutter due to air entrained in rivers flowing over rapids/riffles together with reflection and clutter from uneven riverbeds may degrade the quality of the acoustic data, to such an extent that they become unreliable for small target detection (Kozak, 2006). It is possible, therefore, that animals may be masked by the acoustic clutter and it may be that such systems will be restricted to relatively deep sections of rivers. However, it's important to note that the spatial coverage provided varies across different sonar types as a result of the geometry of the sonar beam, therefore this, along with the range of the sonar and the width and depth of the river will determine how effectively sonar can monitor in any specific river environment.

4.3.2 Sonar seal detection at finfish farms

The work of Hastie et al. (2014; 2019a; 2019b) and Cotter and Polagye (2018; 2020) shows that high resolution imagery, and automatic detection and accurate classification of seal targets is possible with HF sonar. However, as described for video monitoring, the scale of finfish farm sites would present a major problem for monitoring by HF sonar, which is essentially provides a short-range detection system. The effective detection range will vary with conditions and with device, but if for illustration it is assumed to be 120 m (Hastie, 2012; Verfuss et al*.,* 2018), with a 120^{o} horizontal field of view, one sonar would cover approximately 200 m of the perimeter of a farm. An effective triggering system needs to detect a high proportion of seals that approach the cages, so most of the perimeter will need to be monitored. As the perimeter of each farm will several hundred metres, multiple systems would be needed to monitor the entire perimeter.

The choice of sonar in those studies was determined by a specific requirement for high resolution imagery and the need for it to be outside the hearing range of marine mammals, in particular harbour porpoises, to avoid influencing their behaviour in close proximity to the sonar. Such high-resolution imagery may not be needed for a simple seal detector and the problem of audibility at close range is not as important. It should therefore be possible to use lower frequency sonars which will potentially solve problems of limited range. Although the audibility and the potential for disturbance to cetacean species will still need to be considered.

Existing detection and tracking algorithms, developed for HF sonars (e.g., Hastie et al*.,* 2019; Cotter & Polagye, 2018; 2020) should be transferable to detection of seals in the vicinity of finfish cages using lower frequency systems. Although recent work by Cotter and Polagye (2020) suggests that detection and classification algorithms can produce different results for different frequency sonars and will therefore need to be modified for each system.

In practice the positioning of sonars at any farm site will be determined by the arrangement of cages and the environmental conditions (e.g. water depth) around the farm. Sonars would need to be sited to avoid shadows from fish, cages and other farm infrastructure, so the actual number required, and pattern of deployment required to provide complete coverage will vary between sites.

4.3.3 Fish counters

Fish counters are widely used to detect and count salmonids as they move through certain man-made constrictions or narrow sections of rivers on both upstream and downstream migrations. Designed to detect and count large fish, the same technologies could, with appropriate modification, have the potential to detect larger targets such as seals. Braun et al. (2016) provided a detailed description of the methodologies and an extensive literature review; briefly, there are four general types of fish counter suitable for detecting salmon and potentially pinnipeds:

- Hydro acoustic counters are essentially high resolution, short range sonar systems. They are usually classed as either multibeam or split beam devices.
    - Multibeam counters use beamforming to create a grid of up to several hundred echoes to generate high quality video-like images that can be analysed to detect and measure fish passing through the array. Several different multibeam counters are available, for example, Teledyne BlueView and Sound Metrics' DIDSON and ARIS are widely used.
    - Splitbeam echo-sounders transmit a short sound pulse and listen for the returning echo. The echo-sounder then magnifies and filters the returning echoes to produce an image. Several manufacturers produce split beam counters, for example, Simrad, HTI, and BioSonics.

- Resistivity counters detect changes in the bulk resistance of the water as fish swim across an array of electrodes. Resistivity counters can assess the passage time, the length of the signature as an estimate of size of the fish and the direction of passage. These devices are usually coupled with digital video for species identification. Two systems are currently available: Aquantic (Logie 2100C), and EA Technologies (Mark 12).

- Optical beam counters detect fish when they swim through an array of infrared beams and break the beams. The only commercially available optical beam counter appears to be Vaki's Riverwatcher, specifically developed for counting migratory fish.

- Video counters function by placing cameras in fish passes or other constrained channels.

The extensive literature on the effectiveness, accuracy and operational capabilities of the various systems was reviewed by Braun et al. (2016). Resistivity counters have been used in Scotland and North America since the 1970s and provide accurate estimates of fish passage rates (Dunkley & Shearer, 1982; McCubbing, Ward & Burroughs, 1999). Multibeam systems have also been widely used as research tools to estimate numbers and sizes of migrating salmonids (e.g., Boswell et al*.,* 2008; Burwen et al*.,* 2010; Cronkite et al*.,* 2008; Mueller et al*.,* 2010) and in some cases to identify and record the foraging behaviour of piscivorous birds (Burwen et al*.,* 2010). The Vaki optical beam counter has also been widely used and validated as a fish counter (Shardlow et al*.,* 2004; Baumgartner et al*.,* 2006). Vaki, DIDSON and resistivity counters have been cross calibrated and appear to produce generally similar results.

DIDSON and ARIS sonars (Soundmetrics) were found to produce consistent identification of fish and allowed accurate estimates of fish size (Clabburn et al*.,* 2019). The inclusion of extra low frequency beams in the ARIS allowed accurate size estimates at greater ranges (Clabburn et al*.,* 2019). Motion detection algorithms are widely used to identify fish, although this is usually achieved through post-processing of archived data. Detected targets are then usually confirmed visually and identified to species/species group.

The detection efficiency for fish targets that pass through the beam of DIDSON sonars is very high (Clabburn et al*.,* 2019), and where visual confirmation is possible detection rates approach 100%, even at high passage rates. Targets may be missed due to target leakage whereby they pass outside the monitored area. Leakage occurs where the cross-sectional river area to be monitored does not fit the beam pattern and may be high at times, particularly where river levels fluctuate widely (Clabburn et al*.,* 2019). Where such fluctuations are predictable, for example in the tidal reaches of rivers appropriate positioning of the sonar may avoid such problems. Seals are much larger targets than salmon, and dive with significant air spaces in their lungs. Target strength for a seal will therefore be higher than for a salmon, so detection probability will be at least as high for seals, but the same issues of coverage in relation to the cross-sectional area of the river will apply.

Systems such as DIDSON and ARIS are able to monitor fish, and therefore seal, presence in a wide range of river situations. However, providing complete coverage over an entire river channel may be challenging and reliant on careful site selection with consideration given to the behaviour of the target species at that location in a range of river levels. For some salmon stock assessments, sonars are used to sample the river channel rather than provide a complete census of fish passing a point. If sonar is to be used as a detector it will need sufficient detection range to achieve a complete census, i.e. it must be able to cover most of the river channel being monitored rather than merely sampling a portion of it.

Video systems are often used in conjunction with other fish counters to provide a visual record to confirm identification and/or measurement of any fish detected, e.g. the Vaki Riverwatcher installed on a fish pass on the Etterick Water, in the River Tweed catchment incorporates a light tunnel and video system (Tweed Foundation, 2018). This approach could also be useful for seal detection, particularly in early deployments as the detection ability of systems are evaluated.

As far as we are aware, other fish counter technologies have not been calibrated for, or tested with pinnipeds, but each of these systems has the potential to detect seals that pass through the sensor arrays. In order to function effectively, resistivity, optical beam, and video counters require that the targets are constrained to pass through a narrow, confined channel. They are therefore limited in their application, but with appropriate modification, positioning and testing they could be useful tools for detecting seals moving past particular points in a river.

4.3.4 Seal attack detection devices

An alternative method of detecting seal activity at finfish farms would be to detect some indicator of seals attacking the cages. A reliable detector would allow deterrence actions to be targeted when seals were actively involved in depredation.

A device designed to detect seal attacks 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 that was expected if a seal attempted to catch a fish through the net (Smith, 1994), but development of this device does not seem to have gone very far. In the early 1990s Ace Aquatec offered a simple net attack trigger, comprising a bell in a spherical housing that rang when the net was tugged, and triggered an ADD. There are no published data on the effectiveness of this method, but anecdotal reports suggest that it was prone to false triggering in response to wave motion.

Olesiuk et al. (2012), reported that the Airmar manufacturer explored the development of triggers activated by sonar or detection of predator vocalisations, but these were not successful. As grey and harbour seals rarely vocalise underwater, a vocalisation detector would not be a reliable trigger for use at finfish farms.

Ace Aquatec designed a system that was activated by the movement of fish in response to a seal attack (Ace-Hopkins, 2002). It was expected that when a seal approached the net the fish would become agitated and this movement would be detected when they collided with sensors placed inside the net. We are not aware of any independent assessment of the efficacy of these triggers, and anecdotal reports from site managers suggested that false detections were common. Northridge et al. (2010) reported that, among their interview sample, predator triggers had been tried at 27 sites in Scotland, but none of those interviewed had judged them to be successful.

4.3.5 Cetacean detection

Targeting ADD transmissions at times when seals are detected will dramatically reduce the number of transmission sequences. However, this would not preclude the possibility that cetaceans could be in the vicinity when transmissions start. The risk of disturbance and potentially injury could be eliminated if ADD transmissions were blocked whenever cetaceans were in the vicinity. This would require an effective method for detecting their presence. A cetacean detector could also be used to control the use of lower frequency sonar described in 4.3.2 to provide long range seal detection with minimal impact on small cetaceans. However, in areas with high cetacean abundance, ADDs may be prevented from emitting sounds for a significant proportion of time and would therefore be less effective as seal deterrents.

Over the past 20 years there has been a rapid development of passive acoustic detection methods for identifying and quantifying porpoise and dolphin acoustic activity (Thomsen et al*.,* 2005; MacAulay et al*.,* 2017). Archival data loggers such as C-PODS and SoundTraps have been used to monitor harbour porpoise activity in a wide range of environments, including in relation to acoustic disturbances such as ADDs and pile driving (e.g. Graham et al*.,* 2019). These devices do not currently provide automated, real time detection and triggering.

Real time passive acoustic monitoring (PAM) systems are reliant on hydrophones linked to computers running software such as the PAMGuard (Gillespie & Oswald, 2019), for the detection and classification of sounds. Some PAM equipment manufacturers have been developing real time PAM systems for mitigation that could be adapted for this application – a fully comprehensive review of these real time systems is beyond the scope of this review but examples include RTSYS[2], CAB[3], JASCO[4] and Seiche[5]. Gillespie et al*.* (2020) recently demonstrated the ability of an autonomous, real time PAM system to detect porpoises and dolphins around a tidal turbine in the Pentland Firth and it would be possible to adapt such an approach to the detection of echolocating cetaceans in the vicinity of a finfish farm as the basis of an automated detector and trigger system. In addition, automated systems for detecting baleen whale calls have recently been developed and tested (Baumgartner et al*.,* 2019).

[2] https://rtsys.eu/buoys
[3] http://www.smruconsulting.com/products-tools/cab/
[4] https://www.jasco.com/measurements
[5] https://www.seiche.com/underwater-acoustic-products/specialist-systems/wireless-pam/

4.4 Seal detection summary

The available information suggests that there are several potential seal detection systems that could be adapted and built into seal deterrence systems and thus provide the detect part of a detect and deter system for use in salmon rivers. Where a clear view of a sufficiently long stretch of river can be monitored, a CCTV system with night-vision or thermal imagery capabilities can be used to reliably record the presence of seals. Detection algorithms could be developed to provide an automatic detection function for such systems. Commercial systems being developed for use at finfish farms may be directly applicable or easily adapted for use in rivers, but as yet no proven system exists.

Several active sonar systems are available that can record the presence of seals. In these cases, algorithms have been developed for target characterisation that, with some modification/development should allow automatic detection of seals in rivers. To date, only one seems to have been tried and tested for that specific purpose; a sonar detector built by Smith-Root based on a DIDSON device. That system was tested once and does not appear to have been used since (Burger, 2010). Several other sonar systems have clear potential, after the development of specific target identification algorithms. By building on work already done to develop automatic detection systems at marine renewable energy sites (Hastie et al*.,* 2019) or at coastal bag-net fisheries (Conway et al*.,* in press) such systems should be adaptable for use as seal detectors in rivers.

5. Recommendations

The following section comprises brief descriptions of available methods that could prove useful as non-lethal measures to reduce seal predation on salmonids in rivers or at fish farms, and those that would benefit from further research or development to enable the implementation of more effective measures.

These recommendations are based on the reviews in Sections 2, 3 and 4, which should be referred to for additional background information and literature sources. As with the reviews, the difference in the available options and methods for rivers and finfish farms, in addition to differing research and development requirements mean that it is sensible to address the recommendations for each separately.

The measures detailed below address different aspects of the problems of seal predation in rivers and at finfish farms, and the choice of method for each site or predation scenario will depend on local conditions and available resources. They highlight the approaches likely to be most effective in different scenarios and outline recommendations for their development and implementation.

Table 1 provides a summary of the advantages and disadvantage of potential non-lethal measures in terms of their application to seal predation problems in rivers and at finfish farms.

Table 2 (at the end of Section 5) provides an overview of these non-lethal measures for preventing seal depredation in terms of system readiness, development work required, costs involved and legal and licencing considerations. A brief description of each approach is given below, and for convenience, aspects that require additional development are highlighted in the text.

Table 1. Summary of the advantages and disadvantages of non-lethal measures identified in the literature review for preventing seal depredation in river systems and at finfish farms

Non-lethal measure	Pros in rivers	Cons in rivers	Pros at finfish farms	Cons at finfish farms
Direct harassment	• Relatively low cost	• Limited evidence for effectiveness • Some methods may require licensing • Needs method to indicate presence of seals • Labour intensive-high man power costs • Potential effects on migrating salmon and other NTS	• Relatively low cost	• Limited evidence for effectiveness • Effects on Non-Target Species (NTS) • Some methods may require licensing • Needs method to indicate presence of seals • Labour intensive • Potential effects on NTS • Deliberate harassment of seals illegal at designated haulout sites
'Standard' ADDs	• Can be effective if a complete barrier can be achieved • Commercially available	• Equivocal evidence for effectiveness • Achieving total barrier coverage may not be likely in all circumstances • Maintenance required for effective operation • Effects on NTS in estuaries therefore raising licensing and mitigation considerations	• Industry familiarity • Commercially available	• Limited evidence for effectiveness • Maintenance required for effective operation • Effects on NTS therefore raising EPS licensing and mitigation considerations. • Habituation may occur
Tailored signal seal ADDs – startle technology	• Lower noise emissions • Sensitisation occurs so habituation unlikely	• Untested in rivers • Maintenance required for effective operation	• Lower potential for disturbance and injury impact on NTS	• Maintenance required for effective operation • No empirical data on of the potential for effects for some NTS

Non-lethal measure	Pros in rivers	Cons in rivers	Pros at finfish farms	Cons at finfish farms
	• Lower risk of effects on NTS cetacean in estuaries	• Potential for effects on NTS, therefore raising licensing considerations	• Sensitisation occurs so habituation unlikely • Commercially in use • Some empirical data that suggests an absence of effect on NTS (e.g., porpoises)	(therefore raising licensing considerations)
Tailored signal seal ADDs – low frequency	• Lower potential for impact on NTS • Commercially available	• Untested in rivers • No empirical data on lack of NTS effects - testing required • Maintenance required for effective operation • Licensing and mitigation considerations	• Lower potential for impact on some NTS • Commercially available	• Maintenance required for effective operation • No empirical data on lack of NTS effects - testing required • Potential licensing and mitigation considerations • Habituation may occur
Reduce ADD source level	• Lower potential for impact on NTS	• Reduced effect range • Maintenance required for effective operation • Licensing considerations	• Lower potential for impact on NTS	• Reduced effect range • Increased chance of habituation/toleration • Potential licensing and mitigation considerations.
ADD soft start/Ramp-up	• Lower potential for impact on NTS	• Reduced effect range • Increased chance of habituation/toleration • Maintenance required for effective operation • Licensing considerations	• Potential to reduce physical impacts on NTS	• Reduced effect range • Increased chance of habituation/toleration • Potential for impact on NTS therefore raising licensing considerations

