Non-Lethal Seal Deterrent in the North East Scotland Handline Mackerel Fishery.

A Trial using Targeted Acoustic Startle Technology (TAST)

David Whyte, Thomas Götz, Sam F. Walmsley and Vincent M. Janik

University of St Andrews FOUNDED 1413

Scottish Government Riaghaltas na h-Alba gov.scot

marinescotland

R.H.I.F.A

North and East Coast Regional Inshore Fisheries Group

GENUSWAVE

Contents

Project Team

- David Whyte, Rosehearty Harbour and Inshore Fisherman's Association (RHIFA)
- Dr Thomas Götz, University of St Andrews
- Professor Vincent Janik, University of St Andrews
- Lynda Blackadder, Marine Scotland Science (MSS)
- Anne McLay, Marine Scotland Science (MSS)
- Sam Walmsley, University of St Andrews
- Chloe Aird, Marine Scotland (MS)
- Jennifer Mouat, North East Coast Regional Inshore Fishery Group (NECRIFG)
- Steven Alevy (Genuswave)

Funding

This trial was funded by the North East Coast Regional Inshore Fishery Group (NECRIFG), Genuswave and Rosehearty Harbour and Inshore Fisherman's Association (RHIFA).

Executive Summary

Local Rosehearty fishers have observed a steady increase in seal numbers around the north east coast of Scotland in recent years with seals causing significant disruption to the inshore handline fishery for mackerel. Seals often follow boats as they leave the harbour to search for fish and when fish are located, seals interfere with fishing operations by dispersing the shoals. Fishers are keen to reduce these negative interactions with seals. A trial using Targeted Acoustic Startle Technology (TAST) to deter seals in the vicinity of fishing vessels was carried out between late July and early October 2020 on the inshore mackerel grounds in the North East Coast Regional Inshore Fishery Group (NECRIFG) area.

The trial involved five fishing vessels operating from Rosehearty Harbour. Fishers were asked to return a data sheet for each day fished, recording data on seal sightings, fishing operations and catches on days when they were either fishing normally (control) or additionally deploying the TAST device. Data analysis revealed a strong deterrence effect of TAST on seal activity directly around fishing vessels, in which seal detections on the vessels' fish finder (sonar) decreased by 97%. Only one seal was observed under a vessel when TAST was deployed. No significant effect was evident in the visual sighting data, though fewer seals were spotted when TAST was operatiponal. This could be the result of a limited deterrence range of the device and/or a change of seal dive submersion times. Beyond the influence of TAST, visual detections of seals decreased towards the end of the season. Fishing metrics such as 'fishing stop duration' and 'catch weights' were primarily influenced by time-of-year (seasonality). However, fishing stop duration was almost twice as long when TAST was used which may be the result of a reduction in shoal dispersal caused by seals. More data are required to investigate whether TAST also leads to an increase in catch weight. Generally, statistical findings are consistent with reports from fishers, supporting the idea that TAST is effective in its primary function of deterring seals and preventing shoal dispersal caused by seals swimming under or close to the vessel.

The study suffered from an imbalance between control and TAST days and a decline in seal/vessel interactions towards the end of the fishing season. It would be helpful to collect more data during the presumed peak predation season in June and July. It would also be beneficial to

investigate seal/fish shoal interactions at the behavioural level using sonar from a secondary vessel to optimise TAST use and provide fishers with improved fishing practice guidelines.

Introduction

Studies have reported a continuous increase in seal numbers around the east coast of the UK sine 1985 with a four-fold increase in grey seal pup production over 20 years (Thomas et al. 2019). Fishers have also reported an increase in seal numbers around the north east coast of Scotland (and elsewhere in the UK) since the introduction of seal protection measures, initially through the Conservation of Seals act 1970 and more recently the Marine (Scotland) Act 2010 - Part 6 'Conservation of seals'. Interaction between seals and fisheries is an increasingly common occurrence and has been well documented in recent years (MMO 2020, Tixier et al. 2021). .

For a number of years, local fishers in Rosehearty and other east coast harbours, such as Fraserburgh, Whitehills and Eyemouth, have reported problems with seals interfering with the inshore handline mackerel fishery. Hindrance has been increasing year on year, causing frustration to the industry and the locals who rely on this fishery for their income. The main issue is the detrimental effect the seals have on fishing operations by scaring and dispersing the shoals of fish. Seals will remove fish from the handlines, however the quantity of fish lost in this way is negligible compared to the loss of catch due to diminished fishing time on mackerel shoals. In many cases, although fish are present in the area, seal interference makes it extremely difficult for fishers to catch their allocated quota.

