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Acoustic Deterrence Using Startle Sounds: Long-term effectiveness and effects on odontocetes

marine scotland

Acoustic Deterrence Using Startle Sounds:
Long-term effectiveness and effects on odontocetes

Report for Marine Scotland

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Abstract

Pinniped predation on fish farms is a worldwide problem and can result in significant losses to the industry. A wide range of seal control measures are employed at fish farms to minimise the impact of seal predation, including Acoustic Deterrent Devices (ADD) often referred to as seal scarers. Commercially available ADDs can cause stress, hearing damage and deter non-target species such as dolphins and porpoises from their natural habitat. A previous Scottish Government funded study using very short noise bursts to startle seals has shown that alternative methods may be available to deter seals. In this project, a startle ADD prototype was tested for 13 months at a salmon farm. We also tested this method for short periods of time at two other farms with acute seal predation problems caused by seals. During the 13 months test phase at the salmon farm only five minor predation events were noted. Predation was significantly higher at the same farm before ADD deployment and also at two adjacent control farms that did not use ADDs. Seals, porpoises and otters still approached the farm during the 13 months, but no additional predation was observed. Short term tests at two fish farms with high predation, reduced predation to zero within one day of ADD deployment. The study showed that the startle ADD is successful at preventing seal predation over 13 months and does not affect the distribution of harbour porpoises in the area. In other applications such as marine pile driving, cetaceans may need to be deterred for short periods of time to protect them from noise impacts. We therefore also tested whether bottlenose dolphins startle and what their startle threshold would be. This will allow the design of startle sounds for toothed whales. We found the threshold to be at approximately 80 dB above the hearing threshold. This value is very similar to the ones found in other mammals. We recommend the use of the startle method more widely since it is an effective method to prevent seal predation at fish farms, can be tuned to affect only certain species in an environment and has significantly less impact on wildlife than other tested devices.

Executive Summary

Pinniped predation on fish farms is a worldwide problem and causes the industry financial losses of up to 10% of the total farm gate value (Nash et al. 2000). This has led to a need for the industry to look at non-lethal measures controlling seal damage, which include tensioning nets, deployment of a predator net or use of Acoustic Deterrent Devices (ADDs) (Würsig and Gailey 2002). ADDs have often been considered a non-harmful method of dealing with the problem. However, the main problems with ADDs appear to be a lack of long-term efficiency and unintended effects on other marine wildlife (Jefferson and Curry 1996). A recent study has found a new method of acoustic deterrence using the acoustic startle reflex (Gotz & Janik 2011), which proved successful in deterring seals and avoiding effects on harbour porpoises over a two month period. This project tested (a) the effects of startling sounds on seal predation and marine mammal abundance around a test farm compared to adjacent control farms without ADDs over a 13 months period and (b) determined the startle threshold for bottlenose dolphins to prepare the method for use in other applications such as marine construction. The project also tested the short-term effectiveness of the startle method on two additional farms when they experienced high seal predation rates.

The use of the startle method resulted in a highly significant reduction in the number of lost fish on the long-term test site compared to the pre-deployment period (Mann-Whitney U, n=16, U=38, p=0.004, Fig 3). In fact, median losses per month were zero on the test site when the sound was played. This was a highly significant difference in predation losses compared to the control sites (Poll na Gile, Mann-Whitney U, n=22, U=103, p=0.001; Ardmaddy, n=21, U=20.5, p=0.01). Median losses were 41 fish/month on control site 1 (Poll na Gile), 39 fish/month on control site 2 (Ardmaddy), 98 fish/month on the test site before the deployment of the startle equipment and zero fish per month when the equipment was operating (Fig 3). There were only 5 consecutive events of negligible to moderate predation on the test site during the 13 months study, which consisted of 58, 14, 7, 5 and 1 fish losses. The direct comparison of monthly losses between the pre-deployment period, test period and control sites showed that the startle method was capable of reducing predation losses significantly throughout the one year deployment (Fig 3). This was also

confirmed by a statistical model which showed that sound exposure was the most important explanatory factor with respect to variation in seal predation. The model also revealed that predation varied throughout the year, although different sites did not differ in their losses during different times of year. Similarly, overall predation levels did not differ across sites. Seals, porpoises and otters approached the farm throughout the entire test period. There was no significant difference in number of seals and porpoises at different distances from the fish farm throughout the test period.

Rapid response trials at two fish farms with high seal predation rates also proved highly successful. At the first farm 405 fish were killed by seals in the month before the startle equipment was deployed (Fig 8). Dive reports after deployment of the equipment showed no new, seal-related kills for 2 weeks at which time the farm was harvested. At the second farm predation also dropped to zero in the first week after deployment. However, the equipment was damaged in a storm afterwards and predation levels returned to the high levels found prior to deployment.

Our tests showed that the startle method was highly successful in limiting seal predation at an operating fish farm with no evidence for habituation during a 13 month period. Similarly, the method was highly successful at limiting predation in cases where predation pressure was high. A likely explanation for the five events of predation while the startle equipment was operating in the long term test is that the predating individuals could have had compromised hearing which could be either the result of genetic predisposition, disease, old age or previous exposure to anthropogenic noise source (such as commercially available seal scarers).

Movement data of marine mammals showed that the startle method did not influence the distribution of harbour seals, porpoises and otters. The fact that harbour seals still approached the farm quite closely when the startle equipment was operating is in contrast with previous findings when measuring approaches. However, in the previous test sound exposure was more varied and lasted for only 2 months. It is therefore likely that seals observed at the surface near the fish farm did try to avoid the sound by swimming with their heads above the water. The fact that there was virtually no predation confirms that the sound had an effect on seals. Harbour porpoises were also observed at the surface near the equipment, but kept their heads underwater confirming that the sound did not have an effect on them. The deterrence system tested in this study operated at a duty cycle of less than 1% which is between one and two orders of magnitude lower than in current commercially available deterrent devices. The fact that brief, isolated pulses were emitted at only moderate levels means that noise pollution was greatly reduced and the potential for masking of communication signals or hearing damage is low. This is in contrast to current commercially available ADDs which emit sound at high duty cycles and high source levels. We would recommend the use of this novel technology at fish farms.

The startle method would potentially also be useful to temporarily deter cetaceans from marine construction sites. One possible problem with the application for echolocating toothed whales is that these animals produce very loud echolocation pulses and therefore might have an auditory mechanism to avoid startling themselves. We therefore tested whether bottlenose dolphins would startle to pulsed sounds and what their startle threshold would be. We used two captive bottlenose dolphins to conduct tests of their reactions when listening to startle sounds. The startle was quantified through an accelerometer attached to the animal that recorded any kind of muscle flinches during playbacks of sounds. We found that both animals clearly startled to our pulses and that the startle threshold for this species lies at around 80 dB above their hearing thresholds. Since we have shown here that echolocating animals also startle, the method is likely to work also with harbour porpoises. Our results allow us now to design startle sounds specifically for dolphins and porpoises. However, further tests to see whether dolphins and porpoises sensitize in the same way as seals are still needed. If they do, the startle method can be used to deter either only seals, only dolphins and porpoises, or all of these taxa.

Introduction

Pinniped predation on fish farms is a worldwide problem and causes the industry financial losses of up to 10% of the total farm gate value (Nash et al. 2000). This has led to a need for the industry to look at non-lethal measures for controlling seal damage, which include tensioning nets, deployment of a predator net or use of acoustic deterrent devices (ADDs) (Würsig and Gailey 2002). Acoustic deterrent devices have often been considered a benign method of dealing with the problem. However, the main problems with ADDs appear to be the lack of long-term efficiency and unintended effects on other marine wildlife (Jefferson and Curry 1996). Some studies have found prolonged effectiveness of ADDs in applications where devices are used to protect confined areas (Fjalling et al. 2006; Graham et al. 2009), however, the much more common picture is that animals rapidly habituate i.e. avoidance response wane and predation resumes (Götz and Janik 2010; Mate and Harvey 1987). Several studies that tested currently available ADDs around haulout sites (Jacobs and Terhune 2002), salmon runs (NMFS 1995) or fish farms (Norberg 1998) found little or no effect on seals and sea lions.

The potential impact of ADDs on other marine wildlife (non-target species), in particular cetaceans is of concern. There is a possibility that long-term exposure to ADDs may damage the hearing system of target and non-target species (Götz and Hastie 2009; Taylor et al. 1997) and that ADDs could cause long-term habitat exclusion of toothed whale (odontocetes). Olesiuk et al. (2002) showed that harbour porpoise (Phocoena phocoena) sightings in the Broughton Archipelago (British Columbia) dropped to 10 % of the expected value at ranges up to 2500 and 3500m from an operating Airmar ADD. In another study, porpoise numbers were found to be significantly lower in an area of up to 1.5km around a deterrent device (Johnston 2002). Long-term habitat exclusion over several years has also been shown in killer whale (Orcinus orca) and Pacific white-sided dolphins (Lagenorhynchus obliquidens) (Morton 2000; Morton and Symonds 2002). One likely reason is that odontocete hearing is about 30-40 dB more sensitive than pinniped hearing (e.g.Johnson 1967; Kastelein et al. 2002) in the frequency range where most commercial ADDs operate (10-40 kHz).

Sounds produced by current ADDs are not based on biological concepts of aversiveness but aim to transmit loud sound to the target animal. In a previous project funded by the Scottish Government (Janik & Goetz 2008) we developed a deterrent method that used an autonomous, acoustic startle reflex (ASR) to induce controlled and sustained flight responses in phocid seals but not in odontocetes. The startle reflex is elicited if a stimulus reaches an intensity threshold of 80-90 dB above the hearing threshold within 15ms of its onset (Goetz & Janik 2011). Seals exposed to startle stimuli became more likely to exhibit rapid escape responses in repeated exposure, causing animals to leave the exposure pool and show clear signs of fear conditioning (Götz and Janik 2011). Once sensitized, seals even avoided a known food source and showed prolonged location avoidance even in control periods with no sound playback. Harnessing the ASR is beneficial for several reasons:

1. avoidance responses are limited to the desired area around the device where received levels exceed the startle threshold,
2. the use of isolated, infrequent noise pulses greatly reduces noise pollution and removes the risk of hearing damage,
3. the startle threshold runs roughly parallel to the hearing threshold (Fleshler 1965) allowing a stimulus design that exceeds the threshold for one species but not another if their hearing thresholds are different.

The latter point would also allow a further development of the startle method to deter cetaceans instead of seals, or in combination to deter both animal groups. This might be desirable for short periods of time around marine construction work when construction noise levels could potentially damage marine mammal hearing.

This project tested (a) the effects of startle sounds on seal predation and marine mammal abundance around a test fish farm in comparison to adjacent control farms without operational ADDs, (b) the short-term effectiveness of the startle method on two additional farms when they experienced high seal predation rates and (c) startle thresholds in two bottlenose dolphins to develop startle sounds for echolocating marine mammals. These objectives allowed us to address the questions whether the startle method is effective in the long term in deterring seals from fish farms, whether it is possible to use the startle method aimed at seals in areas frequently used by cetaceans without having an adverse effect on cetaceans, and whether the startle method could be used to deter cetaceans if the design was changed accordingly.

The experimental startle setup

Following our previous study we entered into a commercial agreement with Airmar to develop a prototype in view of general production and marketing of a device. This development was funded by Airmar and the University of St Andrews. Over the project, Airmar produced two devices both of which failed to produce the required sounds (Fig 1). After 2 years with Airmar, we decided to try to find alternative ways of commercialisation independently. We therefore assembled our own equipment for the tests described in this project.