Non-lethal measure	Pros in rivers	Cons in rivers	Pros at finfish farms	Cons at finfish farms
New net materials (e.g. HDPE)	• n/a	• n/a	• Highly resistant to seal attack • Potential to remove problem of depredation • No additional work involved	• More expensive than existing netting material • Evaluation of longevity required
Anti-predator nets	• n/a	• n/a	• Already used in Scotland • Insufficient data to assess effectiveness	• Potential problems of entanglement and drowning of seals • Potential problems of entanglement and drowning NTS including diving birds and cetaceans • Additional costs and maintenance and operation effort • May not be practical at high current sites
Bubble curtain around ADD	• n/a	• n/a	• Lower potential for both physical and behavioural impact on NTS	• Reduced effect range • Requires compressor • Technical and operational feasibility needs further R&D
Electric field barriers	• Evidence for potential effectiveness	• Potential effect on migrating salmon and other NTS • Unknown thresholds of response for food motivated seals	• Evidence for potential effectiveness of electrified netting • Commercial system available	• High energy demand/cost • Technical and operational feasibility needs further R&D

Non-lethal measure	Pros in rivers	Cons in rivers	Pros at finfish farms	Cons at finfish farms
		• Would need bespoke design and manufacture for each site • Potential for effects on NTS (raising licensing considerations) • Health and safety considerations		
Non-lethal removal: translocation	• Potential local reduction of predation	• Very difficult to catch seals in rivers – methods need development and test • Likely rapid return • Licensing considerations	• Potential local reduction of predation	• Very difficult to catch targeted individual seals • Likely rapid return • Licensing considerations
Non-lethal removal: temporary captivity	• Potential local reduction of predation • Opportunity to trial Condition Taste Aversion.	• Very difficult to catch seals in rivers • Licensing considerations • Significant investment and ongoing costs for captive seal facility	• Opportunity to trial Condition Taste Aversion.	• Very difficult to catch targeted individual seals • Licensing considerations • Significant investment and ongoing costs for captive seal facility
Conditioned taste aversion	• Potential local reduction of predation	• Difficult to target and catch ‘problem’ seals • Difficulties related to transfer of aversion from dead to live fish • Involves intensive captive trials • Licensing considerations for experimental captive trials	• Potential local avoidance of predation by naïve young seals	• Difficulties related to transfer of aversion from dead to live fish • Unlikely to work where predation already established • Involves intensive captive trials with wild seals • Licencing considerations for experimental captive trials

Non-lethal measure	Pros in rivers	Cons in rivers	Pros at finfish farms	Cons at finfish farms
Conditioned aversion – electric fish	• Used alongside suite of other measures may enhance overall effectiveness • Approach could be adapted to 'electrify' dead fish	• No evidence for effectiveness • Difficult to target 'problem' seals • Difficulties related to transfer of aversion from dead to live fish	• Used alongside suite of other measures may enhance overall effectiveness • Approach could be adapted to 'electrify' dead fish	• No evidence for effectiveness • Currently available model unlikely to be mistaken for a salmon • Difficulties related to transfer of aversion from dead to live fish
• **DETECTION SYSTEMS (for use in conjunction with the measures above, particularly to trigger deterrent and exclusion systems)**				
Detection – HF sonar	• Can be linked with a deterrent to improve effectiveness and reduce effects on NTS • Detection algorithms developed for seals	• Achieving full coverage across river channel may be difficult • Detection algorithms for seals need testing in river environment • Linked detect and deter system needs to be proven • Potential audibility of sonar to cetaceans if in estuary	• Can be linked with a deterrent to improve effectiveness and reduce potential effects on NTS • Detection algorithms developed for seals	• Only effective over short range - achieving full coverage around finfish farm may be difficult • Linked detect and deter system needs to be proven • Potential audibility of sonar to cetaceans therefore raising licensing considerations
Detection – LF or MF sonar	• Longer range detection • Can be linked with a deterrent to improve effectiveness and reduce effects on NTS • Potential transferability of detection algorithms	• Detection algorithms for seals require test and possible development • Linked detect and deter system needs to be proven • Potential audibility of sonar to cetaceans if used in estuary (licensing considerations)	• Longer range detection • Potential transferability of detection algorithms • Can be linked with a deterrent to improve effectiveness and reduce effects on NTS	• Detection algorithms for seals require test and possible development • Linked detect and deter system needs to be proven • Potential audibility of sonar to cetaceans (licensing considerations)

Non-lethal measure	Pros in rivers	Cons in rivers	Pros at finfish farms	Cons at finfish farms
Detection – fish counting sonar	• Dual functionality: seal detection and fish counting • Proven seal detection algorithms • Potential to be linked to deterrents	• Very short range: may require work to constrain river channel which may affect salmon migration or enhance predation opportunities		• Very limited range, not considered suitable for finfish farms
Detection – surface video	• Detection algorithms developed for seals • Infrared tested and can detect seals in darkness • Potential to be linked to deterrents	• Requires development to automate • Algorithms for infrared element require test and development to automate • Linked detect and deter system needs to be proven	• Detection algorithms developed for seals • Infrared tested and can detect seals in darkness • Potential to be linked to deterrents	• Requires development to automate • Algorithms for infrared element require test and development to automate • Linked detect and deter system needs to be proven • Will not detect seals approaching underwater

5.1 Salmon rivers

Seals enter the estuaries of salmon rivers in Scotland to forage and use haulout sites. Some of those seals forage for at least part of the year on migrating salmonids, and a small proportion (so-called 'specialist' or 'rogue' seals) move further up-stream where they can come into direct conflict with anglers and fisheries managers. In Scottish salmon rivers there is a clear need for the development of effective non-lethal management options in light of the impact on declining wild Atlantic salmon stocks (Butler et al., 2006) and to reduce the scale and economic costs of seal predation.

Salmon rivers in Scotland differ in terms of their physical characteristics, their geography, flow characteristics, the scale and timing of salmonid runs and the levels of seal activity. Added to that is the complexity of the management structure, with 41 separate District Salmon Fishery Boards each with its own management requirements, policies and resources. It is therefore not sensible or even possible to define a set of recommendations that will address the seal predation issues in all rivers, and bespoke solutions will be needed in many cases. However, the information below highlights the approaches likely to be most effective, with recommendations for their development and implementation.

The small number of seals involved in predation in rivers will limit the number of possible trials for all of the deterrence measures described below. Any deployment or test of a method should be used as an opportunity to monitor the effects on both target and non-target species, to build up a body of information to assess the efficacy of such systems under different operating conditions and locations.

5.1.1 Barriers to seal passage

The most effective solution would be to prevent seals from entering rivers and/or prevent them travelling upriver to predation hotspots. This can only be achieved by establishing some form of barrier. Options outlined in Section 2 include acoustic deterrent barriers, pulsed electric field barriers and physical barriers. At present none of these methods are widely used in Scottish salmon rivers, although a selection have been trialled in some rivers.

5.1.1.1 Acoustic deterrent device barriers in rivers

An effective acoustic barrier (Section 2.2.3) could prevent seals moving upriver and could potentially remove the threat of predation in some Scottish salmon rivers. They may also be the only potential solution for preventing seals moving through salt or brackish tidal waters where electric barriers would be ineffective.

The method has been field tested and although initial results were equivocal, more recent results suggest that effective acoustic barriers could be built using available ADDs. However, additional work may be required to address remaining knowledge gaps including:

- Further targeted behavioural response trials to assess their effectiveness at deterring grey and harbour seals and if possible, to assess which aspects of the positioning, duty cycling, and signal characteristics would produce the most effective barriers and minimise the likelihood of habituation.
- Targeted behavioural response trials to assess effects on behaviour of otters and beavers (both EPS), and aquatic birds in Scottish salmon rivers.
- Efficiency will be increased and impacts on NTS reduced if ADD transmissions are controlled by an automated seal detection and triggering system. Detection systems are addressed in Section 5.1.2.

5.1.1.2 Pulsed electric field barriers in rivers

An effective electric barrier could prevent seals accessing foraging sites in freshwater sections of Scottish salmon rivers. Electric field barriers have been tested successfully with captive harbour seals and sea lions, but with limited success with wild harbour seals in a salmon river. Additional work may be required to address remaining knowledge gaps including:

- Targeted behavioural response trials with captive and wild fish to assess the response thresholds of Atlantic salmon and sea trout.
- Further targeted behavioural response trials with captive and wild seals to assess the avoidance thresholds for both grey and harbour seals that are motivated to pass a barrier to access prey.
- Targeted behavioural response trials to assess effects on behaviour of otters, beavers and aquatic birds in Scottish salmon rivers.
- A design/development study by a team of engineers and biologists to optimise an effective array structure that maximises the impacts on larger animals such as seals, relative to smaller animals such as salmonids.
- Operational costs relating to power usage, and also potential impacts on NTS, would be reduced if an electric barrier is controlled by an automated seal detection and triggering system. Detection systems are addressed in Section 5.1.2.

5.1.1.3 Physical barriers

In some circumstances, either temporary or permanent physical barriers may be the best option. Development work will be required in each case including:

- An in-depth analysis of the topography and flow characteristics of the river at the proposed sites, and the requirements of other river users to identify appropriate designs for either temporary or permanent barriers.
- Additional work, including in-situ monitoring to assess the behavioural responses of migrating salmon to the presence of any such barriers.

5.1.2 Detection of seals in rivers

The most straightforward method for detecting seals is through reports of visual observations from dedicated observers, river users and members of the public. Such observations should be coordinated e.g. by use of automated reporting schemes (such as the app-based Survey123 reporting scheme developed for the Dee Salmon Fishery Board). However, these methods would only detect a subset of seals swimming up rivers, and detection may be biased to certain conditions.

Automated detection of seals would allow active control measures to be more efficiently targeted and applied only when seals are present. Two technological solutions have the potential to provide effective seal detection in salmon rivers.

5.1.2.1 Sonar detection

Marine mammal detection systems based on high frequency sonars which incorporate algorithms for detecting and differentiating between inanimate objects, fish, and marine mammals have been tested.

Sonar systems capable of acting as seal detectors are widely available, although the specific sonar chosen for any site will depend on the site characteristics. Developing effective, field deployable sonar detectors will require:

- A detailed review of the characteristics of each site to determine the best option in terms of the sonar type, e.g., frequency, beam pattern and coverage, power output, number of sensors etc.
- A protocol for identifying/prioritising locations where such a system would be cost and resource efficient.
- Development and implementation of detection algorithms with the chosen sonars, based on existing algorithms for detecting and classifying seal targets.
- Field testing in situations where detection efficiency and number of false triggers (both positive and negative) can be accurately assessed.
- Assessment of potential impacts on NTS, e.g. small cetaceans in estuaries and otters and beavers upstream, with targeted behavioural response studies where appropriate.

5.1.2.2 Video detection

To date, no fully automated marine mammal video detection systems have been demonstrated. Two systems are currently being developed, but additional work will be required to produce field deployable detectors in rivers. This will include:

- Independent testing of the thermal and video camera system being developed by Ace Aquatec for deployment at finfish farms, to assess its effectiveness and suitability for use in rivers.
- Modification and further development of automated detection and identification algorithms for use with the infrared illuminated CCTV system being tested on the River Dee.
- Testing of detect and track systems for high resolution video, being developed for search and rescue, to assess their effectiveness in detecting and identifying swimming seals.

5.1.3 Direct harassment methods to disrupt predation events.

Various simple, low tech harassment methods have been used to disrupt predation and, where possible, to drive seals away from predation sites. In general, harassment efforts produce short-term reductions in predation at specific locations and times but have not eliminated seal or sea lion predation in the large US salmon rivers, where they have been applied intensively for several years.

In most cases in Scottish rivers, small numbers or even individual seals preying on salmonids could have a significant effect on the salmon run (Butler et al., 2006). Therefore, even a temporary disruption of foraging for those seals could represent a significant reduction in the scale of the predation problem in those rivers. To date, few of these methods have been tested rigorously and there is a clear lack of relevant data on the effects of direct harassment methods on grey and harbour seals. If any of these harassment methods are proposed for use in Scottish rivers, additional work will be required including:

- Testing harassment methods, either singly or as part of integrated studies to quantify their effects on grey and harbour seals in Scottish salmon rivers. A relatively simple observation and/or seal telemetry study will be needed to determine how seals react, how far they move in response to such deliberate disturbances and how long any deterrent effects last.
- Assessing the effects of harassment methods, particularly the use of underwater pyrotechnics, on behaviour of Atlantic salmon and sea trout. A series of targeted behavioural response studies would be needed to identify and quantify responses.

- Assessment of potential impacts on NTS, e.g. otters, beavers and aquatic birds, using targeted behavioural response studies where appropriate.

5.1.4 Physical (non-lethal) removal methods

If neither physical barrier nor direct harassment methods are effective or appropriate at a site, an alternative non-lethal solution may be to remove the problem seals from the predation sites. If the capture of the problem seal(s) were deemed feasible (see section 5.1.5), there are two potential approaches; translocation and temporary captivity. Both of these would require a licence from Marine Scotland, as well as a licence from NatureScot if proposed within an SAC.

5.1.4.1 Non-lethal removal - Translocation

One solution could be to translocate problem seals and release them at a site remote from the river of capture. Although translocation is unlikely to provide a long-term solution to predation problems in rivers, the act of removing a problem seal from a salmon river could provide at least temporary relief until that seal either returned or was replaced by another. If translocation is proposed for use in Scottish rivers, additional work will be required including:

- Assessing the effectiveness of moving a seal. Any translocated seals should be fitted with high resolution telemetry tracking devices, to monitor their behaviour after release. This would identify whether the seal returns to the capture site and if so, how quickly, and if it does not return, whether it changes foraging tactics or transfers to another salmon river closer to the release site.

5.1.4.2 Non-lethal removal - Temporary captivity

An alternative to translocation could be to catch problem seals and hold them in temporary captivity, similar to current management actions for fur seals caught at salmon farms in Tasmania. Captivity could be either short-term to avoid specific times of intense predation, or long-term for seals known to be persistent salmon predators in rivers.

Existing seal holding facilities in the UK are either rehabilitation centres or public display sites, so a dedicated facility would be required to temporarily hold seals for fisheries management. Considerations include:

- If a programme of temporary captivity is proposed, an in-depth study of the available options should be carried out and discussions with animal welfare groups, finfish farming organisations and relevant local and national government departments should be established.
- Constructing a holding facility would require substantial investment in pool facilities, and other infrastructure.

- A lower cost alternative would be to convert a finfish farm cage to act as a seal holding pool. Disused salmon cages have been used to temporarily house fur seals caught at salmon farms in Tasmania and to hold adult harp seals (*Pagophilus groenlandicus*) in Norway. A 30 m diameter circular pen has more than 5 times the minimum surface area and 40 times the minimum volume of the pool size recommended for housing up to six grey seals (EAZA, 2018).

5.1.5 Catching seals in rivers

Any seal removal programmes in rivers will require methods to rapidly catch seals as soon as possible after they are detected. Unfortunately, successful techniques developed for catching grey and harbour seals at coastal haulout locations are not generally applicable for catching free swimming seals in large, fast flowing rivers such as the River Dee.