The handline mackerel fishing season is contingent on the arrival of shoals in the area and typically starts sometime between May and June, continuing into October. The fishery provides a significant source of income for many inshore fishers around the east coast of Scotland, particularly in the Rosehearty area, and is also a diversification opportunity which reduces the effort targeted towards fishing crab and lobster stocks.

The extent of seal interference varies throughout the season and is typically at its highest during June to September. Fishers report that seal interference appears to decrease during September. Grey seals (*Halichoerus grypus*) appear to constitute the majority of seals in the area (Russell et al 2017). Juvenile and adult seals are occasionally observed following the fishing boats and it is possible that juveniles learn to participate in this ‘easy meal’ approach from experienced adults.

A proposal document “Seal conflict with under 10 m summer Handline Mackerel Fishery” (Appendix 1) was tabled to representatives of NECRIFG, Marine Scotland Science, the Sea Mammal Research Unit at the University of St Andrews and other interested parties on the 25th February 2020. The report detailed the detrimental effects of the increase in predatory seals, over at least 16 years. Seal conflict during the mackerel fishery generates the following issues for skippers;

- Frequent returns to port with insufficient quantity of fish to land
- Inability to catch allocated quota
- More time at sea
- Increased fuel consumption
- Loss of earnings
- Injury to seals by entanglement in fishing lines.

The proposal document was written from the perspective of the fishers. It provides background information on the mackerel handline fishery, the fishing methods used and the seasonal nature of the fishery by under 10 m vessels operating from a small harbour. The constraints associated with boat size, the limited fishing opportunities within the fisher's safe area of operation, and the seasonal nature of the fisheries are also explained.

Additionally, an outline of the legal framework associated with the protection of seals is provided within the proposal document. In considering suitable ways to alleviate the seal conflict situation, the report considered the sensitivities associated with licensed seal removal. However, this option was discounted and instead, the use of a non-lethal acoustic deterrent device (ADD), specifically the Targeted Acoustic Startle Technology (TAST) device, was proposed in the hope that TAST might provide a solution

Acoustic deterrent or harassment devices are widely used for mitigating human predator interactions. These devices aim to deter animals by emitting sound at high source levels (>185 dB re 1µPa) and duty cycles (i.e., the duration over which sound is produced) (Götz & Janik, 2013). The long-term success of these devices is often limited and habituation, a decrease in responsiveness to the signal, can be a significant problem in contexts where food motivation is involved (Götz & Janik, 2010). ADDs have also been highlighted as a conservation concern as they could potentially cause hearing damage in target and non-target species, if exposure times are long, source levels are high and the target responsiveness is low (Götz & Janik, 2013).

An alternative is the TAST, which is based on the evolutionarily ancient autonomous startle reflex in the brainstem. This reflex has been found in all mammalian species studied to date (Yeomans et al. 2002). In experimental studies, repeated elicitation of the startle reflex caused sensitisation in avoidance behaviour (i.e., flight responses, spatial avoidance) in the majority of tested seals (Götz & Janik, 2011). This required only low noise doses caused by brief, isolated sound signals emitted at very low duty cycles (typically <1%). Target-specificity has been achieved by choosing a frequency band in which hearing sensitivity of seals is higher than in non-target species such as harbour porpoises (Götz & Janik, 2015, 2016). TAST has also been shown to be successful at keeping seals away from a fish farm while not adversely affecting non-target species (Götz & Janik, 2015). Consecutive studies demonstrated a reduction in seal predation by ~91-97% on fish farms in Scotland, in short term and long-term tests of up to one year (Götz & Janik, 2016). TAST has also been tested in inshore gillnet fisheries that were suffering predation from grey seals. In these trials, there was a 74% increase in catch in protected nets (MMO, 2020). While a recent modelling study suggested that TAST could cause hearing damage in specific conditions (Todd et al. 2021), several of the assumptions used in the model about the TAST signal were false. Signal transmission loss measurements in the field and modelling demonstrated that the TAST signal carries no such risks (e.g., Götz & Janik, 2015).