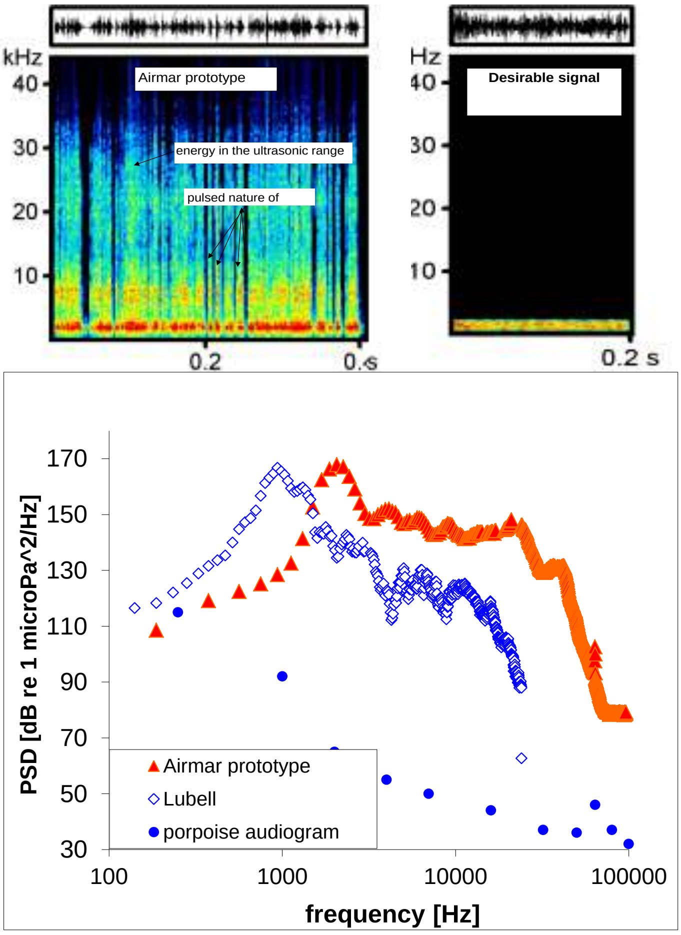


Fig 1: Spectrogram of an emission by a Airmar prototype (left) in comparison to the desirable signal (right). The lower panel shows power spectral density plots for the Airmar prototype and the Lubell loudspeakers used in this study. Note the high frequency scatter of the Airmar signal which would have compromised target-specificity of the device.

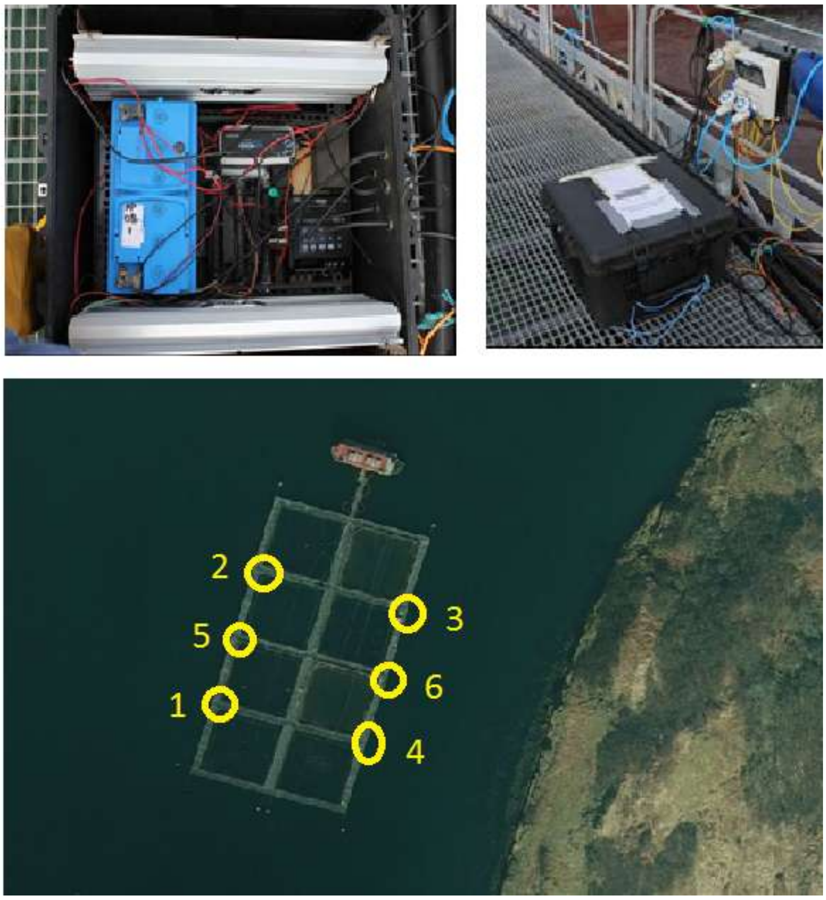


Fig 2: Acoustic deterrent device that was built for long-term experiment described in this report. The upper panel shows the device deployed at the test site. The lower panel shows an aerial view of the fish farm with all transducer positions that were used in this study. However, not that a maximum of only 4 transducers was ever active at any one time.

We used Lubell 9162T loudspeakers (Lubell labs Inc.) as underwater sound projectors since they were capable of emitting sufficient source levels in conjunction with reduced high-frequency scatter. The system we produced consisted of 2-4 sound projectors, two stereo Lanzar Vibe 292 power amplifiers, an Edirol R-44 4-channel recorder (used as a player), various types of marine power supplies (e.g. CTek M200) connected to the generator of the fish farm and a car battery. The car battery was charged from the power supply whenever the generator was running, while the equipment ran from the battery for the rest of the time. All components were mounted on a metal frame in a water-proof pelican case and loudspeakers were connected with cables to the main control box (Fig 2). The initial setup involved two loudspeakers, although approximately a month after deployment, two additional speakers were installed. One of these was removed again later to enable additional tests on other farms. The control box was deployed in the centre of the fish farm; transducer positions are shown in figure 2. The overall deployment period of the equipment was 13 months. The two main loudspeaker configurations consisted of speakers running at positions 1-4 (for approx. 4 months) and at positions 1, 2 & 6 (for approx. 8 months). Various components failed during the 13 months experimental period and substantial maintenance work had to be carried out to keep the system running. The breakdown of two power amplifiers, a power supply and various accidental cable cuts resulted in various “off-periods” throughout the experimental study. A complete record of operation, loudspeaker configurations and reasons of failure is provided in appendix 1. The technical failures experience during the project highlights the importance of engineering an industrial system that can withstand the harsh environment on a fish farm. Two additional setups were produced for tests on problem sites in Orkney and Argyll, one consisting of two transducers, the other of a single transducer. The system deployed in Orkney was flooded in a severe gale 2 weeks after deployment with all components being destroyed.

Long-term test on a fish farm in Argyll

Methods

A long-term field experiment was carried out on fish farms operated by Meridian salmon (Ltd.), formerly known as Lakeland Marine. A fish farm on the northwest tip of Shuna Island was chosen as the test site (Port na Cro). Two additional farms in close spatial proximity (operated by the same company) were designated as control sites (Poll na Gile & Ardmaddy). None of the farms in the area had previously operated ADDs. A questionnaire scheme was introduced which asked farm workers to 1) provide the number of fish lost due to seal predation, 2) overall losses for each stocked cage, and 3) additional information, including whether porpoise or schools of wild fish were seen around the farm. A sample questionnaire is provided in appendix 2.

The test site, Port na Cro, and one of the control sites, Poll na Gile, were stocked in October 2010 and harvested in February/March 2012. The second control site, Ardmaddy, was on a different production cycle and contained large fish before harvesting in April-May 2011. It was then fallow and re-stocked with medium sized fish at the beginning of August 2011.

Monitoring of predation started in November 2010 and was initially carried out in the form of site visits. This involved scientists carrying out detailed mort counts and comparing data with the records in the farms’ logbook and dive reports. Data sheets were fully established at the test site by the middle of December 2010 and are still being filled in. Mort counts either involved sorting through fish retrieved by divers or fish removed from baskets at the bottom of the net (except for Ardmaddy where no baskets are installed). Staff members occasionally failed to fill in the questionnaire on the control sites, therefore predation data was collected using a combination of sources including questionnaires, dive reports, basket counts reported in the farms logbook and basket counts carried out directly by scientists. Predation data was collected for 16 months on the test site (3 month pre-deployment and 13 month sound exposure), 9 months on control site 1 (Poll na Gile) and 8 months on control site 2 (Ardmaddy). The startle system was first installed on 16 January 2011 with two transducers and upgraded to four transducers on 7 February 2011. The equipment was removed on 1 February 2012. A record of loudspeaker operation and setup changes is given in appendix 1.

In addition to the predation monitoring scheme visual observations of marine mammals were carried out around the fish farm. A theodolite tracking method was used to determine surface positions of seals, porpoise and otters in the vicinity of the fish farm. Observations were carried out from the roof of a food barge in conditions of sea state 2 or less. Observers were either scanning by eye or with 10x50 binoculars. If the observer detected an animal he/she tried to locate it with the theodolite and, if successful, started logging consecutive surface positions (called a track). Animals were tracked until no resurfacing occurred within 15 minutes after the last surfacing had been logged. Observations were carried out on 18 days during sound exposure and 12 control observation days. The latter were primarily during the pre-deployment phase but in some cases also during the operational phase when the equipment was temporarily switched off. The overall observation effort was 76 hours 15 minutes during sound exposure, 25 hours 20 minutes during the pre-deployment/control periods and 19 hours 45 minutes on control site 1 (Poll na Gile).

The source level of the acoustic deterrent system was measured in a series of trials from a pontoon in Craobh Haven Marina. Measurements were carried out using a B&K 8103 hydrophone and a B&K 2635 charge amplifier connected to a M-audio Microtrack II recorder. The measured source levels were between 176 and 179 dB re 1µPa. Playback signals consisted of 200ms long, 2 octave-band noise pulses with an onset time of 5 ms played at a duty cycle of between 0.8 and 1%.