Currently there are no standard, reliable methods for routinely catching seals in rivers. Several potential methods have been identified but additional work will be required to assess their effectiveness in rivers (Harris & Northridge, 2018a). Some of these capture methods have been attempted but with limited success. Problems associated with handling long nets and operating large traps in flowing rivers are hard to predict and will only be identified and overcome with extended practice. Additional work will therefore be required to develop a suite of effective methods including further development and testing of one or more of the following:

- Using a baited, floating cage trap.
- Active netting at in-river haulout sites using remotely triggered pop-up nets.
- Simple tangle netting where knowledge of an individual seal's behaviour identifies suitable sites.
- Active sweep netting and/or tangle netting at sites where seals are detected in deep, slow flowing sections of rivers.
- Development and construction of temporary, partial or full width river barriers (using a net or weir structure) to guide seals into a narrow channel(s) where they can be caught or trapped using the methods above.

5.1.6 Summary of recommendations for salmon rivers

Below is a summary of recommendations for development and testing of non-lethal methods for reducing seal depredation in salmon rivers. A more detailed overview of development requirements and additional considerations is provided in Table 2.

Seal detection in rivers

- Development and use of automated reporting apps for river users.
- Site specific evaluation and design of High Frequency sonar deployment – matching river geography/topography with sonar characteristics.
- Testing of commercially available video systems, including high resolution video methods being developed for search and rescue applications.
- Development and testing of efficacy of detection algorithms (sonar and video).

Acoustic barriers

- Testing of effectiveness and optimising positioning, duty cycling and signal characteristics.
- Targeted behavioural response trials to evaluate effects on non-target species such as otters, beavers and birds.
- Development and testing of an automated seal detection and triggering system (see below).

Electric barriers

- Captive trials to determine behavioural response thresholds of salmon and trout.
- Captive trials to determine avoidance thresholds for grey and harbour seals motivated to access prey.
- Desk-based modelling study to optimise array structure to maximise effect on larger animals such as seals relative to smaller NTS.

Physical barriers

- Site specific evaluation and design incorporating topography, flow characteristics and requirements other river users.
- Assessment of the effect of physical barriers on migrating salmonids.

Harassment

- Testing of methods to evaluate and determine effectiveness.
- Assessment of the effect of harassment methods on salmonid behaviour as well as on other NTS such as otters, beavers and birds.

Translocation of problem seals

- Assessment of the effectiveness of translocation – telemetry study to monitor post release behaviour of translocated seal(s).
- Development and testing of effective methods for capture of seals in rivers.
- Evaluation of options for temporary captivity.

5.2 Finfish farms

At Scottish finfish farms several non-lethal measures have already been identified and are currently being employed to reduce the effects of seal depredation. For example, seal blinds are used on most finfish farms in Scotland and operational measures such as maintaining correct net tension and husbandry practices such as frequent removal of dead fish are all widely practiced at Scottish finfish farms and are thought to reduce incidences of depredation. In addition to these husbandry practices, there have been developments in netting material that have the potential to reduce seal depredation, and these are discussed briefly in Section 5.2.1.

Clearly, improvements to cages and operational practices that reduce the ability of seals to gain access to farmed fish must be the first line of defence against seal depredation. However, in some circumstances these may not be available in the short term, may not be sufficient to prevent depredation or will not address the issue of potential stress effects induced by the presence of seals in the vicinity of cages. Additional or potentially alternative methods to reduce seal depredation at finfish farms in Scotland are discussed in Sections 5.2.2 to 5.2.6.

5.2.1 New net materials and anti-predator nets

The use of new, stronger and more rigid HDPE net materials has been widely accepted by the industry. However, the evidence base for their effectiveness is still inadequate, and while there is anecdotal evidence that some types of net are highly resistant to seal attacks, there is insufficient evidence to allow quantitative assessment of their effectiveness. However, the use of anti-predator nets is reported to be increasing in Scotland (Marine Scotland, 2020b), but this is likely to be attributable to new net materials being mislabelled as anti-predator nets. It is important to maintain a distinction between the two so that their efficacy can be assessed.

Incidents of seal entanglement and drowning have, in the past, been reported and given as reasons for not using APNs when applying for licences to shoot seals, but again there are anecdotal reports that entanglement problems have recently decreased. The apparently wider use of APNs in aquaculture industries in other countries suggests that problems with entanglement of animals may have been overcome or that conditions in those overseas industries are somehow different to the Scottish conditions in a way which allows the effective use of APNs (e.g. lower rates of tidal flow or different sensitivity to risk of entanglement).

Understanding and potentially improving the effectiveness of both new netting materials and APNs will require additional work including:

- Collection and analysis of detailed seal damage statistics for cages with existing and new netting materials and cages with and without APNs, over several production cycles.
- Identification of measures employed in the use of both new net materials and APNs at finfish farms in other countries that may be applicable/transferable to finfish farms in Scotland.

5.2.2 Reducing the impact of ADDs

The second line of defence against depredation by seals at Scottish finfish farms is the use of ADDs. However, there is significant uncertainty about the efficacy of ADDs in protecting finfish farms from depredation by seals, as well as clear and well-found concerns over the potential effects of ADD signals on non-target species, particularly cetaceans. A better understanding of ADD efficacy and the operational and environmental factors that influence their effectiveness is required. Coram et al., (in prep) describe research recommendations for investigating the extent and patterns of ADD use in Scotland, as well as the impacts on non-target species and the efficacy of ADDs. These will not be described further here, but rather measures that could be taken to reduce the potential adverse effects on non-target species will be described.

There are four potential approaches to reducing the impact of ADDs on non-target species, all of which have the effect of reducing the overall acoustic energy output by the ADDs and/or targeting transmissions to reduce the probability of injury to non-target species.

5.2.2.1 Soft start/ramping up signals/reducing amplitude

Reducing the disturbance effects of ADDs on non-target species requires some combination of a reduction in the range at which the animals detect and react to the signals, a reduction in the proportion of time for which those signals are transmitted and an increase in the duration of undisturbed periods between transmission sequences. Reducing the potential for hearing damage in non-target species requires a reduction in the total sound energy output from ADDs and a reduced probability that a non-target species will be close to the ADD at the time of transmission.

Three simple alterations to ADD transmission schedules could be used to reduce the total energy output:

- Reducing the source level of the ADD signal will reduce sound exposure for any animal within detection range. A 6 dB reduction in source level will approximately halve the range for a given received level and should therefore reduce the range at which a non-target species will be likely to react.

- Reducing the duty cycle will reduce the total sound energy input to the environment and reduce the cumulative sound exposure of both target and non-target animals.
- Gradually ramping up the signal strength to move non-target species away from the device before full power operation, as recommended by Taylor et al. (1997), may reduce the likelihood of damaging hearing in cetaceans and seals in situations where they can move away from the sound source.

Most commercially available ADDs have some combination of user-controlled duty cycles, power outputs and soft-start sequences, so reducing amplitude and duty cycle should not require significant development. However, reducing the effect range for non-target species will also likely reduce the effect range for the target seals. It is currently not possible to predict the scale of such effects not least because there is no clear estimate of the effectiveness of existing ADD operations.

All three methods would reduce the potential for hearing damage to non-target species, but reduced duty cycle and soft-start will not necessarily reduce the extent or duration of disturbance of non-target species. Understanding the effects of such changes in terms of deterrence of seals and benefits to non-target species will require work including:

- A set of controlled field trials to assess the effectiveness of ADDs with reduced amplitude and duty cycle, compared to full volume, maximum duty cycle operations. These should be designed to assess the responses of seals and/or monitor the number and duration of seal visits and frequency of attack. Controlled experiments would be most effective, but useful information could be obtained by carefully structured monitoring programmes during their use in normal commercial farm operation.
- A set of controlled field trials to assess the behavioural responses of non-target species, in particular cetaceans, to different types of ADDs.

5.2.2.2 Seal specific acoustic deterrents at finfish farms

An alternative or complementary approach is to apply specifically tailored signals, designed to deter seals and not to impact on the behaviour of non-target species. While such devices are currently commercially available for deployment at finfish farms, there are some key knowledge gaps which are considered below.

Published, peer reviewed studies of the effectiveness of these devices at finfish farms and associated effects on non-target species are only available for one of the systems (see Section 3.1.5). Therefore, a key recommendation would be:

- Additional testing of some or all of these devices in a series of field trials at finfish farms should be carried out to provide comparable quantitative information on their effectiveness in deterring seal depredation and level of impact on non-target species.

5.2.2.3 Using marine mammal detection systems to control ADD use

At present, ADDs are either set to transmit continuously or are manually switched on when seal predation is observed or when operators suspect that seal predation is likely. As a result, ADDs may operate for long uninterrupted periods and any disturbance effects on non-target species will also be experienced for long periods. If ADDs were triggered only when seals were either in the vicinity of or actively attacking a finfish farm and switched off as soon as the seal had left, the number and duration of transmission sequences would be reduced and importantly, the intervening quiet periods would be much longer. Responsive ADD use should be more effective, the deterrence effects would be more likely to be associated with the act of approaching a finfish farm, and habituation to the signals should be less likely.

Triggering ADD transmission based on seal presence or detection of predation attempts will require the development of efficient seal detectors. The review in Section 4 indicates that there are two potential automated seal detection methods: 1) development of an active sonar detector and 2) a combined video and infrared detector.

5.2.2.4 Sonar detection

High frequency sonar systems and seal detection algorithms initially developed for detecting and tracking marine mammals in the vicinity of tidal turbines could be used for detection of seals in the vicinity of salmon cages. However, the scale of finfish farm sites presents a major problem for monitoring by HF sonar which is essentially a short-range detection method.

The short range is mainly a consequence of the use of HF sonar, chosen to provide high resolution imagery and also to ensure that sound emissions were outside the sensitive hearing ranges of seals. This is not an issue for a seal detector at a fish farm, so a lower frequency device with longer range may be useable in that situation. However, lower frequencies that are audible to small cetaceans may themselves pose a problem of disturbance. Hastie (2012) predicted that harbour porpoises would show behavioural responses at ranges in excess of 2 km to a sonar that had significant source levels of between 130 and 170 dB re 1 μPa @ 1 m at frequencies between 30 kHz and 110 kHz. We therefore recommend:

- A development programme to evaluate and test lower frequency, longer range sonar systems will be needed to assess the feasibility of such a detection system. This requires the development of automatic seal detection algorithms or adaptation of existing automatic detection and target classification algorithms. The effects of such systems on non-target cetacean species should also be investigated.

5.2.2.5 Video-infrared detection

This is an active and rapidly developing field and there are several potentially useful, ongoing projects that may help develop seal detection systems for finfish farms:

- A video-infrared camera system with automatic seal identification and tracking is being developed in Scotland as part of an integrated seal deterrence system (Ace Aquatec). The system, which is due for deployment in the near future, should be independently tested to assess its effectiveness in detecting seals and if possible, cetaceans.
- Ongoing development of detect and track systems for high resolution video, being developed for search and rescue, should be tested to assess their effectiveness in long range detection and identification of swimming seals and cetaceans.

5.2.2.6 Cetacean detection to control ADDs at finfish farms

Targeting ADD transmissions only when seals are detected will dramatically reduce the number of transmission sequences. However, it is still possible that cetaceans could be in the vicinity when transmissions start. The risk of disturbance and potentially injury could be eliminated if ADD transmissions were blocked whenever cetaceans were in the vicinity. This would require an effective method for detecting their presence. Several automated real time PAM systems are under development and could potentially be modified for use at finfish farms. This would require:

- A feasibility study of the practicality of applying a real time PAM cetacean detection system at finfish farms.
- Field trials to test the effectiveness of automatic detection and identification in noisy environments such as finfish farms.

5.2.3 Attenuating ADD signals

In addition to measures designed to minimise ADD noise output or to tailor signals to avoid disturbance to non-target species, it may be possible to further reduce the risk of hearing damage and the potential for behavioural disturbance to non-target species by attenuating ADD signals. Two possible measures with the potential to reduce transmission of ADD noise to the wider environment but maintain high signal levels within the perimeter of a finfish farm are available; namely the use of small scale bubble curtains or the use of acoustic baffles on strategically positioned ADD transducers. Neither method has been tried or tested and further development and testing would be required, including:

- A preliminary series of trials with a bubble curtain could be carried at farm sites that already operate aeration systems and ADDs, to determine the level of signal attenuation achievable in a realistic finfish farm situation. If successful, this would lead on to a development project to produce a practical ADD attenuation system. Initial designs could use commercially available air bubble tubing and the compressor and control systems currently used to generate bubble curtains to protect Canadian finfish farms from algal blooms.
- A preliminary acoustic modelling study to assess the feasibility of using baffled ADDs to provide a localised sound field at finfish farms sites. If that study confirms feasibility, it should lead to a design project to develop the optimum baffle design and placement to optimize the effectiveness of the ADD sound field and minimise wider transmission.

5.2.4 Conditioned aversion

If neither improved cage security nor the use of ADDs with appropriate signal conditioning and / or duty cycle reduction are appropriate, a number of alternative techniques/methods are available that may reduce the incentive for seals to attack finfish farms. These are generally referred to as aversion therapies and rely on the predator associating an unpleasant stimulus with the action of attacking or eating fish at a finfish farm.

5.2.4.1 Conditioned taste aversion at finfish farms

Conditioned taste aversion (CTA) has been widely used in the management of predation on domestic livestock by terrestrial predators and has been shown to be effective in causing aversion to particular prey in captive California sea lions. It may therefore be possible to develop CTA to farmed fish in individual grey and harbour seals. However, no formal CTA trials have been carried out to date and additional work would be required to develop CTA into a practical method for preventing seal depredation. This would include:

- A series of laboratory-based feeding trials will be needed to establish the effectiveness of the method in grey and harbour seals, to determine the optimum dose and presentation methods, and to assess the longevity of the aversion.
- A programme of field trials at finfish farms in Scotland would be needed, including detailed monitoring of seal activity to assess the effectiveness of CTA as a management tool. This would entail careful development of protocols for presentation of laced baits which ensure that seals associate the CTA with predation on farmed fish.

5.2.4.2 Conditioned aversion - electric fish

Electric shock conditioning has been widely used to reduce unwanted behaviours in both domestic and wild animals by delivering an unpleasant but harmless electric shock when the animal makes contact with, or come very close to, an electrified bait. If a conditioning shock can be applied in such a way that seals associate them with the action of handling and eating farmed fish it may be possible to establish an aversion to that activity. One system (Ace Aquatec's Electric Fish) designed to mimic a dead salmon has been used in finfish farms in Scotland.

Careful consideration of the placement of the electrified fish will be critical to ensure that seals do not associate the stimulus with an unusual and therefore identifiable object. It is also important that seals cannot detect the presence of an electric shock device before trying to handle fish. If they can detect the electric field as they approach, it is likely they will associate that with the shock and the aversion will be less likely to be transferred to other finfish farm cages where there is no apparent electric field.

A realistic assessment of the effectiveness of this system is needed, which will require additional work including:

- A series of controlled trials to assess the effectiveness of the electric fish in deterring depredation, and to determine the duration and specificity of any aversive response, e.g. to determine whether individuals are deterred from attacking salmon only in cages that have held electric fish, or are deterred from attacking cages or farms where they have not experienced the deterrent.
- Further, developing a triggering mechanism to switch the electric field on only when the fish is being handled in order to remove the problem of detectability and increase the likelihood that seals would associate the shock with handling farmed fish.

5.2.5 Non-lethal removal of seals from fish farm cages

Seals occasionally manage to enter fish cages at finfish farms but are sometimes unable then to escape. Maintenance of seal proof cage nets, perimeter fences and potential methods such as electrified deck deterrents should be used where appropriate to minimize the likelihood of seals gaining access.