TAST was selected for this trial in line with one of the initial objectives of the local fishers; 'to minimise the impact on seals and other marine life in the vicinity of fishing activity' (Appendix 1) and due to its previously proven ability to deter seals during studies on salmon farms and also in the Torbay mackerel net fishery (MMO, 2020). The TAST device used in this study operates at a source level and duty cycle that is much lower than most conventional ADDs. The signals are centred in a frequency band where the targeted seal hearing is more sensitive than that of non-target species, making them not aversive to hearing specialists such as dolphins and porpoises (Götz & Janik 2015, 2016, Götz et al. 2020). To avoid causing hearing damage in any marine life, the device was set to a duty cycle of only 1%. This means that sounds were played for only 0.6 s in each minute.

The aim of this trial was to address the objectives outlined in the proposal document (Appendix 1) as follows;

- To formulate a sea trial aimed at identifying a suitable and sustainable method of preventing seal interference with the handline mackerel fishery.
- To implement a scientific trial in the sea area around Rosehearty or another suitable location.
- To provide a cost-effective long-term solution, easily implemented and maintained by under 10 m fishing boat skippers whilst minimising the impact on seals and other marine life in the vicinity of fishing activity.

It was agreed that, between July and October 2020, local fishing vessels from Rosehearty harbour would collect data on their typical fishing practices on the inshore mackerel grounds and make use of TAST to establish if this device successfully prevents seal interference with the fishery.

Fishing methods

The traditional handline fishing method, featuring twelve to fifteen hooks (flies) per line and shaking the fish off by hand as the line is pulled aboard the vessel, is used by very few fishers. This is because of the impalement hazard of hooks in hands and fingers (and other exposed body parts). The risk of serious injury from impalement is greatly increased if a seal pulls on the line. Nowadays, the use of fish stripping mechanisms with handlining and electrical jigging machines is more commonplace, and mackerel are typically caught on lines with 20 to 40 flies (Figure 1).

Figure 1. Typical mackerel fly, stripping box and chute and mackerel on the handline.

Boats operate between one and four sets of flies at a time dependant on available space and boat set up. There are generally four slightly different approaches to handline mackerel fishing on the north east coast of Scotland:

1. When mackerel shoals are relatively abundant the fishers adopt a search and stop method of fishing. This involves the boats searching for the shoals using an echo sounder / sonar. Upon locating a shoal, the skipper will turn and stop the boat whilst deploying the fishing lines. The shoal will thereafter be fished whilst the boat drifts until the shoal disperses either naturally or due to seal presence. The prototype TAST set up can be deployed on boats fishing in this way.
2. A second method uses the same search method as 1 (above) but instead of stopping the boat is turned in a tight circle at low speed whilst fishing. This method is dependent on boat fishing set up and tends to be used when the fish are "flighty". *The prototype TAST could not be deployed using this method.
3. A drift method of fishing tends to be used later in the season when the shoals are scarcer and in deeper water (>30 m depth). The boat will drift on the tide whilst continually deploying the fishing lines until a shoal is located. The prototype TAST can be used during this method of fishing.
4. A trolling method is adopted when the shoals are small and not easily detected by echosounder / sonar. Lines are towed behind the vessel whilst being constantly deployed and reeled in as the vessel moves forwards at a slow speed until fish are located. This enables the skipper to cover more sea area than using the drift method. *The prototype TAST set up cannot be deployed whilst trolling.

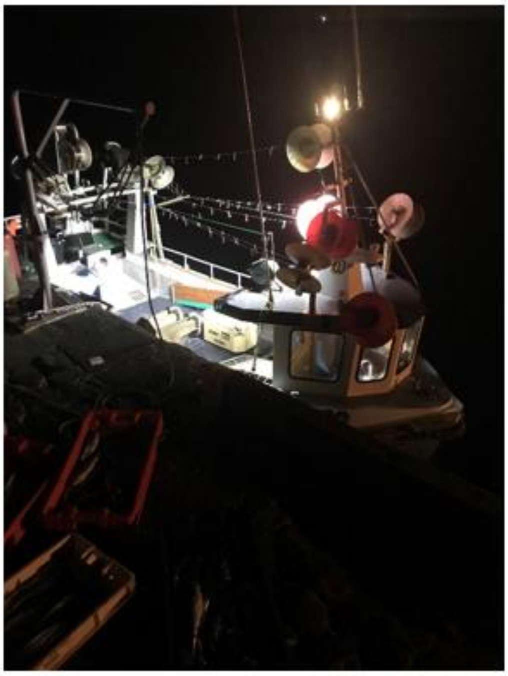
*The TAST speaker array used for this trial was not designed to be deployed from a moving fishing vessel. Deployment depth together with speaker surface area and form made the system susceptible to propellor entanglement whilst a vessel is "under power".