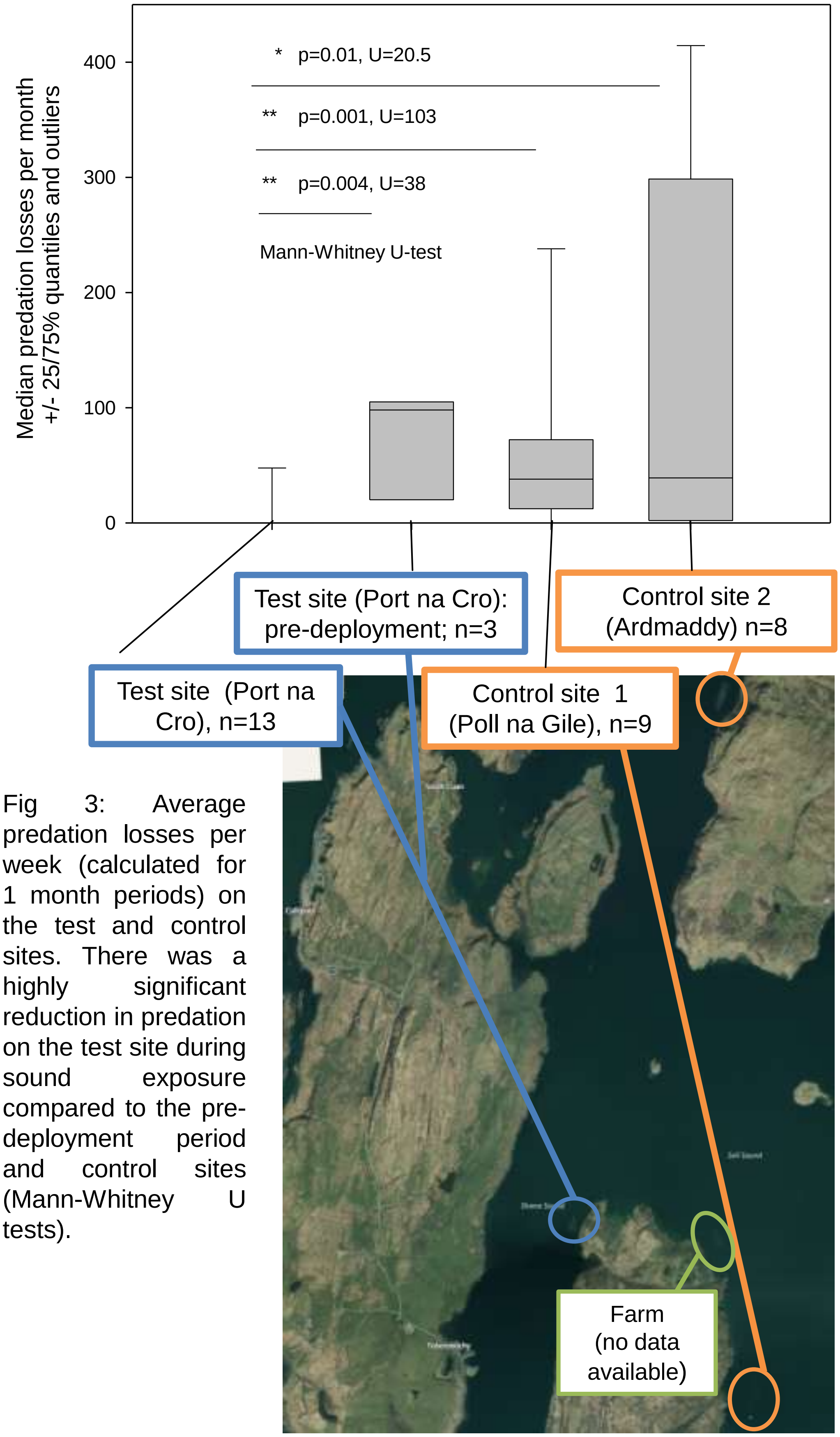


Fig 3: Average predation losses per week (calculated for 1 month periods) on the test and control sites. There was a highly significant reduction in predation on the test site during sound exposure compared to the pre-deployment period and control sites (Mann-Whitney U tests).

Statistical data analysis was carried out in PASW Statistics 19. Direct comparisons between the control and test sites, and between sound exposure and pre-deployment periods were conducted based on the overall counts of lost fish per month (adding up all dead basket counts and dive reports). These comparisons were done on the untransformed data using non-parametric statistics (Mann-Whitney U tests). In one case, data were only available for part of the month (Ardmaddy, May 2011) and in another case, a month was split between two treatments (January 2011, sound versus pre-deployment period); with data scaled up to reflect a one month period. In addition to the comparison on the direct counts, a predation model was calculated taking month (January-December), site (Port na Cro, Poll na Gile, Ardmaddy), sound exposure (yes or no) and the interaction between month and site into account. Data were transformed using a Box-Cox transformation prior to modelling to yield normality.

Results

Predation loss

The overall number of fish losses per month was compared between the pre-deployment and the sound exposure phase at each site (Fig 3). There was a highly significant reduction in the number of fish losses at the test site when the startle system was operating compared to the pre-deployment period (Mann-Whitney U, n=16, U=38, p=0.004, Fig 3). In fact, median losses per month were zero on the test site when the equipment was operating. This was a highly significant difference in predation losses compared to the control sites (Poll na Gile, Mann-Whitney U, n=22, U=103, p=0.001; Ardmaddy, n=21, U=20.5, p=0.01). Median losses were 41 fish/month on control site 1 (Poll na Gile), 39 fish/month on control site 2 (Ardmaddy), 98 fish/month on the test site before the deployment of the deterrent system and zero fish per month when the equipment was operating (Fig 3). There were only 5 consecutive events of negligible to moderate predation on the test site within the whole 13 month sound exposure period, which consisted of 58, 14, 7, 5 and 1 lost fish.

GLM	df	F	P
Corrected Model	29	11.97	.032
Intercept	1	643.9	.000
sound exposure	1	59.1	.005
month	12	12.2	.031
site	2	3.61	.159
month * site	14	4.68	.115

Table 1: General Linear Model (GLM) calculated to predict the influence of various factors on seals

A general linear model was calculated to detect trends and factors influencing predation losses across all three sites. The predation model included predation losses (average fish per week for each month) as dependant variable and 'month', 'site', 'sound exposure' and the interaction term 'month*site' as independent factors. The model was significant and explained 91% of the variance in the data set (see table 1). The factor that had by far the strongest influence on predation losses was 'sound exposure' ($F_{29,1}=59$, $p<0.005$). Seal predation was also influenced by the time of the year (factor 'month') but to a much lesser extent than sound exposure ($F_{29,12}=12.2$, $p=0.031$). In contrast, 'site' and the interaction between 'month and site' did not have a significant influence on predation. Therefore, the model showed that while predation varied across different times of the year the most important factor influencing predation was operation of the acoustic startle system.

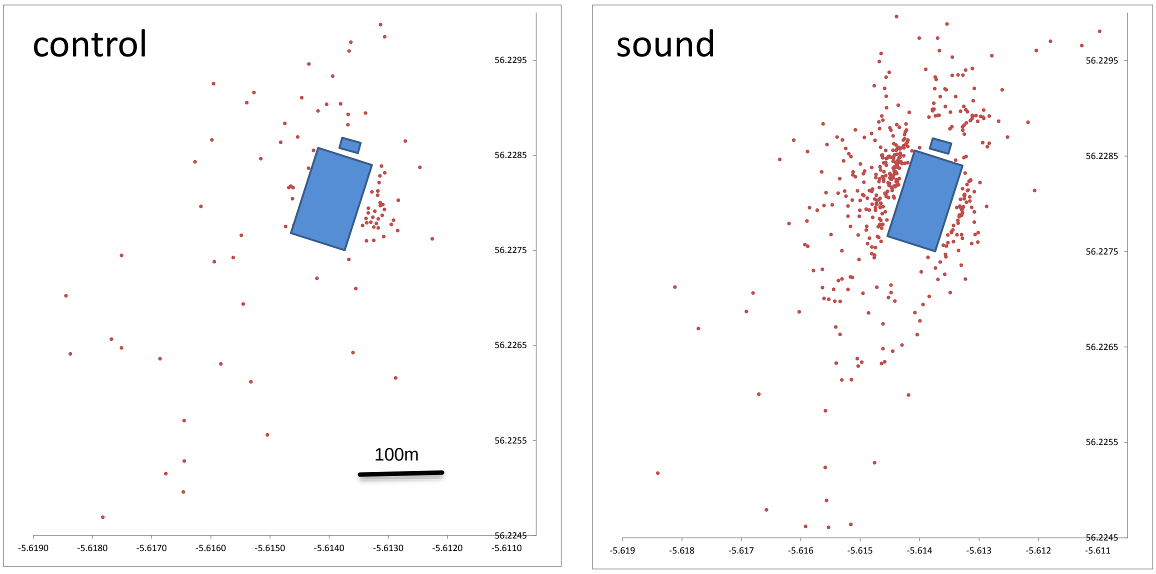
Seal predation accounted for a comparatively small amount of the overall losses on most farms. At the test site, a monthly average of 7% of the overall losses were caused by seals during the pre-deployment period. This value dropped to a monthly average of 0.5% during sound exposure. The average percentage of predation losses on the control sites was 7% (Poll na Gile) and 18% (Ardmaddy) respectively. The highest percentage of seal-inflicted losses was found in Ardmaddy in May 2011 with 80% of the overall losses caused by seals predation. The high number of losses unrelated to seals were partly due to natural 'die-offs' but had primarily to do with the fact that the test site was infected by Pancreas disease (PD) during the early stages of the production cycle. In the later stages of the production cycle, all sites were significantly affected by sea lice and parasitic amoeba.

Abundance and movement of marine mammals around the test and control sites

Surface positions of marine mammals were logged using a theodolite tracking method with an observer positioned on the food barge of the test site. The most commonly observed species around the farm were common seals (Phoca vitulina) and harbour porpoise (Phocoena phocoena). Single grey seals (Halichoerus grypus) were observed passing through the area on two separate control observation days and otters (Lutra lutra) were seen in the vicinity of the farm on four sound exposure and two control observation days. Seals were sighted on all 12 control observation days and on 14 out of 18 sound exposure days. Porpoise sightings were similarly frequent with animals being spotted on 6 out of 12 control observation days and 11 out 18 sound exposure days. The overall distribution of all surface positions for these species is shown on the maps in figure 4. Porpoise sightings were distributed over a wide area but many sightings occurred within a few hundred meters of the fish farm. It is important to note that observation effort was highly unbalanced between sound exposure and control observation periods and the much higher number of logged surface positions during sound exposure is due to the higher observation effort. The number of seal tracks per hour was therefore calculated for each observation day and the mean values of all observation days were compared between sound exposure and control observation periods (Fig 5) at distances of 0-25m, 25-100m and more than 100m from the nearest loudspeaker. The 25m distance cut-off was chosen based on previously measured deterrence ranges using the same deterrence method. However, no significant differences in the mean number of seal tracks per hour were found in any of the distance bins (t-tests; 25m: t=0.73, p=0.47; 25-100m: t=1.5, p=0.885; >100m: t=0.83, p=0.413). The mean number of seal tracks was slightly lower in the closest distance class (<25m) but this difference was not significant. Similarly, there were no changes in the mean number of porpoise tracks per hour as the result of sound exposure at any of the distance classes (Fig 5, t-tests; <25m: t=0.75, p=0.94; 25-100m: t=0.459, p=0.65; >100m: t=-0.112, p=0.912). Additional response variables showed that the overall porpoise abundance throughout the year was not affected by the deterrence equipment. The percentage of observation days on which porpoise were seen within 100m of an operating underwater loudspeaker (Fig 6) was in fact slightly higher during sound exposure (56%) compared to control observation days (38%), although this difference was not significant (Fisher's exact test n=30, p=0.28). As an additional measure for porpoise abundance around the farm, we counted the number of questionnaires which reported opportunistic sightings of porpoise groups. While these reports may not be as reliable as dedicated observations by scientists, farm staff spent much more time on the farm. Farm staff reported sightings of porpoise groups on 33% of the data sheets during control observation periods and 38% during sound exposure. Again, this difference was not significant which indicates that year round presence of porpoise was not influenced by the operation of the experimental acoustic startle system (Fisher's exact, n=68, p=0.71).

The high number of seal surfacings close to the cages raised questions about what factors influence seal distribution around fish farms throughout the year. Figure 6 shows the mean number of seal track/hour calculated over 3 month periods (quarters). A large number of tracks were logged within the 3rd quarter (July-September) for both the test (Port na Cro) and control site (Poll na Gile) where on average 1.5 and 1.7 seal track per hour were logged during that time. Many of the seals observed in July to September were new-born pups. There were several common seal pupping sites within a few miles of the fish farms and the large number of pup sightings around the farms coincided with their weaning period.