A seal in a fish farm cage is likely to damage large numbers of salmon and will cause severe stress to the surviving fish. It is therefore essential to remove it as quickly as possible. At present there are no established non-lethal measures to remove seals from fish farm cages.

A safe method for rapidly removing seals is needed on both fish farm management and animal welfare grounds. Two methods are proposed here as possible solutions.

However, these have not been tested and will require further development to assess their feasibility and practicability:

- Floating deck to cause the seal to haul out. This would involve progressively covering the surface of the cage to make a floating deck, until only a small area of open water is available for the seal to surface and breathe. This could be achieved using plastic floating modular deck blocks; covering a 30 m diameter cage with 1 m^2 blocks would require approximately 750 blocks.
- Fine mesh net trap. Employing a similar principle but using a small mesh net to cover the pool, it may be possible to constrain the seal to breathe in a small (e.g. 1.5 m diameter) breathing hole. The net would need to then be submerged to a depth of approximately 2 m. Access to the surface would be maintained through a closable, detachable net tunnel similar to that for the floating deck method.
- A simple trap mechanism can be incorporated in either method to prevent the seal diving and force it out of the water after a breathing bout, such as a net tunnel giving access to the surface that can be closed off to prevent the seal from diving. The tunnel can then be detached and man-handled to an escape point, where the seal can be released or removed to another location.

There may be alternative methods of capture and anaesthesia developed for other species, and different potential methods for trapping and handling seals within cages as well as potential methods for providing escape routes for seals that prevent fish escapes.

- A recommended first step would be to bring together veterinary experts and fish farm operators with experience of dealing with grey and harbour seals and other species such as sea lions and fur seals in cages. A workshop would be an efficient way to identify and assess the feasibility of these options.

5.2.6 Summary of recommendations for finfish farms

This section provides a summary of the recommendations for development and testing of non-lethal methods for reducing seal depredation at finfish farms. Measures/recommendations are listed in order of priority/potential usefulness. A more detailed overview of development requirements and additional considerations is provided in Table 2.

Use of anti-predator nets (APNs) and/or new netting materials
• Collection of data on the use of APNs and new net materials in Scottish aquaculture and on the corresponding levels of seal depredation recorded over several production cycles. • Collection of data on the use of APNs and new net materials in other countries.
Development of ADDs to reduce impact on non-target species (NTS)

- Simple alterations to ADD output: reduced amplitude, reduced duty cycle and incorporating ramp up – trials required to establish efficacy and demonstrate lack of effect on NTS.
- Development of ADDs specifically tailored to only affect seals: trials required to establish efficacy and demonstrate lack of effect on NTS (some evidence exists for some devices).
- Development of automated seal and cetacean detection and associated triggering methods (see below).
- Attenuation of ADDs using bubble curtains: trials to establish efficacy and demonstrate lack of effect on NTS.

Seal and cetacean detection

- Evaluation and testing of long range, low frequency sonar for seal and cetacean detection, including development and testing of detection and classification algorithms building on work for other applications – used alone, sonar would need to differentiate between seals and cetaceans.
- Evaluation and assessment of potential behavioural effect of sonar systems on NTS.
- Evaluation and assessment of effectiveness of commercially available video detection methods.
- Evaluation and development of existing prototype CCTV/infrared systems (being tested in rivers) for finfish farm application.
- Building on currently available technology, development of automated real-time acoustic detection of cetaceans – requires in-situ development and testing of detection and classification algorithms.

Conditioned taste aversion

- Captive trials to establish effectiveness and longevity of conditioning, then if results are promising, field trials to assess effectiveness as a management tool.

Electric fish aversion

- Captive trials to establish effectiveness and longevity of conditioning, then if results are promising, field trials to assess effectiveness as a management tool.
- Development of trigger mechanism to switch on field when handled to remove detectability prior to handling.

Non-lethal removal of seals from salmon cages

- Workshop to bring together fish farm operators and seal handling experts. Requires test and development to assess feasibility, practicality and effectiveness.

Table 2. Non-lethal measures for reducing seal depredation – summary of system readiness, development requirements, estimated costs and potential legal and licencing considerations

Non-lethal methods for reducing seal depredation	**System readiness**	**Development/research requirements**	**Estimated Costs**	**Effects on Non-Target Species (NTS) and Regulation**
Direct harassment: (in rivers)	• A wide range of acoustic, visual, and tactile harassment methods are readily available, widely used and in some instances tested. • Limited evidence of short- or medium-term effectiveness. Testing has been sporadic. • Most methods may require effective seal detection systems (see below).	• Requires trials to assess effectiveness on grey and harbour seals in Scottish rivers. • Requires trials to assess impacts on salmonids. • Requires trials to assess impacts on non-target species, particularly EPS.	• Relatively low capital and operating cost. • But labour intensive and therefore expensive in terms of resources (e.g., staff).	• Some methods may require licensing (e.g., EPS and licences to disturb Schedule 1 birds). • It is illegal to deliberately injure seals. • Potential effects on migrating salmon. • Most projectile methods would not be acceptable in UK (as targeting the head would likely injure the seal).
Direct harassment: (at finfish farms)	• Not generally applicable.	• N/A	• N/A	• N/A
'Standard' ADDs as acoustic barriers: (in rivers)	• Wide range of commercially available devices. • Equivocal evidence for effectiveness, but potential solution for some rivers.	• Requires additional testing of ADD barriers to prevent movement upriver and methods for driving seals down-river. • Requires assessment of long term effectiveness. • Requires trials to assess impacts on non-target species, particularly EPS. • May require an effective seal detection system.	• Wide range of available devices: prices range from approximately £6000 upwards. • Some devices currently only available as rental packages. • Maintenance required for effective operation thereby requiring staff resources.	• Potential effects on non-target species therefore may require licensing (e.g., EPS) and mitigation. • EPS licence may be required for research purposes.
'Standard' ADDs: (at finfish farms)	• Widely used at Scottish finfish farms.	• Requires some combination of methods for reducing source	• Wide range of available devices: prices range from	• Evidence for effects on non-target species, including

Non-lethal methods for reducing seal depredation	System readiness	Development/research requirements	Estimated Costs	Effects on Non-Target Species (NTS) and Regulation
	• Wide range of commercially available devices. • Equivocal evidence for effectiveness. • Evidence for negative impacts on non-target species.	levels, soft start, signal attenuation and triggered transmissions (see below). • May require effective seal detection systems (see below). • May require effective cetacean detection systems (see below).	approximately £6000 upwards. • Some devices currently only available as rental packages. • Maintenance for effective operation, requiring staff time. • Costs of linked detector system unknown.	harbour porpoises, bottlenose dolphins and minke whales therefore EPS licences and mitigation required.
Tailored signal seal ADDs – startle technology- (in rivers)	• System commercially available.	• Requires testing of tailored seal ADD barrier effectiveness in: ○ preventing seal movement upriver, ○ driving seals down-river, ○ Assess habituation and long-term effectiveness. • May require effective seal detection (see below).	• Systems available as part of rental packages tailored for each situation. • Maintenance required for effective operation requiring staff time. • Costs of linked detector system (where required) unknown.	• Potential effects on non-target species such as European otters and Eurasian beavers, therefore EPS licences and mitigation required. • EPS licence may be required for research.
Tailored signal seal ADDs – startle technology- (at finfish farms)	• System commercially available.	• Requires additional testing on non-target species. • May require effective seal detection (see below). • May require effective cetacean detection (see below).	• Systems available as part of rental packages tailored for each situation. • Maintenance required for effective operation. • Costs of linked detector system (where required) unknown.	• No empirical data on lack of effects for some non-target species, therefore may require an EPS licence. • EPS licence may be required for research.
Tailored signal seal ADDs – low frequency- (**at finfish farms**)	• Commercially available.	• Requires testing for effectiveness on target species. • Requires testing to assess potential effects on non-target	• Systems available as part of rental packages tailored for each situation.	• May impact low frequency cetaceans therefore may require an EPS licence. • EPS licence may be required for any research.

Non-lethal methods for reducing seal depredation	System readiness	Development/research requirements	Estimated Costs	Effects on Non-Target Species (NTS) and Regulation
		species particularly low frequency cetaceans e.g. minke whales. • May require effective seal detection (see below). • May require effective cetacean detection in estuaries (see below).	• Maintenance required for effective operation requiring staff time. • Costs of linked detector system (where required) unknown.	
Reduce ADD source level (at finfish farms)	• Already incorporated in some ADDs. • Relatively easy to implement in other devices.	• Requires targeted studies to assess effectiveness of reduced amplitude signals as seal deterrents, e.g. o to assess any reduced effect range; o to investigate whether there is an increased chance of habituation or toleration.	• No additional cost if using an existing ADDs.	• May impact low frequency cetaceans so may require an EPS licence. • EPS licence may be required for any research.
ADD soft start/Ramp-up (at finfish farms)	• Already incorporated in some ADDs. • Relatively easy to implement in other devices.	• Requires trials to assess the chances of habituation by seals. • Requires trails to assess the responses of non-target species to soft start, to assess actual/realised benefits.	• No additional cost if using existing ADDs.	• May impact low frequency cetaceans so may require an EPS licence. • EPS licence may be required for any research.
ADD signal attenuation, bubble curtains and baffling ADDs (at finfish farms)	• System tested and shown effective in protecting porpoises from piling noise. • Systems used to protect finfish farms from algal blooms in Canada could be	• Requires assessment of the technical and operational feasibility of air bubble curtains at finfish farms. • Requires trials of bubble curtains at operational finfish	• Bubble tubing to surround a typical 12 cage farm. would cost approximately £110,000. • In collaboration with finfish farm, initial trials could use	• Signals likely to fall below the sound threshold of regulatory requirements.

Non-lethal methods for reducing seal depredation	System readiness	Development/research requirements	Estimated Costs	Effects on Non-Target Species (NTS) and Regulation
	effective as acoustic screens. • Bubble tubing commercially available and compressors already widely used on Scottish finfish farms. • Simple structures using foam screens as baffles around ADD transducers and strategic positioning of ADDs to attenuate signals emanating from farms.	farms to assess the level of attenuation of ADD signals achievable in practice. • Requires trials of foam baffles and device placement at operational finfish farms to assess the level of attenuation of ADD signals achievable in practice.	existing compressors and airlines. • Experimental baffles relatively inexpensive. • Staff costs for field trials and measurement.	
New net materials (e.g. HDPE) (at finfish farms)	• Anecdotal but compelling reports suggest they are highly resistant to seal attack. • Already widely and increasingly used in Scotland.	• Collection and analysis of seal damage statistics for cages with existing and new netting materials.	• More expensive than existing nylon nets, currently approximately double the price.	• No negative impacts expected.
Anti-predator nets (at finfish farms)	• Already used in Scotland. • Insufficient data to assess effectiveness.	• Collection and analysis of seal damage statistics for cages with and without APNs. • Identification of measures employed in use of APNs in other countries and assessment of potential use Scotland.	• Material costs depend on type and sizes of cages to be protected. • Additional installation and operational cost.	• There may be potential issues associated with entanglement and drowning of seals. • There may be potential issues associated with entanglement and drowning NTS including diving birds and cetaceans.
Electric field barriers (in rivers)	• No off-the-shelf solution. Would need bespoke design and manufacture for each site. • Evidence for potential effectiveness.	• Requirement to assess the potential effect on migrating salmon and other NTS • Requires investigation of thresholds of response for food motivated seals.	• An expensive option. A single mobile field system is available at a cost of approximately £250,000.	• Potential health & safety risks • Potential for disturbance impacts on non-target species (e.g., beavers, otters, aquatic birds).

Non-lethal methods for reducing seal depredation	System readiness	Development/research requirements	Estimated Costs	Effects on Non-Target Species (NTS) and Regulation
		• Development of optimal array configurations. • Requires effective seal detector system.		• Requirement for EPS licence at some sites.
Non-lethal removal: translocation (rivers & finfish farms)	• Effectiveness unknown, e.g. likely rapid return but rate not estimated in UK seals or rivers. • Lack of efficient capture methods.	• Requires development and testing of methods for catching seals in rivers and at finfish farms. • Requires post release monitoring to assess effects of translocation, e.g. likelihood or speed of return and post release movements and behaviour.	• Significant staff resources required for capture and translocation activities. • Capital cost will depend on setting and equipment required – e.g. barrier net costs £500-£2500; cage trap & trigger system including CCTV costs £4,000-£5000; construction of river weir/barrier potentially high cost and entirely site dependent. • Requires specialist skills and experience.	• Licensing requirements would need to be determined as this has not been attempted commercially. Such a method would require a seal licence under the Marine (Scotland) Act 2010. • Initial trials may fall under the Animals (Scientific Procedures) Act 1986.
Non-lethal removal: temporary captivity (rivers & finfish farms)	• No existing seal holding facilities. • No captivity duration and release protocols. • Lack of efficient capture methods.	• Requires development of captive seal holding facilities/protocols etc. • Requires the development and testing of methods to catch seals in rivers.	• Cost heavily dependent on the availability of captive animal facility. • Requires specialist skills and experience. • Preliminary trials using a disused salmon finfish farm cage should be relatively inexpensive. • Seal maintenance (food, supplements, vet bills) costs per seal would be approximately £300 initial cost plus £15 per day plus staff costs.	• Licensing requirements would need to be determined as this has not been attempted commercially. Such a method would require a seal licence under the Marine (Scotland) Act 2010. • Initial trials may fall under the Animals (Scientific Procedures) Act 1986.

Non-lethal methods for reducing seal depredation	System readiness	Development/research requirements	Estimated Costs	Effects on Non-Target Species (NTS) and Regulation
			• Staff costs will depend entirely on the set up, e.g. whether as part of larger organisation or stand-alone facility.	
Conditioned taste aversion (at finfish farms)	• Effective CTA demonstrated in captive California sea lions but found to be ineffective in rivers No direct evidence available for grey or harbour seals. No existing protocols or methods of delivery.	• Requires trials with captive seals to assess CTA methods for grey and harbour seals, to develop appropriate delivery methods. • Requires field trials to assess practicality of the method. • Requires structured monitoring of use in practice to assess benefits of use.	• Significant staff resources for captive animal studies • Field application of baited fish would be low cost.	• Captive animal trials will fall under Animals (Scientific Procedures) Act 1986.
Conditioned aversion – electric fish (at finfish farms)	• Commercially available system exists. • Used alongside suite of other measures may enhance overall effectiveness. • Approach could be adapted to 'electrify' dead fish.	• Requires structured tests to assess effectiveness. • Requires development of method involving dead salmon as the electrified bait.	• Research with captive seals expensive. • Requires specialist skills and experience. • Application of electric fish at finfish farms currently available as part of integrated control package.	• Licensing requirements would need to determined. The effect is essentially the same as that in low voltage electric fences that are widely used in agriculture to control movements of both wild and domestic animals.
Non-lethal removal of seals trapped in finfish farm cages				
Anaesthesia & capture (at finfish farms)	• Methods for confining seals to a small area of the pool and darting with anaesthetic have been proposed. • Experience with wild seals cautions against this	• Recommend a workshop to bring together expertise on removing different species from cages and different restraining/anaesthesia methods.	• Workshop costs/ online meeting costs low. • Applying such methods would require specialist skills and experience.	• Initial trials may fall under the Animals (Scientific Procedures) Act 1986. • This would raise seal licensing considerations under the Marine (Scotland) Act 2010.