Trial Methodology

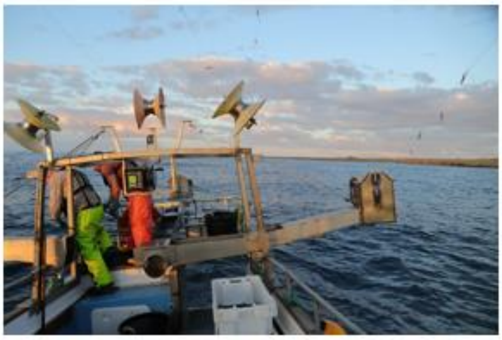
The trial was conducted on the north east coast of Scotland with vessels from Rosehearty harbour. Following on from meetings held with commercial fishers from RHIFA, nine skippers initially agreed to participate in a sea trial of the TAST device. However, due to various factors (including the COVID-19 pandemic), the number eventually reduced to five vessels (Jenny Lass, Oystercatcher, Relentless, Tranquillity, Amanda Jane) (Figure 2). All participating vessels are between six and seven metres in length and operate a handline and/or jigging machine method for catching mackerel. Participating vessels fish in the local area within a maximum 15-mile radius of the harbour. For this trial, data was collected from an area encompassing eight miles west, six miles east and four miles offshore from Rosehearty harbour.

Figure 2. Photographs of the five fishing vessels participating in the sea trial and the Rosehearty Harbour, where vessels are typically berthed.

The study started at the end of June 2020, slightly later than planned due to the later than normal arrival of the mackerel, with participating boats recording baseline data (i.e., no TAST device deployed). Fishers were asked to fill in a data sheet for each fishing trip (appendix 2). The initial data recorded information on fishing gear, dwell time on shoals, catch weight and marine mammal sightings. The data sheets were amended to include additional relevant data as the trial progressed. This included the catch recorded for each stop (based on the number of baskets) (Figure 3). A copy of the final data recording sheet is available in Appendix 2. The crewing level of vessels differed with either the skipper and an additional deckhand or the skipper operating singlehandedly (except for the pilot trial when TG was present too).



Jenny Lass FR 980 at the landing berth in Rosehearty harbour. Three sets of 42 hook (fly) lines on jigging machines and one 35 hook handline on the starboard side are set up. Three fish stripper boxes aft; one to starboard, one to port and one at the stern. One stripping-box can be seen on the starboard side forward on mid ship. All are shown in the retrieved transit position.



Aft view showing the stripping boxes and chutes in the fishing position.

Figure 3. The Jenny Lass FR980 rigged for handline fishing for mackerel and measuring catch for each stop.

Previous studies suggest that TAST does not adversely affect most cetaceans (e.g., Götz & Janik, 2015, 2016). However, at the request of NatureScot, controls were put in place and all fishers were instructed to conduct a visual check of the surrounding area for cetaceans (whales, dolphins and porpoises) before the TAST was deployed and, in the event of any sightings, to delay deployment until the cetacean moved away from the vessel. However, if a cetacean approached the vessel whilst the TAST was deployed then the operation was allowed to continue with information recorded on the data sheet accordingly.

Dr Thomas Götz (TG, University of St Andrews) conducted an initial trial using the TAST equipment aboard the Jenny Lass between the 25^{th} and 27^{th} July 2020. This involved calibrating and mounting the TAST equipment onboard (Figure 4), conducting observations of seals at the water surface and on images of seals on the sonar, taking photographs/videos of sonar images and seals, trailling the existing data sheets and establishing an improved catch weight measurement system (baskets), with the TAST deployed (TAST) and when not deployed (Control). The speaker array suspension depth was set at 5 m for all deployments with the use of a cable grip. The speaker array was only deployed when the vessel was stationary / drifting due to the entanglement risk of the transducer cable in the propellor. In addition, qualitative observations on mackerel shoal behaviour were conducted using the sonar and a GoPro camera.