Seals



Porpoise

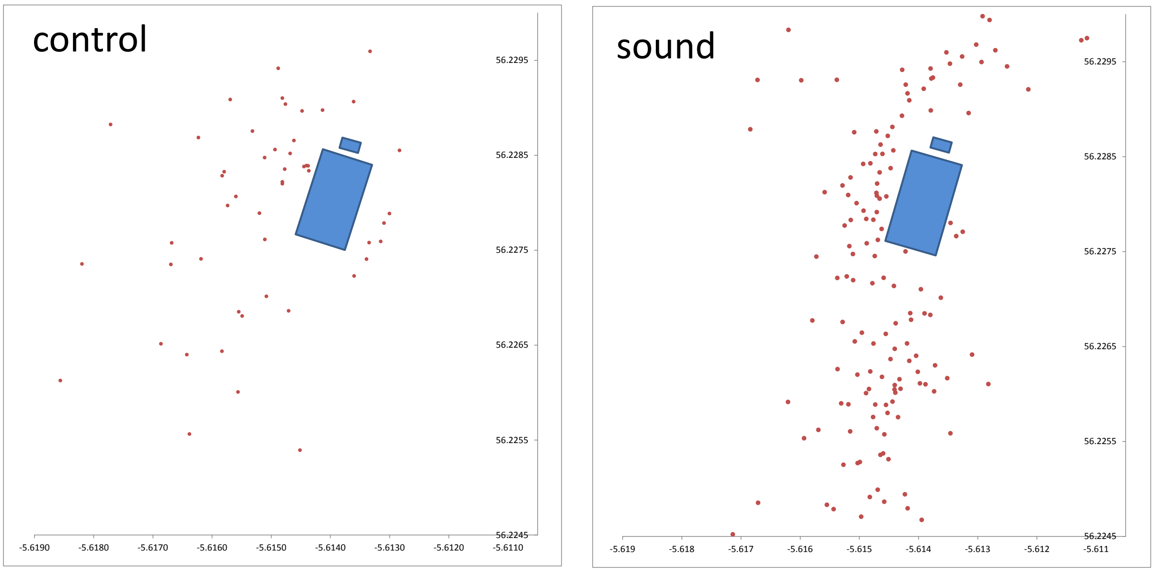
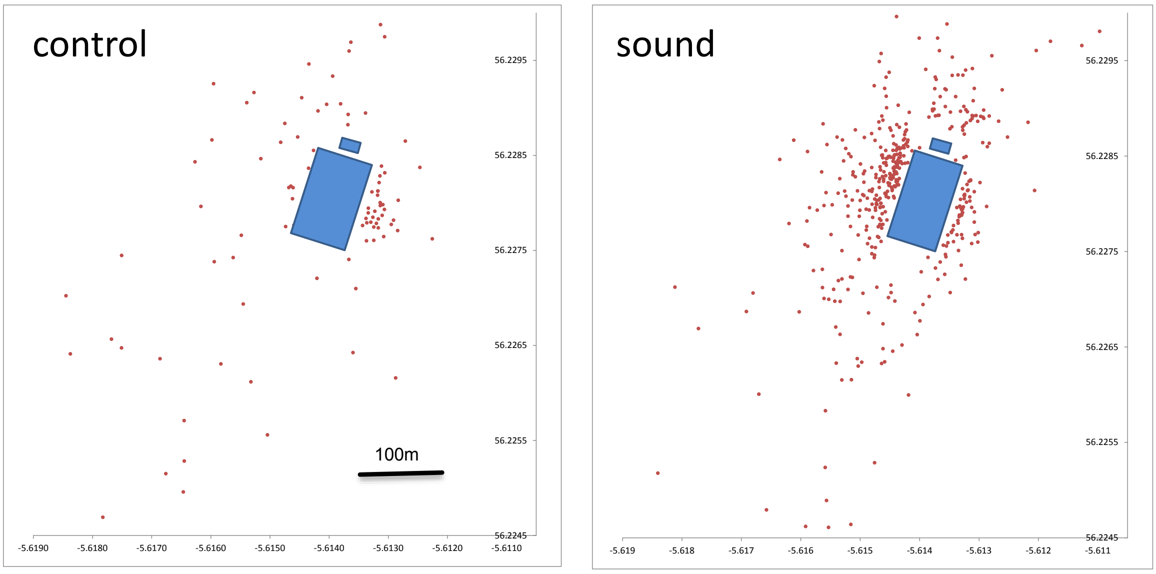


Fig 4: Distribution of seal (upper panels) and porpoise (lower panels) sightings around the fish farm during control observation days (left column) and sound exposure days (right columns). The large blue rectangle marks the area covered by the fish farm while the small blue rectangle depicts the feed barge where the visual observer was positioned.

Seals



Porpoise

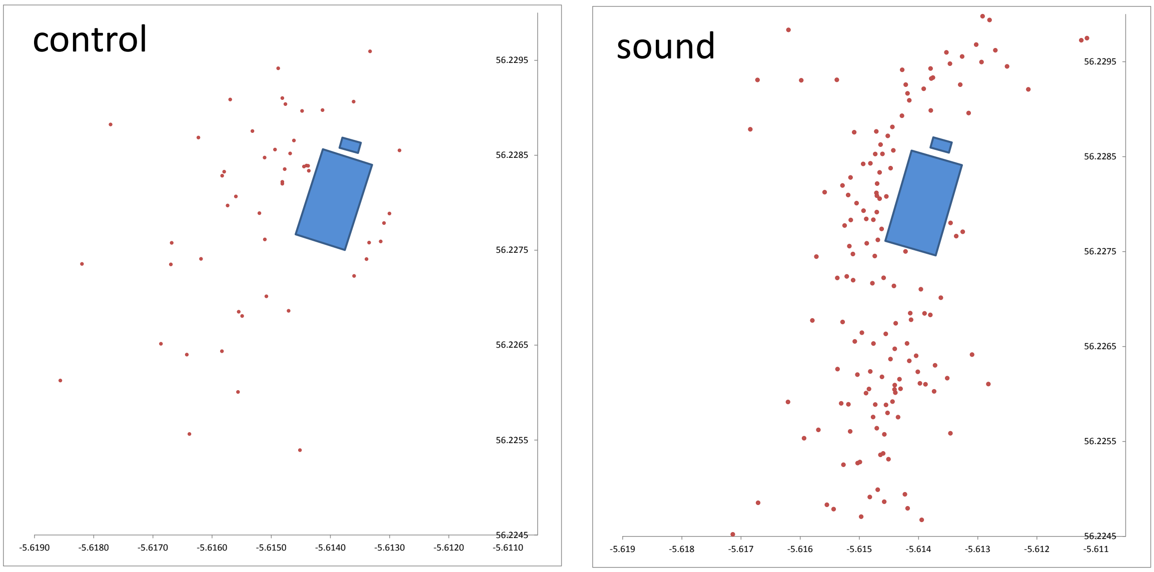


Fig 4: Distribution of seal (upper panels) and porpoise (lower panels) sightings around the fish farm during control observation days (left column) and sound exposure days (right columns). The large blue rectangle marks the area covered by the fish farm while the small blue rectangle depicts the feed barge where the visual observer was positioned.

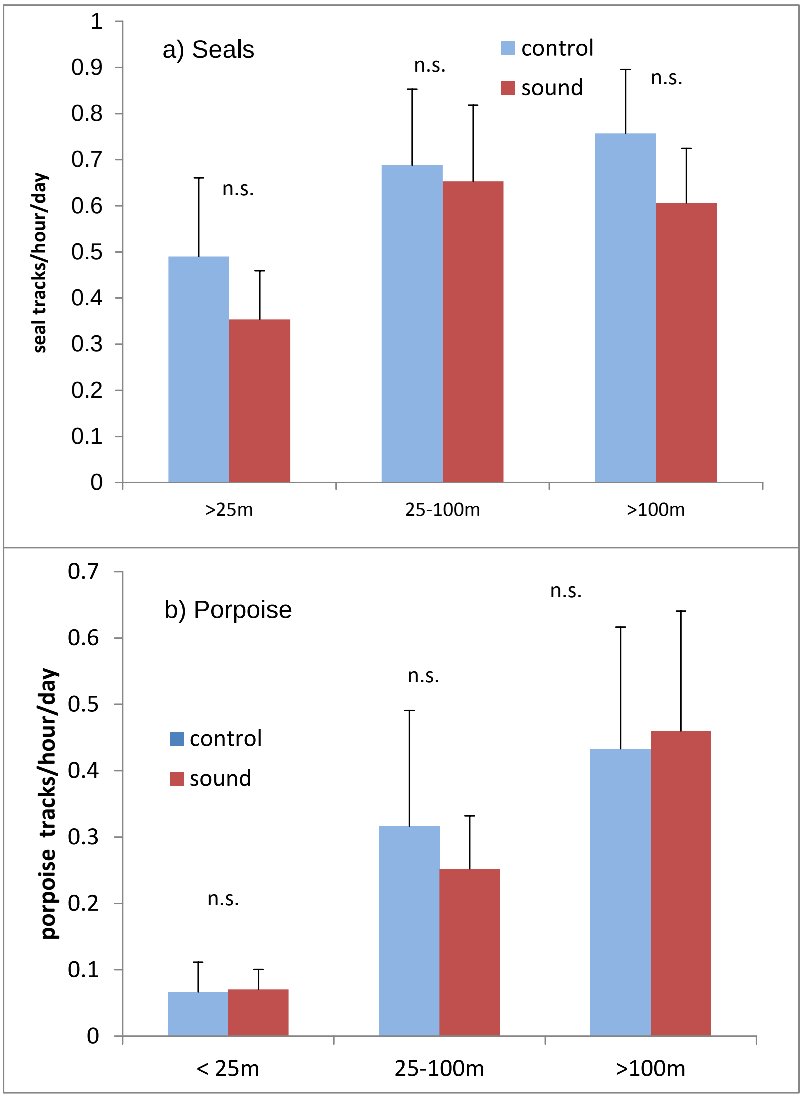


Fig 5: Mean number of seal a) and porpoise tracks b) per hour per day for the three distance bins (distance to the closest loudspeaker).

While the known presence of porpoise and seals in the area was a reason for choosing the study site, sightings of otters were unexpected and originally not intended to be part of the study. However, we logged otter sightings systematically (Fig 7). Most otter tracks occurred along the shoreline southeast of the farm. Otters were sighted on 4 sound exposure days (4 tracks) and 2 control observation days (2 tracks). The closest observed approach distance during sound exposure was 50m and 15m during control observation days.

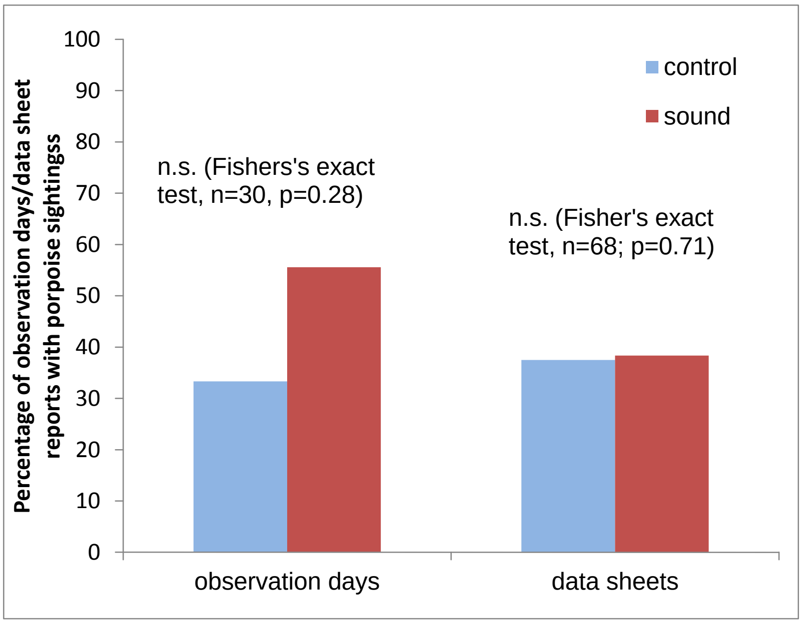


Fig 6: Percentage of observation days on which porpoise where seen within 100m of a loudspeaker (left block) during sound exposure (red) and control observation days (light blue). The block on the right shows the percentage of questionnaires (data sheets) which reported porpoise sightings around the farm.