Non-lethal methods for reducing seal depredation	System readiness	Development/research requirements	Estimated Costs	Effects on Non-Target Species (NTS) and Regulation
	method, but groups in Canada and Australia are investigating possible methods.			• There may be other legislative requirements.
Restricted surface trapping methods (at finfish farms)	• No tried or tested methods exist, but simple procedures based on covering the water surface in a cage to constrain a seal are conceptually feasible.	• Consideration should be given to the practical feasibility of such methods. • Requires the design and testing of a floating deck of plastic pontoon cubes, with a seal capture and retrieval net. • Requires an initial feasibility study of netting methods and careful design to avoid potential drowning risk to seals.	• Floating deck costs approximately £5,000. • Netting methods depend on developing a practical and safe method/design and costs will depend on the chosen design. • Workshop costs dependent on number of participants and whether it is held online or in person.	• Initial trials may fall under the Animals (Scientific procedures) Act 1986. • This would raise seal licensing considerations under the Marine (Scotland) Act 2010.
DETECTION SYSTEMS (for use in conjunction with the measures above, particularly to trigger deterrent and exclusion systems)				
Detection – High Frequency (HF) sonar. (at finfish farms)	• Commercially available devices. • Effective detection algorithms developed and tested for seals. • System already tested at a tidal turbine site and in a salmon river to detect marine mammals. • Limited range so not currently applicable to finfish farms.	• Testing of detection algorithms for seals in river environment with specific sonar devices. • Choice of system will depend on the site characteristics and the required capabilities, e.g. whether simple detection and identification or sophisticated target identification and tracking are required. • Very short range: may require work to constrain river channel	• Costs will depend on the chosen system: ○ HF fish counting sonars can cost in excess of £100,000 (at time of writing), ○ a single HF multibeam sonar head can cost approximately £25-35,000 (at time of writing). • Installation costs will depend on the site, but for	• Potential audibility of sonar to cetaceans if used in estuaries leads to the possibility of disturbance. • Assessment of the likelihood of presence of cetaceans and the range of detectability will be required to determine whether an EPS licence is required. • HF sonar should not be audible to otters or beavers.

Non-lethal methods for reducing seal depredation	System readiness	Development/research requirements	Estimated Costs	Effects on Non-Target Species (NTS) and Regulation
	• Dual functionality: seal detection and fish counting.	which may affect salmon migration or enhance predation opportunities. • Detection algorithms for seals require test and possible modification/development.	initial trials the cost of construction/installation of a temporary or mobile system would be relatively small.	
Detection – Low Frequency (LF) or Mid Frequency (MF) sonar (at finfish farms)	• Commercially available devices. • Detection algorithms developed for HF sonar potentially transferable to LF or MF sonar detection algorithms.	• Testing of detection algorithms for seals and possible modification/development. • Requires investigation of potential audibility of MF and LF sonar to cetaceans.	• Costs dependent on chosen system. Requires review of suitable systems from perspective of range and suitability. Commercial costs unknown at time of writing.	• Potential audibility of sonar to cetaceans if used in estuaries leads to the possibility of disturbance. • Assessment of the likelihood of presence of cetaceans and the range of detectability will be required to determine whether an EPS licence is required.

Detection – surface video (in rivers & at finfish farms)	• One system close to market:
	  ○ Detection algorithms developed for seals,
	  ○ IR tested and can detect seals in darkness
	  ○ Linked to ADD operation.
	• Other systems under development and testing.
	• Detection algorithms under development for search & rescue may be adaptable.
		• Requires testing of commercial systems to assess target detection and identification accuracy.
		• Requires linked detect and deter system to be proven.
		• Development and testing of additional systems.
		• Assessment of algorithms developed for search and rescue, and modified if appropriate.
			• Commercial system costs not available at time of writing.
			• Cost of trial multi camera/IR system under test is approximately £10,000 (at the time of writing) plus £10,000 installation cost.
			• Software/ID algorithm development will depend on the system requirements specified.
				• Licensing requirements would need to determined, as well as compliance with data protection regulations (if the system has the potential to capture images of people).

Passive acoustic cetacean detection (at finfish farms)	• No off-the-shelf automated real-time detection system available.	• Requires initial feasibility study to identify potential solutions and test automatic cetacean vocalisation detectors.	• Costs will be determined by outcomes of the feasibility study.	• Licensing requirements would need to be determined for development or deployment of passive acoustic detectors

6. References

ABC (2018). https://www.abc.net.au/news/2018-10-12/seals-being-shot-with-thousands-of-beanbag-bullets-to-protect-s/10366006

Ace-Hopkins, J. (2002). Humane Predator Control; The Case for Acoustics. AA-01-044 Industry Report. pp 14.

Ace-Hopkins, J. (2006). Ace Aquatec Universal Scrammer Mk2 US2 Version 2.0.1-18.

Ace Aquatec (2020). Progress report on development of automated seal detection system available on request from https://aceaquatec.com/case-studies/mmpa-thermal-triggers/

ADFG (2010). Tasers for Moose and Bears: Alaska Explores Law Enforcement Tool for Wildlife. *Alaska Fish & Wildlife News*, March 2010. https://www.adfg.alaska.gov/index.cfm?adfg=wildlifenews.view_article&articles_id=450

Anderson, S.S. & Hawkins, A.D. (1978). Scaring Seals by Sound. *Mammal Review*. 8.

Arnold, H. (1992). *Experimental predator control measures on marine salmon farms in Shetland*. A report for Greenpeace UK submitted to the Planning and Coordinating Committee of the Marine Mammal Action Plan, United Nations Environmental Programme. pp 18.

Awbrey, F. T. & Thomas, J. A. (1986). Measurement of sound propagation from several acoustic harassment devices. in Acoustic Deterrents in Marine Mammal Conflicts with Fisheries. A Workshop Held Feb 17-18, 1986, eds B. R. Mate & J. T. Harvey (Newport, OR: Oregon Sea Grant), 85–104.

Baker, J.R., Anderson, S.S. & Fedak , M.A. (1988) The use of ketamine-diazepam mixture to immobilise wild grey seals (*Halichoerus grypus*) and southern elephant seals (*Mirounga leonina*). *The Veterinary record* 123(11), 287-9. DOI:10.1136/vr.123.11.287

Balseiro, P., Moe, O.,Gamlem, I., Shimizu, M., Sveier, H., Nilsen, T., Kaneko, N., Ebbesson, L., Pedrosa, C., Tronci, V., Nylund, A. & Handeland, S.O. (2018). Comparison between Atlantic salmon *Salmo salar* post-smolts reared in open sea cages and in the Preline raceway semi-closed containment aquaculture system. *Journal of Fish Biology*, 93, 567-579 https://doi.org/10.1111/jfb.13659

Baumgartner, L.J., Reynoldson, N., Cameron, L. & Stanger, J. (2006). Assessment of a Dual frequency Identification Sonar (DIDSON) for application in fish migration studies. NSW Department of Primary Industries Fisheries. Final Report Series No. 84 ISSN 1449D 9967

Baumgartner, M. F., Bonnell, J., Van Parijs, S. M., Corkeron, P. J., Hotchkin, C., Ball, K., Pelletier, L.-P., Partan, J., Peters, D., Kemp, J., Pietro, J., Newhall, K., Stokes, A., Cole, T. V. N., Quintana, E., and Kraus, S. D. (2019). " Persistent near real-time passive acoustic monitoring for baleen whales from a moored buoy: System description and evaluation," Meth. Ecol. Evol. **10**, 1476–1489. https://doi.org/10.1111/2041-210X.13244,

Beach, R.J., Geiger, A.C., Jeffries, S.J. S., Treacy D. & Troutman. B. L. (1985). Marine mammals and their interactions with fisheries of the Columbia River and adjacent waters, 19801982. NMFS-AFSC Processed Rep. 8504,

Benjamins, S., Risch, D., Lepper, P. & Wilson, B. (2018). SARF112 – Influences of Lower-Frequency Acoustic Deterrent Devices (ADDs) on Cetaceans in Scottish Coastal Waters. A Study Commissioned by the Scottish Aquaculture Research Forum (SARF). Available online at: www.sarf.org.uk/ (accessed January 14, 2020).

Bennett, S., Wernberg, T. & de Bettignies, T. (2017). Bubble Curtains: Herbivore Exclusion Devices for Ecology and Restoration of Marine Ecosystems? *Frontiers in Marine Science*, 4(302), 1-8. DOI:10.3389/fmars.2017.00302

Benoit-Bird, K.J. & Au, W.L. (2003a). Hawaiian spinner dolphins aggregate midwater food resources through cooperative foraging. *The Journal of the Acoustical Society of America* 114:2300

Benoit-Bird, K.J. & Au, W.L. (2003b). Prey dynamics affect foraging by a pelagic predator (Stenella longirostris) over a range of spatial and temporal scales. *Behav Ecol Sociobiol* 53:364–373

Benoit-Bird, K.J., Wursig, B. & McFadden, C.J. (2004). Dusky dolphin (*Lagenorhynchus obscurus*) foraging in two different habitats: active acoustic detection of dolphins and their prey. Mar. Mamm. Sci. 20:215–231

Boatner, R. (2000). Willamette Falls sea lion observation project. ODFW Progress Report.

BPFI (2017). Bonneville Pinniped Fishery Interaction Task Force: March 2017 Task Force Meeting Summary. https://www.fisheries.noaa.gov/west-coast/marine-mammal-protection/marine-mammal-protection-act-section-120-pinniped-removal-2#2017-actions-and-documents

Bolt, H.E., Harvey, P.V., Mandleberg, L. & Foote, A.D. (2009). Occurrence of killer whales in Scottish inshore waters: temporal and spatial patterns relative to the distribution of declining harbour seal populations. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 19,671–675

Boswell, K.M., Wilson, M.P. & Cowan Jr., J.H. (2008). A Semi automated Approach to Estimating Fish Size, Abundance, and Behavior from Dual Frequency Identification Sonar (DIDSON) Data. *North American Journal of Fisheries Management* 28 (3):799D 807, DOI: 10.1577/M07D116.1

Brandt, M.J., Höschle, C., Diederichs, A., Betke, K., Matuschek, R., Witte, S. & Nehls, G. (2012a). Effectiveness of a sealscarer in deterring harbour porpoises (*Phocoena phocoena*) and its application as a mitigation measure during offshore pile driving. Bioconsult SH, Husum, Germany. 0-109.

Brandt, M.J., Höschle, C., Diederichs, A., Betke, K, Matuschek, R. Witte, S. & Nehls, G. (2012b). Title missing. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 23(2), 222-232.

Brandt, M.J., Höschle, C., Diederichs, A., Betke, K,. Matuschek, R. & Nehls, G. (2013). Seal scarers as a tool to deter harbour porpoises from offshore construction sites. *Marine Ecology Progress Series.* 475:291-302.

Braun, D., McCubbing, D. Ramos-Espinoza, D, Chung, M., Burroughs, L., Burnett, N., Thorley, J., Ladell, J., Melville, C., Chillibeck, B. & Lefevre, M. (2016). Technical, Logistical, and Economic Considerations for the Development and Implementation of a Scottish Salmon Counter Network. *Scottish Marine and Freshwater Science.* 7(2).

Brown, R., Jeffries, S., Hatch, D. & Wright, B. (2008). Field Report: 2008 Pinniped Management Activities at Bonneville Dam. Oregon Department of Fish and Wildlife, 7118 NE Vandenberg Ave. Corvallis, OR 97330. pp 9.

Brown, R., Jeffries, S., Hatch, D. & Wright, B. (2016). Field Report: 2016 Pinniped Research and Management Activities at Bonneville Dam. Oregon Department of Fish and Wildlife, 7118 NE Vandenberg Ave. Corvallis, OR 97330. pp 18.

Brown, T.G., Munro, B., Beggs, C., Lochbaum, E. & Winchell, P. (2003). Courtenay River Seal Fence. *Canadian Technical Report of Fisheries and Aquatic Sciences 2459.* pp 65.

Burger, C. (2010). Innovative Technology for Marine Mammal Deterrence in the Columbia River Basin: Summary Report of Research Results. Project Number: 2007-524-00 Smith-Root Inc. Vancouver.

Burger, C. V., Parkin, J. W., O'Farrell, M., Murphy, A. & Zeligs, J. (2012). Non-Lethal Electric Guidance Barriers for Fish and Marine Mammal Deterrence: A Review for Hydropower and Other Applications. Industry report presented at the international conference - *HydroVision Brazil 2012*. pp 31.

Burwen, D.L., Fleischman, S.J. & Miller, J.D. (2010). Accuracy and Precision of Salmon Length Estimates Taken from DIDSON Sonar Images. *Transactions of the American Fisheries Society* 139(5): 1306–1314.

Butler, J.R.A., Middlemas, S.J., Graham, I.M. Thompson, P.M. & Armstrong, J.D. (2006). Modelling the impacts of removing seal predation from Atlantic salmon (*Salmo salar*) rivers in Scotland: a tool for targeting conflict resolution. *Fisheries Management and Ecology,* 13: 285–291.

Butler, J.R.A., Middlemas, S.J., Mckelvey, S.A., Mcmyn, I., Leyshon, B., Walker, I., Thompson, P. M., Boyd, I.L., Duck, C.D., Armstrong, J.D., Graham, I.M. & Baxter, J.M. (2008). The Moray Firth Seal Management Plan: an adaptive framework for balancing the conservation of seals, salmon, fisheries and wildlife tourism in the UK. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 18, 1025–1038. DOI:10.1002/aqc

Butler, J.R.A., Radford, A., Riddington, G. & Laughton, R.L. (2009). Evaluating an ecosystem service provided by Atlantic salmon, sea trout and other fish species in the River Spey, Scotland: the economic impact of recreational rod fisheries. *Fisheries Research.* 96, 259–266.

Butler, J.R.A., Middlemas, S.J., Graham, I.M. & Harris, R.N. (2011). Perceptions and costs of seal impacts on salmon and sea trout fisheries in the Moray Firth, Scotland: implications for the adaptive co-management of Special Areas of Conservation. *Marine Policy,* 35, 317–323

Cardia, F. & Lovatelli, A. (2015). Aquaculture operations in floating HDPE cages: a field handbook. FAO Fisheries and Aquaculture Technical Paper No. 593. Rome, FAO. 152 pp.

Casper, B.M., Popper, A.N., Matthews, F., Carlson, T.J. & Halvorsen, M. (2012). Recovery of barotrauma injuries in chinook salmon from exposure to pile driving sound. *PloS ONE,* 7(6):e39593. doi:10.1371/journal.pone.0039593

Clabburn, P., Davies, R., Griffiths, J. & Davis, J. (2019). Using multi-beam sonar in open river channels to derive run estimates and assess fish passage. In: The SAMARCH Project: International Salmonid Coastal and Marine Telemetry Workshop. Edited by: Whelan, K., Roberts, D. & Gray, J. Southampton. 5-6 November 2019.

CoGP (2014). Scottish Salmon Farming Code of Good Practice: Growing a sustainable industry. Available at: https://www.scottishsalmon.co.uk/code-of-good-practice

Conover, M. R. (1989). Potential Compounds for Establishing Conditioned Food Aversions in Raccoons. *Wildlife Society Bulletin*, 17(4), 430–435.