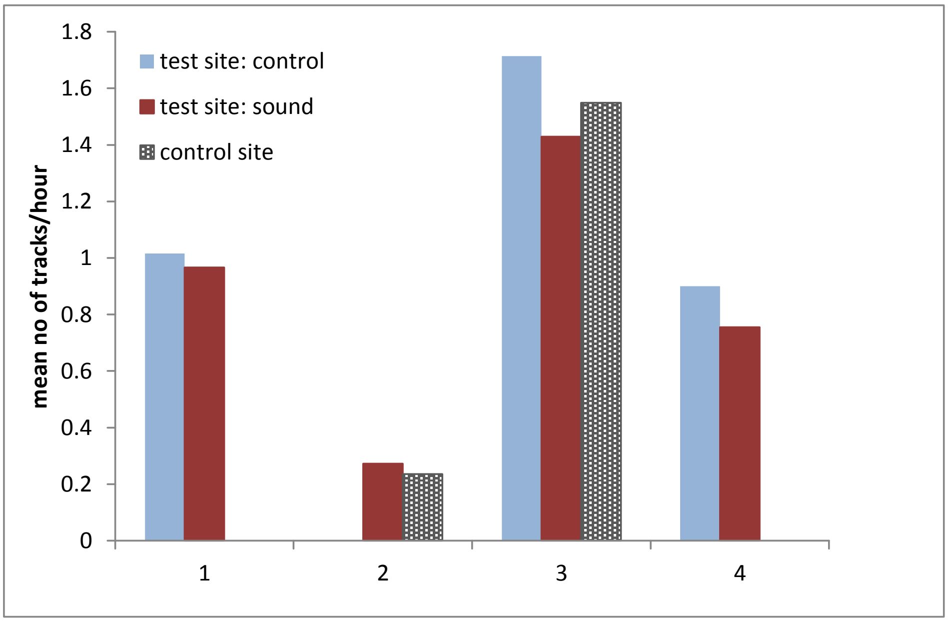


Fig 7: Mean number of tracks per hour calculated for the 4 quarters of the year for the test site during sound exposure, the test site prior to deployment and the control site 1 (1: Jan-Mar, 2: Apr-June, 3: Jul-Sep, 4: Oct-Dec). Missing columns indicate that no data was collected for the respective quarter.

Short-term trials on farms with predation problems

a) Ardmaddy (Argyll)

At the beginning of April 2011 predation losses at the Ardmaddy control site began to rise. The site manager reported that food intake was dropping, possibly due to the presence of seals around the cages. The farm was stocked with 2 cages with fish fully grown and awaiting harvest in May 2011. To prevent significant loss, a single loudspeaker deterrence system was placed at the fish farm for the two weeks before harvest.

<u>Methods</u>

Ardmaddy fish farm consists of square steel cages connected by walkways which made deployment of the equipment easy, enabling coverage of the two cages with one loudspeaker. The two stocked cages were positioned adjacent to each other on the landside of the farm. The deterrence system was deployed on 18 May 2011. The equipment could not be connected to mains power so that farm staff had to change batteries every 2-3 days. Predation was monitored in detail by the site manager prior to, and during deployment of our equipment, based on the fish retrieved by divers.

Results

Predation levels at Ardmaddy were high in April and May 2011 with most dive reports revealing losses ranging from 30-70 fish (150-350 kg biomass, Fig 8). Predation levels in both adjacent cages were similar across the one month pre-deployment period (cage 7: 202 fish, cage 8: 203 fish). Overall, 405 fish were killed by seals during the pre-deployment period when monitoring was carried out (Fig 8) with seal inflicted losses accounting for 65% of the overall losses at the farm. The first dive report after deployment of our startle system showed no seal-related kills in cage 8. Cage 7 was harvested a week after deployment of the equipment with no fresh seal kills found in the net. The net contained 10 fish with bite wounds but all were in a state of highly advanced decomposition indicating that these fish were previously missed by the divers. Fish removals by divers are more likely to miss dead fish compared to harvest which reveals the full content of the cage. Cage 7 remained stocked for another week before it was harvested. The full count of all dead fish at harvest revealed only a single fish killed by a seal (Fig 8). No monitoring of seal behaviour was carried out.

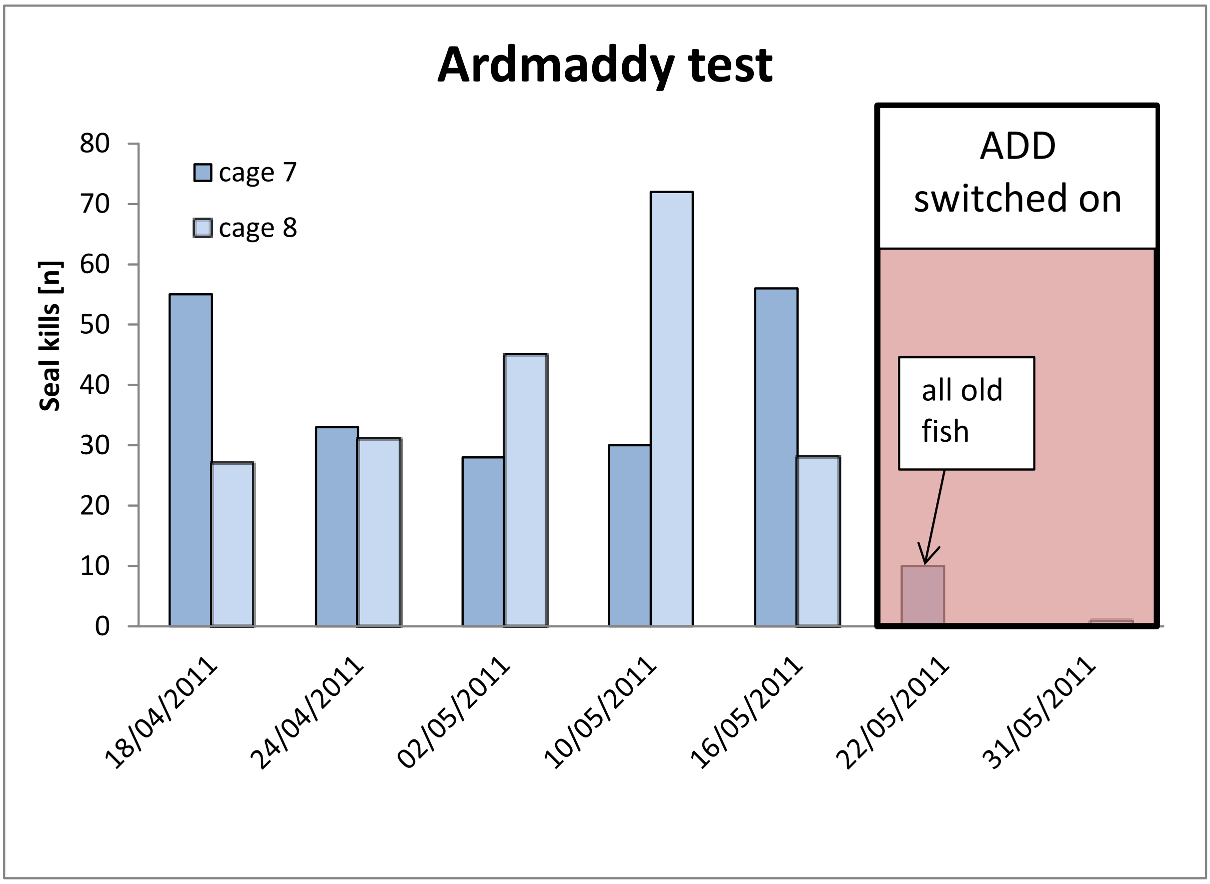


Fig 8: Predation losses (seal kills) inflicted by seals on Ardmaddy farm prior to the deployment of the single transducer (white area) and during its operation (pink area). Only one fish was lost due to seal predation when the transducer was in operation.

b) Quanterness (Orkney)

Methods

Seal predation on fish farms in Orkney is understood to be primarily caused by grey seals. Several farms in Orkney suffered heavy predation in winter and spring 2011 but predation was reported to be highly dynamic. On 02 July 2011 we deployed a startle system with 2 transducers and a source level of 174 to 176 dB re 1µPa on a Meridian Salmon (Ltd.) farm with 4 isolated circular cages stocked with smolts. The two loudspeakers were fitted on two separate cages.

Results

Seal predation levels were moderate to low and highly variable prior to deployment of our system (Fig 9). During the first week following deployment no fish mortality attributed to seals was found in the cages but during the second week numbers were comparable to the pre-deployment period. However, the equipment was not operating for parts of the second week due to power failure. The last confirmed operation of the equipment was at the end of week 1 on 19 July 2011. Several severe gales in the following weeks caused the control box to flood destroying all electronic components. The equipment was removed and no additional trials were carried out at this farm.

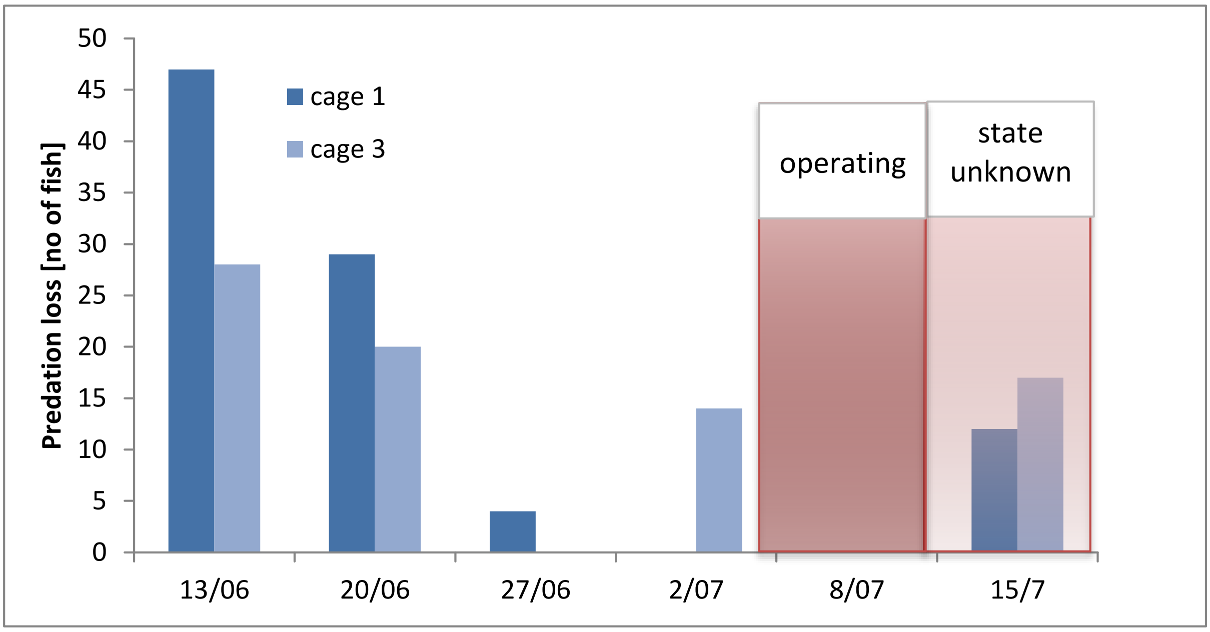


Fig 9: Predation losses on Quanterness farm prior to the deployment of the single transducer (white area) and during its operation (pink area). ‘State unknown’ indicates the system was off (battery depleted) for some unknown time during that period.