Conway, A., Durbach, I., McInnes, A. & Harris, R.N. (*in press*). Frame-by-frame annotation of video recordings using deep neural networks. *Ecosphere.*

Coram, A., Gordon, J., Thompson, D. & Northridge, S. (2014). Evaluating and Assessing the Relative Effectiveness of Acoustic Deterrent Devices and other Non-Lethal Measures on Marine Mammals. *Scottish Government*. ISBN: 978-1-78412-873-9

Coram, A., Mazilu, M., Northridge, S. (2016). Plugging the Gaps - Improving Our Knowledge of How Predators Impact Salmon Farms. A study commissioned by the Scottish Aquaculture Research Forum (SARF). http://www.sarf.org.uk/

Coram, A.J., Ragnarsson, V., Sparling, C.E. & Thomas, L. (in prep). The Use, Impact and Efficacy of Acoustic Deterrent Devices (ADDs) in Aquaculture. *Marine and Freshwater Science (currently under review*-- due in 2021*).*

Cotter, E.D., Joslin, J. & Polagye, B. (2018). Tracking and classification of targets detected by a moving multibeam sonar. *The Journal of the Acoustical Society of America*, 143, 1957; https://doi.org/10.1121/1.5036430

Cotter, E. & Polagye, B. (2020). Detection and classification capabilities of two multibeam sonars. *Limnology and oceanography: methods.* DOI: 10.1002/lom3.10393

Cronkite, G.M.W., Enzenhofer, H.J. & Holmes, J.A. (2008). Evaluation of the BlueView ProViewer 900 Imaging Sonar as a tool for counting adult sockeye salmon in the Adams River, British Columbia. *Canadian technical report of fisheries and aquatic sciences* 2798: iv + 21 p

Crowell, S.E., Wells-Berlin, A.M., Carr, C.E., Olsen, G.H., Therrien, R.E., Yannuzzi, S.E. & Ketten, D. R. (2015). A comparison of auditory brainstem responses across diving bird species. *Journal of comparative physiology. A, Neuroethology, sensory, neural, and behavioral physiology*, 201(8), 803–815. https://doi.org/10.1007/s00359-015-1024-5

Dähne, M., Tougaard, J., Carstensen, J., Rose, A. & Nabe-Nielsen, J. (2017). Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises. *Marine Ecology Progress Series*, 580, 221–237.

Deecke, V.B., Slater, P.J.B. & Ford, J.K.B. (2002). Selective habituation shapes acoustic predator recognition in harbour seals. *Nature,* 420:171–173.

Deecke, V.B., Nykänen, M., Foote, A.D. & Janik, V.M. (2011). Vocal behaviour and feeding ecology of killer whales (*Orcinus orca*) around Shetland, UK. *Aquatic Biology,* 13:79-88. doi: 10.3354/ab00353

Doksæter, L., Godø, O.R., Olsen, E., Nøttestad, L. & Patel R (2009). Ecological studies of marine mammals using a seabed-mounted echosounder. *ICES Journal of Marine Science,* 66, 1029–1036

Dolan, C.R. & Miranda, L.E. (2003). Immobilization Thresholds of Electrofishing Relative to Fish Size, *Transactions of the American Fisheries Society*, 132(5), 969-976, DOI: 10.1577/T02-055

DPIPWE (2018). Seal Management Framework (2018). Department of Primary Industries, Parks, Water & Environment. Tasmanian Government. https://dpipwe.tas.gov.au/wildlife-management/management-of-wildlife/seal-management

Dunkley, D. & Shearer, W. (1982). An assessment of the performance of a resistivity fish counter. *Journal of Fish Biology* (1982) 20, 717D737

EAZA (2018). EAZA and EAAM: Best practice guidelines for Otariidae and Phocidae. Eds. Gill, Meijer & Lacave. European Association of Zoos and Aquaria. Available at: https://www.eaza.net/assets/Uploads/CCC/EAZA-EAAM-PinnipedGuidelines-approved.pdf

Findlay, C.R., Ripple, H.D., Coomber, F., Froud, K., Harries, O. van Geel, N.C.F., Calderan, S.V., Benjamins, S., Risch, D. & Wilson, B. (2018). Mapping widespread and increasing underwater noise pollution from acoustic deterrent devices. *Marine Pollution Bulletin*, 135, 1042-1050. https://doi.org/10.1016/j.marpolbul.2018.08.042

Finneran, J.J. (2015). Noise-induced hearing loss in marine mammals: a review of temporary threshold shift studies from 1996 to 2015. *Journal of the Acoustical Society of America*, 138, 1702–1726. doi: 10.1121/1.4927418

Fish, J.F. & Vania, J.S. (1971). Killer whale (*Orcinus orca*) sounds repel white whales, (*Delphinapterus leucas*). *Fishery Bulletin*, 69(3), 531-535

Fishbio (2020). Fish counting weir. Accessible at https://fishbio.com/field-notes/fish-monitoring/fish-counting-weir.

Fisheries Management Scotland. (2020). Fisheries Management Scotland Annual Review 2020. Available at: http://fms.scot/publications/fisheries-management-scotland-annual-review-2020/

Fjälling, A., Wahlberg, M. & Westerberg, H. (2006). Acoustic harassment devices reduce seal interaction in the Baltic salmon-trap, net fishery. *ICES Journal of Marine Science*, 63(9), 1751–1758. DOI:10.1016/j.icesjms.2006.06.015

Forrest, K.W., Cave, J.D., Michielsens, C.G.J., Haulena, M. & Smith, D.V. (2009). Evaluation of an Electric Gradient to Deter Seal Predation on Salmon Caught in Gill-Net Test Fisheries. *North American Journal of Fisheries Management*, 29(4), 885–894. DOI:10.1577/M08-083.1

Gates, N. (1989). Chemical restraint and anesthesia of pinnipeds: a review. *Marine Mammal Science,* 5(3), 228-256**.** DOI:10.1111/j.1748-7692.1989.tb00338.x

Gearin, P., R. Pfeifer, E.A. Jeffries, S., DeLong, R. & Johnson, M. (1988). Results of the 1986/87 California sea lion steelhead trout predation control program at the Hiram M. Chittenden Locks. NWAFC Processed Rep. 8830, 111 p. Alaska Fisheries Science Center, Natl. Mar. Fish. Serv., NOAA, 7600 Sand Point Way NE, Seattle, WA 98115.

Geelhoed, S.C.V., von Asmuth, R., Al Abbar, F., Leopold, M.F. & Aarts, G.M. (2017). Field testing the efficiency of the FaunaGuard Porpoise Module (FG-PM) in the Marsdiep area. Wageningen Marine Research report C076/17.

Geiger, A.C. & Jeffries, S. J. (1987). *Evaluation of Seal Harassment Techniques to Protect Gill Netted Salmon*. In Mate & Harvey (eds.) proceedings of a workshop held February 17-18, 1986 at Newport, Oregon. Oregon State University, Publ. No. ORESU-W-86-001. Pages 37-55.

Gillespie, D.M. & Oswald, M. (2019). PAMGuard Beta Release 2.00.15: Software for automatic Detection, Classification and Localisation of marine mammals. Software http://www.pamguard.org/

Gillespie, D., Palmer, L., MacAulay, J., Sparling, C. & Hastie, G. (2020). Passive acoustic methods for tracking the 3D movements of small cetaceans around marine structures. *PLoS ONE*, *15*(5), [e0229058]. https://doi.org/10.1371/journal.pone.0229058

Global Aquaculture Advocate (2018a). *Developments in closed-containment technologies for salmonids, part 1*. *Recap of the 2017 Aquaculture Innovation Workshop.* Workshop report available at: https://www.aquaculturealliance.org/advocate/closed-containment-technologies-salmonids-part-1.

Global Aquaculture Advocate (2018b). Developments in closed-containment technologies for salmonids, part 2. Improved knowledge of closed-systems, innovations in aquafeeds. Workshop report available at: https://www.aquaculturealliance.org/advocate/closed-containment-technologies-salmonids-part-2.

Gonzalez-Socoloske D, Olivera-Gomez LD, & Ford RE (2009). Detection of free-ranging West Indian manatees *Trichechus manatus* using side-scan sonar. *Endangered Species Research,* 8, 249–257

Gonzalez-Socoloske D, & Olivera-Gomez LD (2012). Gentle giants in dark waters: using side-scan sonar for manatee research. *The Open Remote Sensing Journal*, 5, 1–14

Gordon, J., Blight, C., Bryant, E. & Thompson, D. (2019). Measuring responses of harbour seals to potential aversive acoustic mitigation signals using controlled exposure behavioural response studies. *Aquatic Conservation: Marine and Freshwater Ecosystems.* 29:157-177

Gosch, M., Luck, C., Cosgrove, R., Götz , T., Tyndall, P., Jessopp, M. & Cronin, M. (2017). Development of an acoustic deterrent device to mitigate seal fisheries interactions. Bord Iascaigh Mhara (BIM).

Gosch, M., Horne, M., Jessopp, M., Cosgrove, R.& Luck, C. (2018). Mitigation of interactions between seals and fishing gears. Bord Iascaigh Mhara (BIM).

Götz, T. & Janik, V.M. (2010). Aversiveness of sounds in phocid seals: psycho-physiological factors, learning processes and motivation. *Journal of Experimental Biology*, 213(9), 1536–1548. DOI:10.1242/jeb.035535

Götz, T. & Janik, V. M. (2011). Repeated elicitation of the acoustic startle reflex leads to sensitisation in subsequent avoidance behaviour and induces fear conditioning. *BMC Neuroscience*, 12(1), 30. DOI:10.1186/1471-2202-12-30

Götz T. & Janik, V.M. (2013). Acoustic deterrent devices to prevent pinniped depredation: efficiency, conservation concerns and possible solutions. *Marine Ecology Progress Series,* 492: 285-302.

Götz, T. & Janik, V.M. (2015). Target-specific acoustic predator deterrence in the marine environment. *Animal Conservation*, 18(1), 102–111. DOI:10.1111/acv.12141

Götz, T., Pacini, A.E., Nachtigall, P.E.& Janik, V.M. (2020). The startle reflex in echolocating odontocetes: basic physiology and practical implications. *Journal of Experimental Biology*, doi:10.1242/jeb.208470

Götz, T. & Janik, V.M. (2016a). Non-lethal management of carnivore predation: Long-term tests with a startle reflex-based deterrence system on a fish farm. *Animal Conservation*, 19, 212-221. DOI:10.1111/acv.12248

Götz, T.& Janik, V.M. (2016b). The Startle Reflex in Acoustic Deterrence: An Approach with Universal Applicability? *Animal Conservation*, 19, 225–226. DOI:10.1111/acv.12295

Graham, I.M., Harris, R.N., Denny, B., Fowden, D. & Pullan, D. (2009). Testing the effectiveness of an acoustic deterrent device for excluding seals from Atlantic salmon rivers in Scotland. *ICES Journal of Marine Science*, 66(5), 860–864. DOI:10.1093/icesjms/fsp111

Graham, I.M., Harris, R.N., Matejusová, I. & Middlemas, S.J. (2011). Do “rogue” seals exist? Implications for seal conservation in the UK. *Animal Conservation*, 14(6), 587–598. DOI:10.1111/j.1469-1795.2011.00469.x

Graham, I.M., Merchant, N.D., Farcas, A., Barton, T.R., Cheney, B., Bono, S. & Thompson, P.M. (2019). Harbour porpoise responses to pile-driving diminish over time. *Royal Society Open Science*, 6:190335. https://doi.org/10.1098/rsos.190335

Halvorsen, M.B., Casper, B.M., Woodley, C.M., Carlson, T.J., & Popper, A. N. (2012). Threshold for onset of injury in Chinook salmon from exposure to impulsive pile driving sounds. *PLoS ONE*, 7(6), e38968.

Hanan, D. & Scholl, J. (1987). *Acoustic Harassemnt Testing in the Klamath River Salmon Fishery*. In Mate & Harvey (eds.) proceedings of a workshop held February

17-18, 1986 at Newport, Oregon. Oregon State University, Publ. No. ORESU-W-86-001. Pages 58-59.

Harding, H., Bruintjes, R., Radford, A.N. & Simpson, S.D. (2016). Measurement of Hearing in the Atlantic salmon (*Salmo salar*) using Auditory Evoked Potentials, and effects of Pile Driving Playback on salmon Behaviour and Physiology. *Scottish Marine and Freshwater Science,* 7(11).

Harlan, L., Smith, D., Holliman, M., Burger, C., Taccogna, G., Miller, D., Munro, B., Olesiuk, P., Baillie, S., Matthews, I. & Bonnell, G. (2009). Evaluation of an Electric Barrier as a Seal Deterrent on the Puntledge River. Report Prepared For Pacific Salmon Commission, Southern Boundary Restoration & Enhancement Fund Committee. Vancouver, B.C., Canada

Harrington, A., Harrington, L. & Macdonald, D. (2013). Acoustic deterrents for otter management at stillwater fisheries: preliminary investigation. Published by: Environment Agency, Horizon House, Deanery Road, Bristol, *BS1 5AH.* ISBN: 978-1-84911-307-6

Harris, R.N. (2011). Long-Term Effectiveness of an Acoustic Deterrent for seals in the Kyle of Sutherland. SMRU report to the Scottish Government.

Harris, R.N., Harris, C.M., Duck, C.D. & Boyd, I.L. (2014). The effectiveness of a seal scarer at a wild salmon net fishery. *ICES Journal of Marine Science,* 71(5), 1913-1920.

Harris, R.N. & Northridge, S. (2015). Seals and Wild Salmon Fisheries. Report to Scottish Government SSI. http://www.smru.st-andrews.ac.uk/documents/scotgov/SSI_seals_and_salmon_VF1.pdf

Harris, R.N. & Northridge, S. (2016). Seals and Wild Salmon Fisheries. Report to Scottish Government SSI. http://www.smru.st-andrews.ac.uk/files/2016/10/SSI-annual-report-year-1.pdf

Harris, R.N. & Northridge, S.P. (2017). Seals and Wild Salmon Fisheries. Interim report to Scottish Government – SSI SMRU report to the Scottish Government.

Harris, R.N. & Northridge, S.P. (2018a). Seals and Wild Salmon Fisheries. Annual Report to Report to Scottish Government MMSS/002/15. SSI.

Harris, R.N. & Northridge, S.P. (2018b). Seals and Wild Salmon Fisheries. Interim Report to Scottish Government MMSS/002/15. SSI.

Harris, R.N. & Northridge, S.P. (2019). Seals and Salmon Interactions. Annual report to Scottish Government – SSI. Sea Mammal Research Unit, University of St Andrews, St Andrews. pp 25

Harris, R.N., Welsh, J., Lacey, C. & Northridge, S.P. (2020). Use of a CCTV system for seals. Marine Mammal Scientific Support Research Programme MMSS/002/15. Report to Scottish Government SSI.

Harvey, J.T., Mate, B.R. & Brown, R.F. (1987). The Feasibility and effectiveness of using an acoustic barrier to restrict movements of seals into netart Bayt, Oregon. In Mate & Harvey (eds.) proceedings of a workshop held February 17-18, 1986 at Newport, Oregon. Oregon State University, Publ. No. ORESU-W-86-001. Pages 75-78

Hasselman, D.J., D.R. Barclay, R. Cavagnaro, E. Cotter, D.M. Gillespie, G.D. Hastie, J.K. Horne, J. Joslin, C. Long, R.P. Mueller, C.E. Sparling & B.J. Williamson. (2020). Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Marine Renewable Energy Devices. Chapter S10. In: *OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World.* Copping, A.E. & Hemery, L.G. (eds.). Report for Ocean Energy Systems (OES).

Hastie G.D. (2012). Tracking marine mammals around marine renewable energy devices using active sonar. SMRU Ltd, St Andrews. Report to the Department of Energy and Climate Change. Report SMRUL-DEC-2012–002

Hastie, G.D., Gillespie, D. M., Gordon, J. C. D., MacAulay, J. D. J., McConnell, B. J. & Sparling, C. E. (2014). Tracking technologies for quantifying marine mammal interactions with tidal turbines: pitfalls and possibilities. *Marine Renewable Energy Technology and Environmental Interactions.* Shields, M. & Payne, A. (eds.). Dordrecht: Springer Science and Business Media, (Humanity and the Sea)

Hastie, G. D., Wu, G-M., Moss, S., Jepp, P., MacAulay, J. D. J., Lee, A., Sparling, C. E., Evers, C. H. M. & Gillespie, D. M. (2019a). Automated detection and tracking of marine mammals: a novel sonar tool for monitoring effects of marine industry. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 29, S1, 119-130

Hastie, G. D., Bivins, M., Coram, A., Gordon, J., Jepp, P., MacAulay, J., Sparling, C. & Gillespie, D. (2019b). Three-dimensional movements of harbour seals in a tidally energetic channel: application .of a novel sonar tracking system. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 29(4), 564-575

Jacobs, S. R. & Terhune, J.M. (2002). The effectiveness of acoustic harassment devices in the Bay of Fundy, Canada: seal reactions and a noise exposure model. *Aquatic Mammals*, 28(2), 147–158.