Startle threshold in bottlenose dolphins

Methods

Experiments were carried out with trained captive bottlenose dolphins (Tursiops truncatus) at the Marine Mammal Research Facility of the Hawaii Institute of Marine Biology. The test subjects, a female (BJ) and a male (Boris), were trained to enter a hoop station which enabled them to remain stationary in front of a sound projector (Fig 10). A data logger which consisted of a three-dimensional acceleromter sensor

(GCDC X 6-2) was placed in a custom-made underwater housing and attached with suction cups latero-dorsally to the animal (Fig 10). The accelerometer sampled 320 data points per second and was used to quantify brief muscle flinches typically associated with the startle reflex. The tested sound stimuli were 50ms long 1/3 octave band noise pulses with centre frequencies of 1khz, 10kHz, 25 kHz and 32 kHz and an onset time of 1-2ms. The accelerometer tag was either positioned cranially (10kHz) or caudally (1kHz, 25 kHz and 32 kHz) of the dorsal fin. The sound projector consisted of either a Lubell loudspeaker 9162T (1 kHz & 10kHz) or an ITC 1032 hydrophone (25 kHz & 32 kHz) positioned 1.5m in front of the hoop station (Fig 10). The digital signals were played through a National Instruments card (controlled by LabView) onto a power amplifier which was connected to the respective sound transducer.

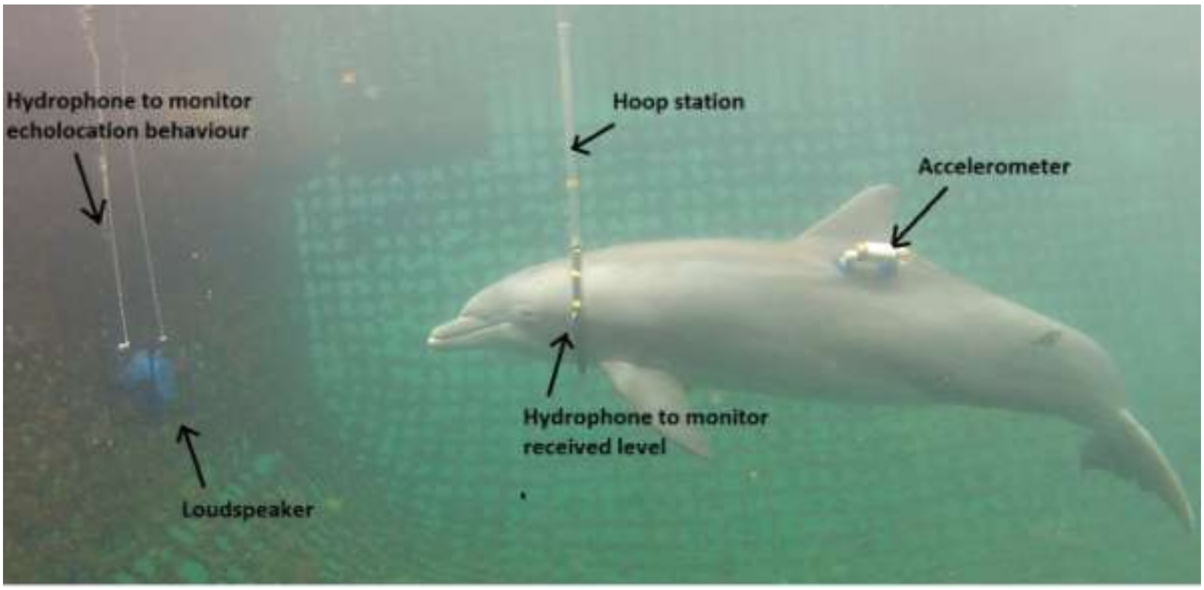


Fig 10: Experimental setup with one of the dolphins stationing in the hoop. Startle responses were quantified with the accelerometer tag attached to the animals.

In addition to the playback setup two montoring hydrophones were installed (B&K 8103, Reson TC 4103), one placed on the hoop station and one approximately 30 cm above the sound projector. The hydrophone located at the hoop station was used to monitor received levels in proximity to the dolphins' ear. The ouput of the two hydrophones was amplified with two Etec pre-amplifiers, digitized with a National

Instruments card (sampling rates of 300kHz or 400 kHz) and recorded onto a second laptop computer.

An experimental trial started with the dolphin positioning at a touch pad in front of the trainer. The trainer gave the dolphin a signal to enter the hoop station while the behaviour of the animal was monitored with an underwater camera connected to an LCD screen. Once the animal had settled into the hoop station, a countdown to the start of the playback began. The time between start of the countdown and the playback was varied randomly across trials with intervals ranging from approximately 2s to 58s. The animal was then called back with an acoustic signal (trainer whistle), returned to the touch pad and received a food reward. Each experimental session consisted of 12 sound exposure trials and one no sound control during which exactly the same experimental procedure was followed but no playback was carried out. In each session the playback output was decreased in 6 dB steps from the first trial towards the 6th trial, then increased by 3 dB and consecutively increased again in 6 dB steps up to the 12th trial. Some playback sessions contained less trials due to malfunction of equipment.

Data analysis involved calculating received levels and time of playback from the calibrated acoustic record. Received levels measured at the hoop station were compensated for transmission loss between the hydrophone and the presumed acoustic window on the dolphin’s head. Startle response magnitude was quantified by measuring peak to peak acceleration on all three axes of the accelerometer and calculating the overall vector acceleration (in Matlab R 2011). This was performed within a 1s time window after the onset of the sound pulse. The same procedure was carried out for the ‘no sound control’ trial in which case five 1s time windows were randomly selected when the animal was stationed without any sound playback. Startle thresholds were determined by two alternative methods. The first method involved fitting Generalized Linear Models with a gamma distribution of errors and a log-link function in R. The models included peak to peak acceleration (in m/s^2) as dependent variable, received level (in dB re 1 µPa) as independent variable, playback session as an ordered factor and playback number or log of playback number (within a session) as a covariate. The model with the lowest Akaike information criterion was used to predict the data. If playback number was included as a covariate then predicted values for an intermediate trial number were used (i.e.

trial 6.5). The startle threshold was determined in two different ways. In the first one, we used the model output received level that corresponded to the first predicted peak to peak acceleration value that was greater than the average acceleration found in the no sound control. The second method defined the threshold as the received level that caused an observed acceleration above the average acceleration measured during the no sound control.

Results

The data show that startle responses could be reliably elicited in the animals. Figure 11 shows the typical relationship between startle response magnitude i.e. the strength of the muscular flinch and received level. Startle response magnitude increased with increasing received level in a logarithmic fashion and did not seem to reach a ceiling within the tested range of received levels. The startle threshold in figure 11 corresponds to the point where the predicted curves cross the average peak to peak vector acceleration level during the respective no sound control trials. The modellling results revealed that received level was by far the most important predictor for startle magnitude while session number or playback number was much less important.

Average startle thresholds differed across the tested range of frequencies by approximately 20 dB (Fig 12). The lowest startle thresholds were measured in the ultrasonic range at a frequency of 32 kHz. The lowest average threshold at 32 kHz was found in BJ, the female dolphin. The average startle threshold increased by approximately 13 dB when frequencies were lowered from 32 kHz to 10 kHz. A further increase by another 5 dB can be found when comapring thresholds at 10 kHz and 1 kHz (Fig 12). The highest threshold of 151 µPa re 1µPa was found in the measured response at 1 kHz in the male dolphin. These differences roughly correlate with differences in the auditory sensitivity of the test subjects at the respective frequencies. Figure 12 shows the averaged hearing thresholds of the two dolphins at frequencies of 10 khz , 25 kHz and 32 kHz and the extrapolation of these data down to 1 kHz. The hearing threshold of these animals was measured electro-physiologically through auditory evoked potentials in a previous study. Startle thresholds followed the auditory threshold with a difference of 44-46 dB. We found considerable differences between the thresholds obtained by the two different methods. The method based on modelling the relationship between received level and startle magnitude consistently yielded lower levels than the observed startle data. This is due to the fact the fitted curves often had low slopes as they approached the ‘no sound control’ (Fig 11). Thresholds can therefore be viewed as the minimum received levels at which the reflex begins to cause a small muscle contraction.

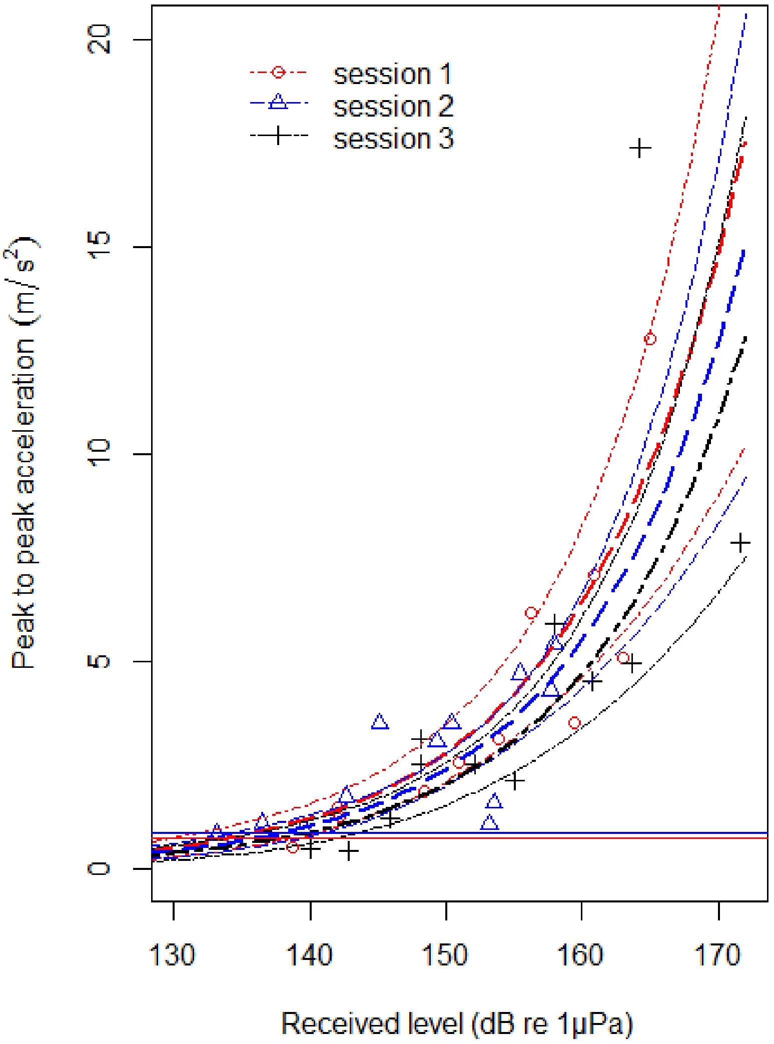


Fig 11: Maximum peak to peak acceleration measured in the 1s time window after onset of the sound for all playback sessions using the 10 kHz noise pulse (female dolphin, BJ). The curves represent predicted values and confidence intervals obtained from the Generalised Linear Model. The horizontal lines give the average peak-to-peak acceleration levels during no sound controls for each playback session.

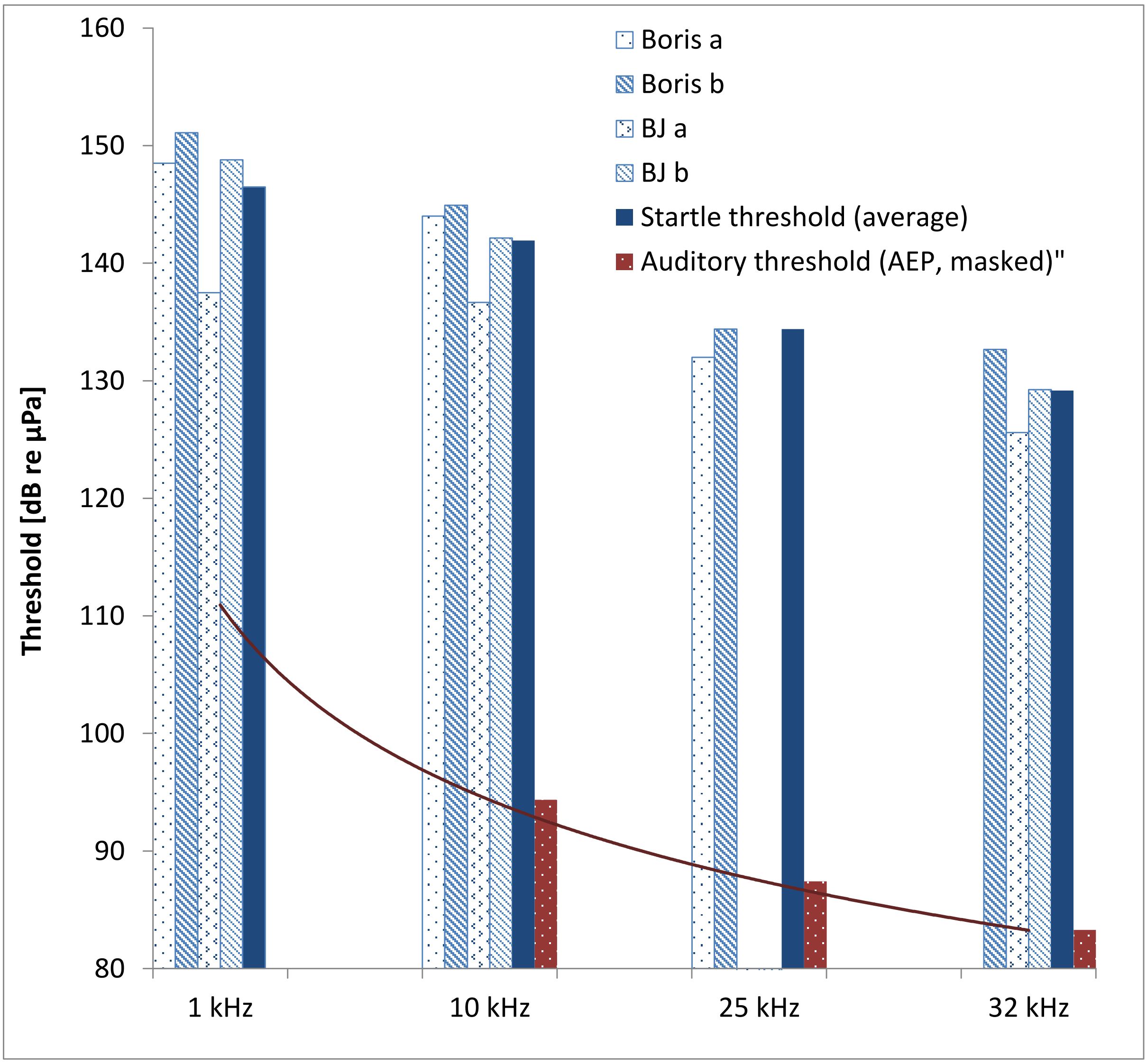


Fig 12: Startle thresholds obtained from the two test subjects at various frequencies. The dark blue column gives average values across the different methods and test subjects. Method a) refers to thresholds obtained from the models while method b) represents observed thresholds. The red bars represent an average of the electro-physiologically obtained hearing threshold for the two subjects. The solid line is a curve fitted to the hearing data in the red columns and was based on a power function.

General discussion

Seal predation

The direct comparison of monthly losses between the pre-deployment period, test period and control sites showed that the startle method was capable of significantly reducing predation losses throughout the one year deployment period (Fig 3). This is confirmed by the predation model which showed that sound exposure was the most important explanatory factor with respect to variation in seal predation. The model also revealed that predation varied throughout the year, although different sites had similar fish losses during different times of year with overall predation levels similar across sites. This shows that the low level of predation on the test site during sound exposure was not due to seasonality of predation but was due to the deterrence equipment.

Furthermore, predation was completely absent for 8 consecutive months (June 2011 to January 2012). Throughout the 13 months period of systems operation, there were only 5 events of predation on the test site, three of which were negligible. The most likely explanation for the occurrence of predation while the equipment was operating is that the predating individuals had compromised hearing which could be either the result of genetic predisposition, old age or previous exposure to anthropogenic noise source (such as commercially available seal scarers).

The experiment at Ardmaddy showed that the startle method is capable of reducing predation where losses prior to deployment were high. The experiment in Orkney at the Quanterness fish farm remains inconclusive. While predation was absent in the week after deployment, we do not know when it was operational in the following week when predation returned to pre-deployment levels. The exact breakdown date is unknown making further quantitative analysis impossible.

Animal abundance and movement

A unexpected result was that seals were frequently seen in the vicinity of the cages during sound exposure. This is in contrast to results from our earlier report (Janik & Götz 2008) where surface positions proved to be a good predictor for movement responses. In these earlier studies seals were excluded from a zone of about 25m around the transducer and seal numbers were lower up to 60m from a transducer operating at a source level of 180 dB re 1µPa.

The main difference between these studies was that the current study involved continuous sound exposure for 24 hours a day over several months while the previous studies used limited exposure times in a controlled experimental setup with several repetitions of different treatments. There are two possible interpretations for these results. First, it is possible that seals habituated to the deterrent sound pulses and were therefore not affected in their movement responses. However, this seems unlikely given that predation levels were low and predation was virtually absent for the second half of the test period. The alternative and more likely explanation is that seals sensitised to the sound and increasingly reduced dive times. Through extended surface swimming seals could have removed themselves from sound exposure making them more likely to be detected by human observers on the barge. This second scenario is consistent with previous captive studies that showed that repeated exposure to startling pulses result in a decrease in diving behaviour (Götz and Janik 2011).

Further observations to investigate the diving behaviour of seals were conducted on a single day when we measured 7 seal tracks underwater using a Tritech Gemini 720 sonar. In only one of these tracks did a seal approach the speaker to a distance of less than 20m, slightly less than the exclusion zone found in our previous study. There is an additional factor that should be considered regarding seal movement behaviour. A large percentage of the close tracks occurred in August/September 2011, approximately 2-3 month following the harbour seal pupping season. Juvenile seals are often positively buoyant (due to high fat content after weaning) and juveniles accounted for most tracks in our study. Thus, energetic constraints may have reduced dive times and led to increased surface swimming.

Harbour porpoise movement behaviour and abundance throughout the year was not affected by the deterrence setup with porpoises regularly seen within 15m of the loudspeakers. This confirms findings from our previous report which showed that the startle method can be tuned towards the hearing thresholds of target species, so that it affects seals but not porpoises. Furthermore, the deterrence method can be adjusted for other species so that it targets porpoises but not seals, or deters both taxa. This could be useful when trying to clear an area of marine mammals during industrial operations such as wind farm construction.

Distribution of otters around the farm did not seem to be affected by the deterrence system. Although the closest observed approach distance was smaller during control periods the data showed that this species is not negatively affected in areas beyond 50m from the farm. Therefore, the startle method can be used safely for seal deterrence in areas where otters are present.

The startle reflex in echolocating toothed whales

Bottlenose dolphins use brief high-intensity sound pulses for echolocation and are known to possess the ability to regulate their auditory sensitivity when solving echolocation tasks (Nachtigall & Supin 2008). This has posed the question whether dolphins are capable of suppressing the startle reflex under certain circumstances. However, the data from this study showed that external sound pulses at sound pressure levels much lower than those used by dolphins for echolocation are capable of eliciting the startle reflex. One contributing factor may be that the time of the playback could not easily be predicted by the dolphins due to the randomly selected sound presentation times.

The fact that the startle threshold roughly followed the hearing threshold of the dolphins across a range of different frequencies is consistent with data on terrestrial mammals (Pilz et al. 1987). We found that the difference between the auditory threshold and startle threshold appeared to be only 45 dB. This would be considerably lower than for any other mammal. However, the hearing thresholds obtained from the dolphins were almost 40 dB higher than previously measured thresholds for this species (Johnson 1967). The reasons for this are: a) the hearing threshold was a masked threshold due to the noise caused by snapping shrimp in the test pens, b) the thresholds were obtained with an electro-physiological method which typically yields approximately 20 dB higher thresholds than traditional psycho-physical methods, and c) the animals may have had some degree of age-related hearing loss at higher frequencies. Hence, even when excluding the possibility of mild hearing loss it seems fair to assume that actual unmasked hearing thresholds obtained with a psycho-physical method would have been at least 35 dB lower. This means that sensation levels needed to trigger the startle reflex in dolphins are more likely to be in the order 80 dB which is much closer to values previously reported for other species (Stoddart et al. 2008).

The startle reflex has previously been shown to induce flight responses, interrupt foraging behaviour and cause sensitisation of subsequent avoidance behaviour in pinnipeds (Götz and Janik, 2011). One dolphin tested in this study also backed out of the hoop station during the first exposures. This behaviour in a highly trained animal suggests that a startle response is likely to be followed by flight and avoidance behaviour in wild untrained dolphins. Thus, we think it is possible to develop a deterrence system for dolphins and porpoises by choosing a startle sound at a frequency of around 40 kHz. This means that a startle-based deterrence system could potentially be used to keep porpoises and dolphins away from areas of harm such as noisy marine construction sites. Further applications could involve guiding marine mammals around tidal turbines to mitigate collision risk or deterring porpoises from gillnets more reliably than can be achieved with current pingers.

While our study confirmed that startle thresholds are frequency specific, it also demonstrated that startle responses can be elicited at moderate levels outside the most sensitive hearing range of dolphins. This means that many anthropogenic pulsed noise sources also have the potential to startle animals and therefore cause strong behavioural responses. If the startle reflex is the underlying mechanism for such strong aversion responses then noise effects could be mitigated by increasing the onset-time of the sounds that cause the reactions.

Implications for regulators and management

The deterrent system tested in this study operated at a duty cycle of less than 1% which is between one and two orders of magnitude lower than the current commercially available deterrent devices. The fact that brief, isolated pulses were emitted at only moderately loud source levels means that noise pollution was greatly reduced and the potential for masking communication signals or hearing damage is low. This is in contrast to current commercially available seal scarers, which emit sound at high duty cycles and high source levels (Lepper et al. 2004).

Noise pollution for cetaceans however is a concern. Long-term and large-scale habitat exclusion has been found for odontocetes around operating ADDs at relatively low received levels (e.g. Morton and Symonds 2002; Olesiuk et al. 2002). While most of these reactions were reported for Airmar devices, ADDs of other manufacturers produce even more energy at high frequencies where odontocetes are most sensitive, and may therefore have an even more severe effect. Furthermore, porpoises have been shown to suffer temporary hearing damage at relatively low levels (Lucke 2007) and current commercially available acoustic deterrent devices may have the potential to damage the ears of odontocetes (Götz and Hastie 2009). The use of lower source levels, low duty cycles and large gaps between brief acoustic emissions as tested in this study will remove the risk of hearing damage. We recommend a scientific evaluation of the potential for damage to wildlife before a device is approved for use in the marine environment.