Jamieson, G.S. & Olesiuk, P. F. (2001). Salmon Farm - Pinniped Interactions in British Columbia; An Analysis of Predator Control, its Justification and Alternative Approaches. Research Document 2001/142. *Fisheries and Oceans Science*. pp 75.

Johnston, D.W., (2002). The effect of acoustic harassment devices on harbour porpoises (*Phocoena phocoena*) in the Bay of Fundy , Canada. *Biological Conservation*, 108, 113–118.

Kastelein, R.A., Bunskoek, P., Hagedoorn, M., Au, W.W.L. & de Haan, D. (2002). Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency-modulated signals. *Journal of the Acoustical Society of America,* 112: 334−344

Kastelein RA, Wensveen PJ, Hoek L, Verboom WC, Terhune JM (2009). Underwater detection of tonal signals be tween 0.125 and 100 kHz by harbor seals (Phoca vitulina). *Journal of the Acoustical Society of America,* 125: 1222−1229

Kastelein, R.A., Hoek, L., Jennings, N., de Jong, C. A. F., Terhune, J. M. & Dieleman, M. (2010). Acoustic mitigation devices (amds) to deter marine mammals from pile driving areas at sea: audibility & behavioural response of a harbour porpoise & harbour seals. *COWRIE Ref: SEAMAMD-09, Technical Report 31 July 2010.* ISBN 978-0-9565843-7-3.

Kastelein, R.A., Horvers, M., Helder-Hoek, L., Van de Voorde, S., ter Hofstede, R. & van der Meij, H. (2017a). Behavioral Responses of Harbor Seals (*Phoca vitulina*) to FaunaGuard Seal Module Sounds at Two Background Noise Levels. *Aquatic Mammals*, 43(4), 347–363. DOI:10.1578/AM.43.4.2017.347

Kastelein, R.A., Huybrechts, J., Covi, J. & Helder-Hoek, L. (2017b). Behavioral Responses of a Harbor Porpoise (*Phocoena phocoena*) to Sounds from an Acoustic Porpoise Deterrent. *Aquatic Mammals*, 43(3), 233-244. DOI 10.1578/AM.43.3.2017.233

Kerr, A. & Scorse, J. (2018). The Use of Seal Bombs in California Fisheries. Monterey, CA: Middlebury Institute of International Studies.

Kozak,G., (2006). Side scan sonar target comparative techniques for port security and MCM Q-Route requirements. Report to L-3 Communications Klein Associates, Inc. [Google Scholar]

Kuljis, B.A. (1986). Report on food aversion conditioning in sea lions (*Zalophus californianus*). In NMFS Contract Report 84-ABC-00167. National Marine Fisheries Service, NOAA, Washington, DC.

Larsen, O.N., Wahlberg, M., & Christensen-Dalsgaard, J. (2020). Amphibious hearing in a diving bird, the great cormorant (*Phalacrocorax carbo sinensis*). *Journal of Experimental Biology*, 223(6). DOI: 10.1242/jeb.217265

Lehtonen, E. & Suuronen, P. (2010). Live-capture of grey seals in a modified salmon trap. *Fisheries Research*, 102(1–2), 214–216. DOI: 10.1016/j.fishres.2009.10.007

Lepper, P.A., Goodson, A.D. & Black, K.D. (2004). Source levels and spectra emitted by three commercial aquaculture antipredation devices. In Proceedings of the Seventh European Conference on Underwater Acoustics, ECUA 2004 Delft, The Netherlands.

Lepper, P., Gordon, J., Booth, C., Robinson, S., Theobald, P., Northridge, S. & Wang, L. (2014). Establishing the sensitivity of cetaceans and seals to acoustic deterrent devices in Scotland. http://www.snh.org.uk/pdfs/publications/commissioned_reports/517.pdf.

Long, K.J., DeAngelis, M.L., Engleby, L. K., Fauquier, D.A., Johnson, A.J., Kraus, S. D. & Northridge, S. (2015). Marine Mammal Non-Lethal Deterrents : Summary of the Technical Expert Workshop on Marine Mammal Non-Lethal Deterrents. *NOAA Technical Memorandum*, *NMFS-OPR-5* (February 2015), 10–12.

López, B. D., and Mariño, F. (2011). A trial of acoustic harassment device efficacy on free-ranging bottlenose dolphins in Sardinia, Italy, *Marine and Freshwater Behaviour and Physiology*, 44, 197–208, DOI: 10.1080/10236244.2011.618216

Lucke, K., Lepper, P.A., Blanchet, M-A. & Siebert, A. (2011). The use of an air bubble curtain to reduce the received sound levels for harbor porpoises (*Phocoena phocoena*). *The Journal of the Acoustical Society of America* 130(5):3406-12. DOI:10.1121/1.3626123

Lunneryd, S.G. (2001). Fish preference by the harbour seal (*Phoca vitulina*), with implications for the control of damage to fishing gear. *ICES Journal of Marine Science*, 58, 824–829.

MacAulay, J.D.J., Gordon, J.C.D., Gillespie, D.M., Malinka, C. E. & Northridge, S. P. (2017). Passive acoustic methods for fine-scale tracking of harbour porpoises in tidal rapids. *Journal of the Acoustical Society of America*, *141*(2), 1120-1132. https://doi.org/10.1121/1.4976077

Madson, P.L., van der Leeuw, B. K., Gibbons, K. M. & Van Hevelingen, T.H. (2017). Evaluation of Pinniped Predation on Adult Salmonids and Other Fish in the Bonneville Dam Tailrace. *U.S. Army Corps of Engineers, Portland District, Fisheries Field Unit Bonneville Lock and Dam Cascade Locks, OR 97014*, *97014*(541).

Marine Scotland. (2015). A Technical Standard for Scottish Finfish Aquaculture. The Scottish Government, Edinburgh. Available at https://www.gov.scot/publications/technical-standard-scottish-finfish-aquaculture/

Marine Scotland. (2017). An Analysis of the Value of Wild Fisheries in Scotland. A report for Marine Scotland prepared by PACEC. Available at https://www.gov.scot/publications/value-of-the-wild-fisheries-sector-analysis/

Marine Scotland (2020a). SCOTTISH FISH FARM PRODUCTION SURVEY 2019. ISBN : 978-1-80004-158-5 available @ https://www.gov.scot/publications/scottish-fish-farm-production-survey-2019/

Marine Scotland (2020b). Second review of the operation of the seal licensing system under the Marine (Scotland) Act 2010. Available at https://www.gov.scot/publications/marine-european-protected-species-protection-from-injury-and-disturbance/

Marine Scotland (2020c). The protection of Marine European Protected Species from injury and disturbance. Guidance for Scottish Inshore Waters (July 2020 Version). Available at https://www.gov.scot/publications/second-review-operation-seal-licensing-system-under-marine-scotland-act-2010/

Mate, B.R. & Harvey, J.T. (1987a). Acoustic Deterrents in Marine Mammal Conflicts with Fisheries. A workshop held February 17-18, 1986 at Newport, Oregon. Oregon State University, Publ. No. ORESU-W-86-001. pp 116.

Mate, B.R., Brown, R.F., Greenlaw, C.F., Harvey, J.T. & Tempte, J. (1987b). An acoustic harassment technique to reduce seal predation on salmon. In B.R. Mate & J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 23-36). Corvallis, Oregon: Oregon State University.

McCubbing, D., Ward, B. & Burroughs, L. (1999). Salmonid escapement enumeration on the Keogh River: a demonstration of a resistivity counter in British Columbia. *Fisheries Technical Circular No 104*

McGarry, T., Boisseau, O., Stephenson, S. & Compton, R. (2017). Understanding the Effectiveness of Acoustic Deterrent Devices (ADDs) on Minke Whale (*Balaenoptera acutorostrata*), a Low Frequency Cetacean. ORJIP Project 4, Phase 2. RPS Report EOR0692. Prepared on behalf of The Carbon Trust. November 2017.

McGarry, T., De Silva, R., Canning, S., Mendes, S., Prior, A., Stephenson, S. & Wilson, J. (2020). Evidence base for application of Acoustic Deterrent Devices (ADDs) as marine mammal mitigation (Version 2.0). JNCC Report No. 615, JNCC, Peterborough. ISSN 0963-8091.

Mesa, M.G. & Copeland, E.S. (2009). Influence of a weak field of pulsed DC electricity on the behavior and incidence of injury in adult steelhead and Pacific lamprey. Draft report to Bonneville Power Administration, Portland, Oregon. Project No. 2007-524-00.

Mesa, M.G. & Dixon, C.J. (2010). Influence of a low-intensity electric sea lion deterrence system on the migratory behavior of fishes in the upstream migrant tunnel (UMT) at Bonneville Dam. Final Report to Bonneville Power Administration, Portland, Oregon. Project No. 2007-524-00.

Meyer-Loebbecke, A., Fraiser, K., Simonis, A., Reese, F., Kim, E. B., Denzinger, A., Schnitzler, H-U. & Baumann-Pickering, S. (2017). Squid as common target: do areas with fishery-related explosions and dolphin foraging habitats overlap? (poster) in *Proceedings of the 31st Annual Meeting of the European Cetacean Society*, May 1-3, 2017, Middelfart. Denmark

Mikkelsen, L., Hermannsen, L., Madsen, P. T. & Tougaard, J. (2017). Simulated seal scarer sounds scare porpoises, but not seals: species-specific responses to 12 kHz deterrence sounds. *Royal Society Open Science*, 4(7).

Milne, R., Lines, J., Moss, S. & Thompson, D. (2013). Behavioural responses of seals to pulsed, low-voltage electric fields in sea water (preliminary tests) *.* (SARF commissioned reports SARF071). Scottish Aquaculture Research Forum.

Moore, A., & Potter, E. (2014). Provisional Assessment of the River Tees Barrage Fish Passage. Centre for Environment, Fisheries and Aquaculture Science (CEFAS). pp 16.

Mueller, A.M., Burwen, D.L. Boswell, K. & Mulligan, T.K. (2010). Tail Beat Patterns in DIDSON Echograms and their Potential Use for Species Identification and Bioenergetics Studies. *Transactions of the American Fisheries Society*, 139, 900-910.

Myrick, A.C., Cassano, E.R. & Oliver, C.W. (1990). Potential for physical injury, other than hearing damage, to dolphins from seal bombs used in the yellowfin tuna purse-seine fishery: Results from open-water tests, Admin. Rep. LJ-90-08. U.S. National Mar. Fish.Serv. La Jolla, CA.

Nedwell, J.R., Turnpenny, A. W., Lovell, J.M. & Edwards, B. (2006). An investigation into the effects of underwater piling noise on salmonids. *The Journal of the Acoustical Society of America*, 120(5), 2550-2554.

Nelson, M. L., Gilbert, J. R. & Boyle, K. J. (2006). The influence of siting and deterrence methods on seal predation at Atlantic salmon (*Salmo salar*) farms in Maine, 2001-2003. *Canadian Journal of Fisheries and Aquatic Sciences*, 63(8), 1710–1721.

NESFC. (2008). Impacts of seal predation on commercial fisheries. Summary Report to the North Eastern Sea Fisheries Committee, UK. pp 24.

NFU (2012). Bird deterrents and bird scarersProtecting your crop – NFU Code of Practice. Accessible at: https://www.nfuonline.com/assets/4662

National Marine Fisheries Service (NMFS). (1997) Investigation of scientific information on the impacts of California sea lions and pacific harbor seals on salmonids and on the coastal ecosystems of Washington, Oregon, and California. *NOAA Technical Memorandum NMFS-NWFSC-28.* pp 113.

NMFS. (1995a). Proposed recovery plan for Snake River salmon. NMFS Report. (Available from Northwest Regional Office, Natl. Mar. Fish. Serv., NOAA, 7600 SandPoint Way NE, Seattle, WA 98115.)

NMFS. (1995b.) Environmental assessment on protecting winter-run wild steelhead from predation by California sea lions in the Lake Washington ship canal. NMFS Environ. Assess. Rep., 122 p. (Available from Northwest Regional Office, Natl. Mar. Fish. Serv., NOAA, 7600 Sand Point Way NE, Seattle, WA 98115.)

NMFS. (1996a). Environmental assessment on conditions for lethal removal of California sea lions at the Ballard Locks to protect winter steelhead. NMFS Environ. Assess. Rep., 81 p. (Available from Northwest Regional Office, Natl. Mar. Fish. Serv., NOAA, 7600 Sand PointWay NE, Seattle, WA 98115.)

NMFS. (2008a). Final environmental assessment: reducing the impact on at-risk salmon and steelhead by California sea lions in the area downstream of Bonneville Dam on the Columbia River, Oregon and Washington. NMFS Environmental Assessment.

NMFS. (2008b). Environmental Assessment for the Take of California Sea Lions at Bonneville Dam Pursuant to Section 120 of the Marine Mammal Protection Act. Silver Spring, MD: National Marine Fisheries Service.

NMFS. (2017). Final report and recommendations of the Bonneville pinniped-fishery interaction task force. Marine Mammal Protection Act, section 120. April 2017. Accessible at: https://repository.library.noaa.gov/view/noaa/23910

NMFS & WDFW. (1995). Environmental assessment on protecting winter-run wild steelhead from predation by California sea lions in the Lake Washington Ship Canal. National Marine Fisheries Service and Washington Department of Fish and Wildlife. Environmental Assessment Report. Seattle, Washington: 107 p.

NMFS & ODFW. (1997). Environmental assessment of preventing California sea lion foraging and predation on salmonids at Willamette Falls, Oregon. NMFS Environmental Assessment.

National Oceanographic Atmospheric Administration (NOAA) (2018). Deterring nuisance pinnipeds. Accessible at https://www.fisheries.noaa.gov/west-coast/marine-mammal-protection/deterring-nuisance-pinnipeds#deterrence-methods

NOAA (2020a). Guidelines for safely deterring marine mammals. Proposed Rule. Accessible at https://www.fisheries.noaa.gov/action/guidelines-safely-deterring-marine-mammals

NOAA (2020b). NOAA Fisheries authorizes states to remove sea lions that threaten salmon. NOAA Fisheries: West Coast Region. Accessible at: https://archive.fisheries.noaa.gov/wcr/newsroom/2016/05_noaa_fisheries_authorizes_states_to_remove_sea_lions_that_threaten_salmon.html

Nøttestad L, Ferno A, & Axelsen, B.E. (2002). Digging in the deep: Killer whales' advanced hunting tactic. *Polar Biology*, 25, 939-941. https://doi.org/10.1007/s00300-002-0437-0

Northridge, S.P., Gordon, J., Booth, C., Calderan, S., Cargill, A., Coram, A., Gillespie, D., Lonergan, M. & Webb, A. (2010). Assessment of the impacts and utility of acoustic deterrent devices. (SARF commissioned reports; SARF044). Scottish Aquaculture Research Forum. pp 34.