Apart from decreasing noise pollution and effects on non-target species, the startle method also appeared to be more effective at reducing seal predation than existing commercial ADDs (Götz & Janik 2010). The 13 months trial reported here confirmed the high effectiveness of the startle method using seal predation (rather than approaches) as a measure. This creates benefits for the farm and for seal populations. While farmers will experience less predation, the requirement for lethal removal of seals may be reduced. Furthermore, our comprehensive theodolite tracking data set showed that seals spent significant amounts of time in the vicinity of the cages but did not predate on farmed fish. Hence, removal of seals close to the farm does not necessarily solve the problem of fish damage since close approaches do not necessarily mean predation takes place. In relation to seal conservation and the decline of harbour seal populations in Scotland (Lonergan et all, 2007), efforts to reduce shooting and encourage the use of alternative technologies such as the startle method are important.

Our results on the startle threshold in bottlenose dolphins show that the startle method can be finely tuned to deter only seals, only toothed whales or both, depending on the exact design of the signal. Further tests on the potential for sensitization in delphinids and porpoises are needed. If successful, the startle method could be used for the control of marine mammal movement in fields beyond aquaculture such as marine construction and the operation of marine renewable energy devices.

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Appendix 1: Record of seal scarer operation and loudspeaker configuration

Date (change of state)	Transducers deployed	Transducers operating	Reason for failure/notes
16.1.2011	5, 6	5,6	Installed and running
31.1.2011	5,6	none	power supply failure
4.2.2011	1,2,3,4	1,2,3,4 (low source level)	repair job interrupted by storm
7.2.2011	1,2,3,4	none	battery drained, power supply issue still not resolved
14.2. 2011	1,2,3,4	1,2,3,4	
23.2. 2011	1,2,3,4	none	power supply failed again
25.2.2011	1,2,3,4	1,2,3,4 (2 (transducers firing synchronously)	power amplifier broke down
8.3.2011	1,2,3,4	1,2,3,4 (transducers firing pseudo-randomly)	new power amplifier installed
12.5.2011	1,2,6	1,2,6	one transducer removed for “rapid response trial” at Ardmaddy fish farm
10.7.2011	1,2,6	1,2,6	cable of transducer 1 was cut accidentally by fish farm staff; transducer not operating for previous 2 weeks

16.7.2011	1,2,6	none (on intermittently)	battery drained, generator running only during the day, top net came down (high morts in cage 6)
26.7.	1,2,6	1,2,6	battery re-charged
3.8.2011	1,2,6	1,2,6	cable of transducer 1 was found cut again and repaired
30.8.2011	1,2,6	none	battery drained, charger not strong enough
31.08.2011	1,2,6	1,2,6	battery re-charged
8.9.2011	1,2,6	none	battery drained, charger not strong enough
9.9.2011	1,2,6	1,2,6	battery recharged
11.09.2011	1,2,6	none	battery drained
15.09.2011	1,2,6	1,2,6	battery recharged
Nov	1,2,6	1,2	one power-amplifier broke down
15.11.2011	1,2,6	2,6	transducers re-wired
16.12.2011	1,2,6	1,2,6	new power-amplifier installed

Appendix 2: Sample data sheet/questionnaire for the test site

Port na Cro: Dead Removal Datasheet

1. Please tick the date when the fish were collected:

MARCH 2012						
SUN	MON	TUE	WED	THU	FRI	SAT
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

2. Who did the count?

3.) Fish collected today from…

Baskets only ☐ Baskets & Divers ☐ Divers only ☐

4.) Did you see any of these species around the nets since last collection?

1 Seal ☐ 2 Seals ☐ more than 2 seals ☐ Mackerel ☐ Other wild fish ☐ Porpoise ☐

5.) Please write down how many dead fish were removed:

Cage 5	**Cage 6**	**Cage 7**	**Cage 8**	
Total: ☐ **Seal damage:** ☐	**Total:** ☐ **Seal damage:** ☐	**Total:** ☐ **Seal damage:** ☐	**Total:** ☐ **Seal damage:** ☐	
Cage 4	**Cage 3**	**Cage 2**	**Cage 1**	Barge
Total: ☐ **Seal damage:** ☐	**Total:** ☐ **Seal damage:** ☐	**Total:** ☐ **Seal damage:** ☐	**Total:** ☐ **Seal damage:** ☐	

6.) Seal spooking fish since last count **often** ☐ **sometimes** ☐ **never seen** ☐

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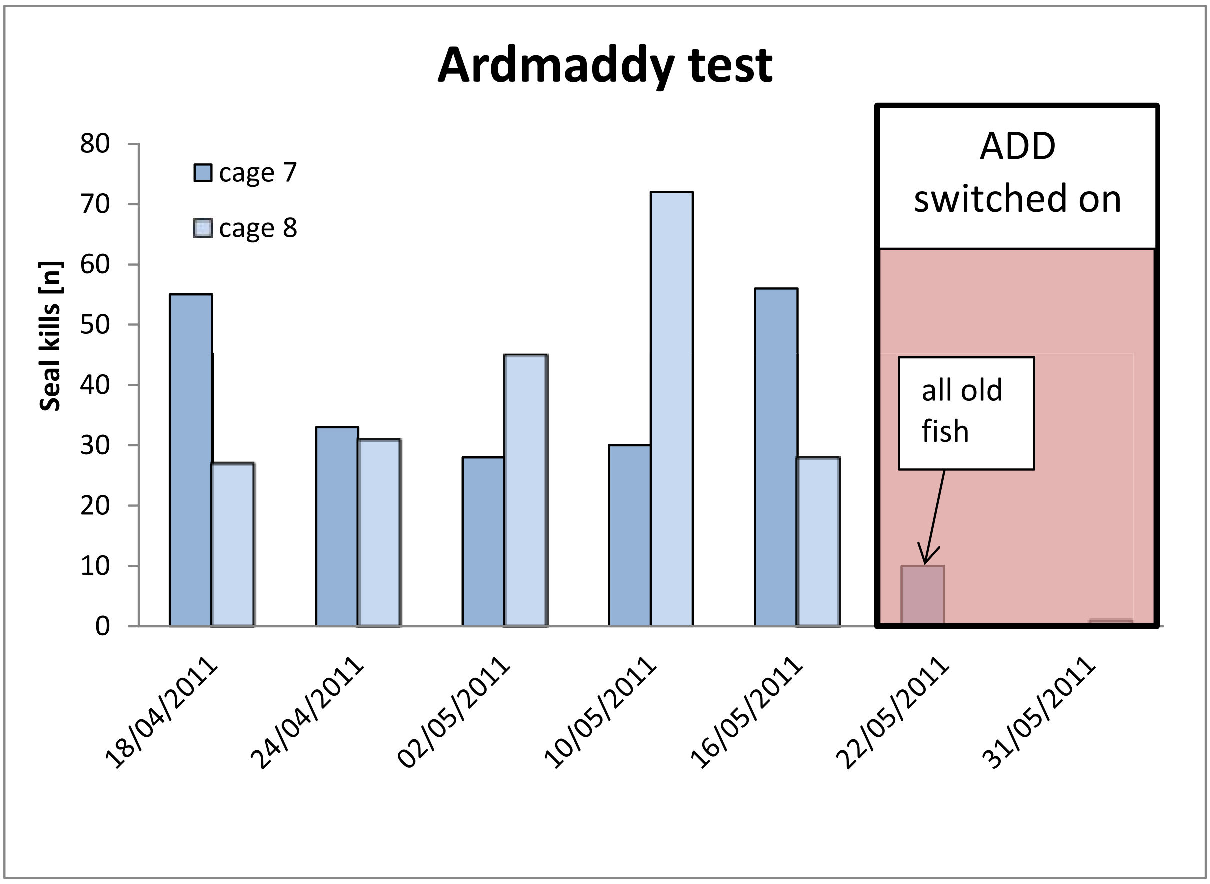

Fig 8: Predation losses (seal kills) inflicted by seals on Ardmaddy farm prior to the deployment of the single transducer (white area) and during its operation (pink area). Only one fish was lost due to seal predation when the transducer was in operation.

b) Quanterness (Orkney)

Methods

Seal predation on fish farms in Orkney is understood to be primarily caused by grey seals. Several farms in Orkney suffered heavy predation in winter and spring 2011 but predation was reported to be highly dynamic. On 02 July 2011 we deployed a startle system with 2 transducers and a source level of 174 to 176 dB re 1µPa on a Meridian Salmon (Ltd.) farm with 4 isolated circular cages stocked with smolts. The two loudspeakers were fitted on two separate cages.

Results

Seal predation levels were moderate to low and highly variable prior to deployment of our system (Fig 9). During the first week following deployment no fish mortality attributed to seals was found in the cages but during the second week numbers were comparable to the pre-deployment period. However, the equipment was not operating for parts of the second week due to power failure. The last confirmed operation of the equipment was at the end of week 1 on 19 July 2011. Several severe gales in the following weeks caused the control box to flood destroying all electronic components. The equipment was removed and no additional trials were carried out at this farm.

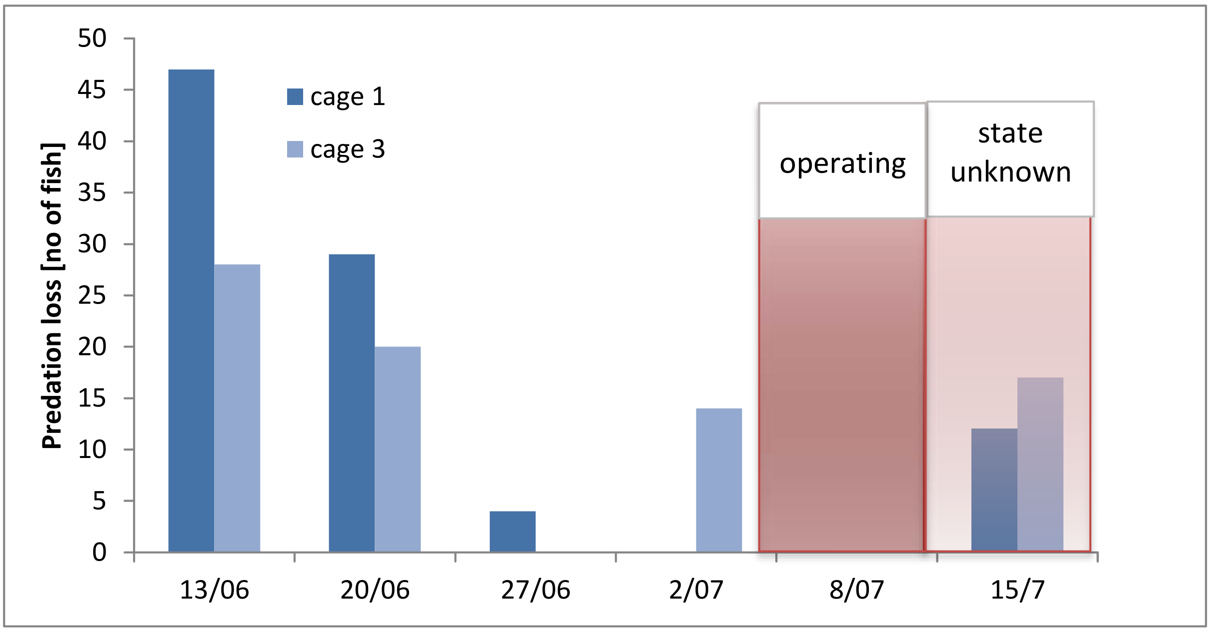

Fig 9: Predation losses on Quanterness farm prior to the deployment of the single transducer (white area) and during its operation (pink area). 'State unknown' indicates the system was off (battery depleted) for some unknown time during that period.

Startle threshold in bottlenose dolphins

Methods

Experiments were carried out with trained captive bottlenose dolphins (Tursiops truncatus) at the Marine Mammal Research Facility of the Hawaii Institute of Marine Biology. The test subjects, a female (BJ) and a male (Boris), were trained to enter a hoop station which enabled them to remain stationary in front of a sound projector (Fig 10). A data logger which consisted of a three-dimensional acceleromter sensor

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