Northridge, S., Coram, A. & Gordon, J. (2013). Investigations on seal depredation at Scottish fish farms. Edinburgh: Scottish Government. Available at: https://synergy.st-andrews.ac.uk/smru/files/2015/10/1758.pdf

Oregon Department of Fish and Wildlife (2017). Request for marine mammal protection act section 120 authorization to remove California sea lions from the Willamette River. Submitted by Oregon Department of Fish and Wildlife: 5 October 2017. Available at https://www.fisheries.noaa.gov/west-coast/marine-mammal-protection/marine-mammal-protection-act-section-120-pinniped-removal

O'Farrell, M., Burger, C.V., Crump, R. & Smith, K. (2014). Blocking or guiding upstream-migrating fish: a commentary on the success of the graduated field electric fish barrier. *Proceedings of the International Fish Screening Techniques Conference* 2011, pp 165-175, Eds A.W.H Turnpenny & R.A. Horsfield International Fish Screening Techniques, WIT Press Southampton UK.

Olesiuk, P.F., L.M. Nichol, M.J. Sowden & J.K.B. Ford. (2002). Effect of the sound generated by an acoustic harassment device on the relative abundance and distribution of harbor porpoises (*Phocoena phocoena*) in retreat passage , British Columbia. *Marine Mammal Science,* 18, 843–862.

Olesiuk, P.F., Lawson J.W. & Trippel E.A. (2012). Pathways of effects of noise associated with aquaculture on natural marine ecosystems in Canada. DFO Canadian Science Advisory Secretariat. Research Document. 2010/025. vi + 64 p.

Oliver, G.W., Morris, P.A., Thorson, P.H. & LeBoeuf, B.J. (1998). Homing behavior of juvenile northern elephant seals. *Marine Mammal Science,* 14, 245-256

OTAQ (2020). Aquaculture- SF4-Specification Sheet – accessed at https://otaq.com/content/uploads/sites/2/2019/01/OTAQ-Aquaculture-SF4-Spec-sheet.pdf on 21/10/2020

Pemberton, D. & Shaughnessy, P. D. (1993). Interaction between seals and marine fish-farms in Tasmania, and management of the problem. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 3, 149–158.

Pfeifer, B. (1989). Monitoring of the 1988-89 California sea lion control program in the Lake Washington estuary. *Fishery Management Report 90-17*, Washington Department of Wildlife, Mill Creek, Washington.

Press. (2019a). 'Salmon farms and seals can co-exist' https://www.shetnews.co.uk/2019/02/03/salmon-farms-and-seals-can-co-exist-aquaculture-industry-insists/ accessed July 2020.

Press. (2019b). Protective nets reduce Scottish Sea Farms seal cull. https://www.fishfarmingexpert.com/article/protective-nets-reduce-scottish-sea-farms-seal-cull/ accessed July 2020.

Press. (2019c). Hopes that 2019 will be the first year no seals are shot in Shetlandhttps://www.pressandjournal.co.uk/fp/news/highlands/1669908/hopes-that-2019-will-be-the-first-year-no-seals-are-shot-in-shetland/ accessed July 2020.

Pyç, C.D., Geoffrey, M. & Knudsen, F.R. (2016). An evaluation of active acoustic methods for detection of marine mammals in the Canadian Beaufort Sea. *Marine Mammal Science*, 32, 202-219. https//doi.org/10.111/mms.12250

Quick, D.L.F., Gustavson, C.R. & Rusiniak, K.W. (1985). Coyote Control and Taste Aversion. *Appetite*, 6, 253–264.

Quick, N., Scott-Hayward, L., Sadykova, D., Nowacek, D. & Read, A. (2016). Effects of a scientific echo sounder on the behavior of short-finned pilot whales (*Globicephala macrorhynchus*). *Canadian Journal of Fisheries and Aquatic Sciences,* 74(5), 716-726

Ridoux, V., Guinet, C., Liret, C., Creton, P., Steenstrup, R. & Beauplet, G. (1997). A video sonar as a new tool to study marine mammals in the wild: measurements of dolphin swimming speed. *Marine Mammal Science.* 13:196–206

Robinson, S., Terauds, A., Gales, R. & Greenwood, M. (2008a). Mitigating fur seal interactions : relocation from Tasmanian aquaculture farms. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 18, 1180–1188. DOI:10.1002/aqc

Robinson, S., Gales, R., Terauds, A. & Greenwood, M. (2008b). Movements of fur seals following relocation from fish farms. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 18, 1189–1199. DOI:10.1002/aqc.972

Ross, A. (1988). Controlling Nature's Predators on Fish Farms. Ross-on-Wye: Marine Conservation Society.

Rueggeberg, H. & Booth, J. (1989). Interactions between wildlife and salmon farms in British Columbia: Results of a survey. Technical Report Series 67. Canadian Wildlife Service, Pacific and Yukon Region, British Columbia. pp 74.

Ruggerone, G.T., Goodman S. & Miner R. (2008). Behavioural Responses and Survival of Juvenile Coho Salmon Exposed to Pile Driving Sounds. Natural Resources Consultants, Inc.1-42 pp. Available at: https://www.researchgate.net/publication/261026301

Ruiz-Monachesia, M.R. & Labrab, A. (2020). Complex distress calls sound frightening: the case of the weeping lizard. *Animal Behaviour.* 165, 71-77 DOI:10.1016/j.anbehav.2020.05.004

Schaffeld, T., Ruser, A., Woelfing, B., Baltzer, J., Kristensen, J. H., Larsson, J., Schnitzler, J. G. & Siebert, U. (2019). The use of seal scarers as a protective mitigation measure can induce hearing impairment in harbour porpoises. *Journal of the Acoustical Society of America,* 146, 4288–4298

Schakner, Z. A., Götz, T., Janik, V. M. & Blumstein, D. T. (2017). Can fear conditioning repel California sea lions from fishing activities? *Animal Conservation*, 20, 425-432. DOI:10.1111/acv.12329

Schotte, R., & D. Pemberton. (2000). Anti-predator stock protection research project, Final Report. 99/361, Fisheries Research & Development Corporation, Hobart.

Scordino, J. (2010). West Coast Pinniped Program Investigations on California Sea Lion and Pacific Harbor Seal Impacts on Salmonids and Other Fishery Resources. Pacific States Marine Fisheries Commission Report. pp 106.

Scordino, J. & Pfeifer. B. (1993). Sea lion/steelhead conflict at the Ballard Locks. A history of control efforts to date and a bibliography of technical reports. Washington Department of Fish and Wildlife. Report, 10 p. (Available from Northwest Regional Office, Natl. Mar. Fish. Serv., NOAA, 7600 Sand Point Way NE, Seattle, WA 98115.)

Seamans, T.W. & Blackwelll, B.F. (2011). Electric shock strips as bird deterrents: does experience count? *International Journal of Pest Management*. 57(4), 357–362

Sepulveda, M. (2015). Plan de Pruebas para la disuasión del Lobo Marino en su interacción operacional con la Pesca Artesanal, en la comuna de San Antonio, Región de Valparaíso. Report for Subsecretaría de Pesca y Acuicultura, Chile. pp. 111.

Sepulveda, M. & Oliva, D. (2005). Interactions between South American sea lions *Otaria flavescens* (Shaw) and salmon farms in southern Chile. *Aquaculture Research*, 36(11), 1062–1068. DOI:10.1111/j.1365-2109.2005.01320.x

Shardlow, T.F. & Hyatt, K.D. (2004). Assessment of the Counting Accuracy of the Vaki Infrared Counter on Chum Salmon. *North American Journal of Fisheries Management*, 24(1): 249-252. DOI:10.1577/M02-037.

Shivik, J. A., Treves, A. & Callahan, P. (2003). Nonlethal Techniques for Managing Predation: Primary and Secondary Repellents. *Conservation Biology*, 17(6), 1531–1537. DOI:10.1111/j.1523-1739.2003.00062.x

Simonis, A.E., Forney, K.A., Rankin, S., Ryan,J., Zhang,Y., DeVogelaere, A., Joseph, J., Margolina, T., Krumpel. A. & Baumann-Pickering, S. (2020). Seal Bomb

Noise as a Potential Threat to Monterey Bay Harbor Porpoise. *Frontiers in Marine Science*, 7(142). doi: 10.3389/fmars.2020.00142

Simpson, P. (2008). A hydroacoustic cueing system for a sea lion deterrence array in the Columbia River Basin: target differentiation and range testing. Report submitted to Bonneville Power Administration as part of Project 2007-524-00, Contract 43248. (Also available from Patrick Simpson, Scientific Fisheries Systems, Inc., Anchorage, AK. Tel. 907-563-3474).

Smith, R.J. (1994). Literature survey on measures to control seal predation around aquaculture installations. Review prepared for Department of Fisheries and Oceans, Canada.

Smith-Root (2017). Pinniped Dock Deterrence, www.smith-root.com/sealions.

Sparling, C.; Sams, C.; Stephenson, S.; Joy, R.; Wood, J.; Gordon, J.; Thompson, D.; Plunkett, R.; Miller, B. & Götz, T. (year). The use of Acoustic Deterrents for the mitigation of injury to marine mammals during pile driving for offshore wind farm construction. ORJIP Project One, Phase Two. https://tethys.pnnl.gov/sites/default/files/publications/orjip-add-study-final-report-stage-1-phase-2.pdf Accessed October 2020.

SPICe (2019). Wild Salmon, SB 19-48, 19 August 2019. P 76

Stirling Aquaculture (2018). Technical Considerations of closed containment sea pen production for some life stages of salmonids. A report produced by the Institute of Aquaculture, University of Stirling for the Scottish Aquaculture Research Forum (SARF) http://www.sarf.org.uk/

Scottish Salmon Producers Organisation . (2020). Scottish salmon exports explained. https://www.scottishsalmon.co.uk/facts/business/scottish-salmon-exports-explained
Accessed July 2020.

Sverdrup A., Kjellsby E., Krüger P.G., Floysand R., Knudsen F.R., Enger P.S., Serck-Hanssen G. & Helle K.B. (1994). Effects of experimental seismic shock on vasoactivity of arteries, integrity of the vascular endothelium and on primary stress hormones of the Atlantic salmon. *Journal of Fish Biology*, 45, 973-995

Swan, G. J.F., Redpath, S.M., Bearhop, S. & McDonald, R.A. (2017). Ecology of Problem Individuals and the Efficacy of Selective Wildlife Management. *Trends in Ecology & Evolution*, 32(7), 518-530. DOI:10.1016/j.tree.2017.03.011

Thistle Environmental Partnership. (2010a). Assessment Of Protocols And Development Of Best Practice Contingency Guidance To Improve Stock Containment At Cage And Land-Based Sites. Available at: http://www.sarf.org.uk/cms-assets/documents/28923-913107.sarf054--- volume1.pdf.

Thistle Environmental Partnership. (2010b). Assessment of Protocols and Development of Best Practice Contingency Guidance to Improve Stock Containment at Cage and Land-Based Sites Volume 2 : Supporting Information,

Thistle Environmental Partnership. (2012). A report presenting proposals for a Scottish Technical Standard for Containment at Marine and Freshwater Finfish Farms. Available at: http://www.sarf.org.uk/cms-assets/documents/48448-527836.sarf073.pdf

Thomsen, F., Van elk, C., Brock, V. & Piper, W. (2005). On the performance of automated porpoise-click-detectors in experiments with captive harbor porpoises (*Phocoena phocoena*) (L). *The Journal of the Acoustical Society of America,* 118., 37-40. Doi: 10.1121/1.1937347.

Thompson, D., Duck, C.D., Morris, C.D. & Russell, D.J.F. (2019). The status of harbour seals (*Phoca vitulina*) in the United Kingdom. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 21:S1, 24-39. Doi: 10.1002/aqc.3110

Tixier, P., Gasco, N., Duhamel, G., & Guinet, C. (2014). Habituation to an acoustic harassment device (AHD) by killer whales depredating demersal longlines, *ICES Journal of Marine Science*, 71, 9, https://dx.doi.org/10.1093/icesjms/fsu166

Todd, V.L., Jiang, J., & Ruffert, M. (2019). Potential Audibility of Three Acoustic Harassment Devices (AHDs) to Marine Mammals in Scotland, UK. *International Journal of Acoustics and Vibration,* 24(4), 792-800. Doi: 10.20855/ijav.2019.24.41528

Trites, A. W. & Spitz, J. (2016) One–two punches to eliminate depredation by marine mammals on fish caught or raised for human consumption. *Animal Conservation*, 19(3), 222–224. Doi:10.1111/acv.12291

Tweed Foundation (2018). Valuable Tweed spring salmon now monitored by new fish counter. Accessible at: https://www.rivertweed.org.uk/news/?p=6201

Van der Meij, H., Kastelein, R., Van Eekelen, E. & Van Koningsveld, M. (2015). Faunaguard: A Scientific Method for Deterring Marine Fauna. *Terra et Aqua*, 138, 17-24.

Vilata, J., Oliva, D. & Sepulveda, M. (2010). The predation of farmed salmon by South American sea lions (*Otaria flavescens*) in southern Chile. *ICES Journal of Marine Science*, 67, 475-482.

Vongraven, D. & Bisther, A. (2014). Prey switching by killer whales in the north-east Atlantic: observational evidence and experimental insights. *Journal of the Marine Biological Association of the United Kingdom,* 94(6), 1357-1365.

Washington Department of Fish and Wildlife (2020). WDFW, partners receive approval to expand removals of sea lions on Columbia River and tributaries. Accessible at - https://wdfw.wa.gov/news/wdfw-partners-receive-approval-expand-removals-sea-lions-columbia-river-and-tributaries#

Westerberg, H. (2010). Potential Solutions To The Seals-Fisheries Conflicts. *European Parliament - Committee on Fisheries*. pp 48. Available at: https://www.europarl.europa.eu/RegData/etudes/note/join/2010/438614/IPOL-PECH_NT(2010)438614_EN.pdf

Wever, E.G., Herman, P.N., Simmons, J.A. & Hertzler, D.R. (1969). Hearing in the blackfooted penguin, *Spheniscus demerits*, as represented by the cochlear potentials. *Proceedings of the National Academy of Sciences*, 63, 676–680.

Whyte, K. F. (2015). Investigating Seal Depredation at Scottish Salmon Farms. Masters Thesis. University of St Andrews. pp 49.

Wiggins, S. M., Krumpel, A., Dorman, L., Hildebrand, J. & Baumann-Pickering, S. (2019). Seal Bomb Sound Source Characterization. *MPL Technical Memorandum 633*. La Jolla, CA: University of California San Diego.

Wright, B., Tennis, M. & Brown, R. (2010). Movements of Male California Sea Lions Captured in the Columbia River. *Northwest Science*, 84(1), 60-72. DOI:10.3955/046.084.0107

Würsig, B., Greene, C., & Jefferson, T. (2000). Development of an air bubble curtain to reduce underwater noise of percussive piling. *Marine Environmental Research,* 49(1), 79–93, DOI:10.1016/s0141-1136(99)00050-1

Ya Supin, A., & Nachtigall, P.E., (2013). Gain control in the sonar of odontocetes. *Journal of Comparative Physiology. A, Neuroethology, Sensory, Neural, and Behavioral Physiology*, 199(6), 471–8. DOI:10.1007/s00359-012-0773-7.

Yun, K.L., Nguyen, T., Nguyen, D., Kim, S., Eldin, A., Huyen, T.Lu., & Chow, E., (2019). Small Target Detection for Search and Rescue Operations using Distributed

Deep Learning and Synthetic Data Generation. *Computer Vision and Pattern Recognition*. arXiv:1904.11619

Yurk, H. & Trites, A.W., (2000). Experimental attempts to reduce predation by harbor seals on out-migrating juvenile salmonids. *Transactions of the American Fisheries Society*, 129(6), 1360–1366.