The TAST unit was set to operate at a duty cycle, i.e., percent time sound is emitted of 1%, The source level in one third octave bands (TOB) was calculated as both a single signal sound exposure level (SEL) and as a sound pressure level (SPL). Detailed information is shown in appendix 5. The highest value in a TOB represents a source level of 167.8 dB re 1 μPa^2-s in units of SEL and 175.6 dB re 1µPa in units of SPL.

Covid-19 pandemic restrictions delayed the transfer of TAST equipment and commencement of the TAST segment of the trial. As a result, there was only one set of TAST equipment, being shared by the fishers involved in the trial, and a rota system established to try and ensure that each vessel was able to make use of the system. Some of the fishers had other employment which meant they could not be present throughout the trial period. Fishing opportunities with the TAST equipment were also limited in August and September because of some unusual stormy weather; high winds and significant groundswell.

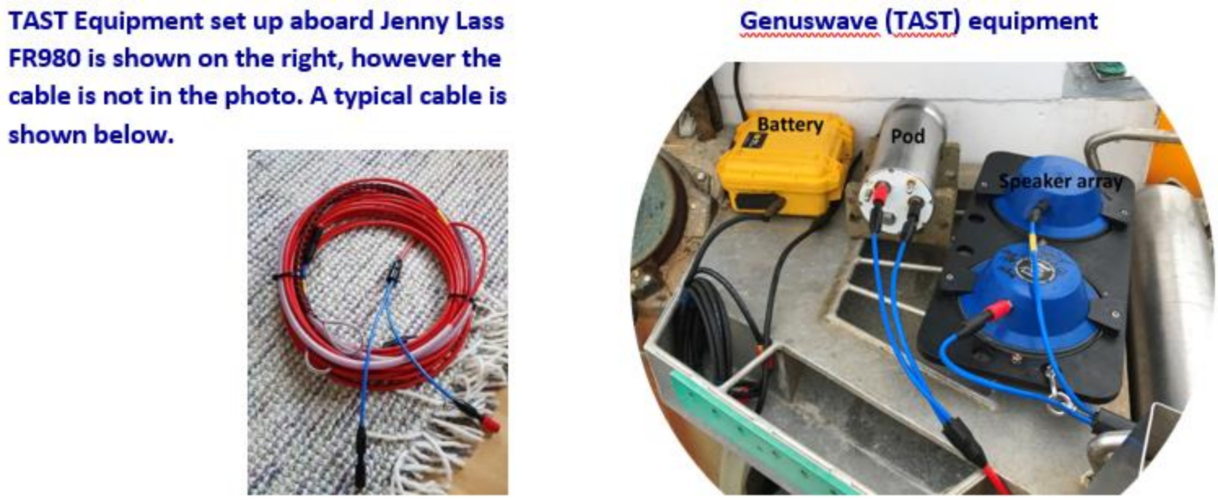


Figure 4. Photographs of the TAST equipment used in this trial.

The data sheets asked fishers to report the presence of seals on their echosounders, i.e., their 'fish finders'. The reliability of this method was evaluated qualitatively by a scientist who is experienced in using active acoustics for detecting and tracking marine mammals (TG). This work was conducted during the pilot trial by visiting fishing vessels, observing the fishers' interpretation of their sonar images at sea and checking recordings of sonar videos and mobile phone pictures provided by other fishers. An onboard evaluation during fishing operation conducted on Jenny Lass resulted in a 100% agreement on detections between TG and the fisherman. The first challenge was to reliably classify fish shoals which was verified by lowering a GoPro camera during fishing stops and checking for presence of mackerel. Mackerel shoals typically present themselves on the sonar screen as dispersed multi-target aggregations with target strength of individual fish being low. In contrast, seals present as long targets with a high individual target strength. They also show clear directional movement through the water column (see also video link for an example in the supplementary material below). Figure 5 shows a typical sequence of a shoal of mackerel being present under the vessel, a seal suddenly appearing and dispersing the shoal, the seal then moving to the right (bow), turning around and swimming back. Whenever such a mammalian target was spotted on the sonar screen a grey seal was detected later at the water surface (even though sometimes at some distance, i.e., a few hundred metres). Theoretically, other large mammals such a porpoises or dolphins could have produced similar targets on the sonar but this is unlikely to account for many of our observations as no porpoise or dolphins were seen surfacing after mammal targets were seen on the sonar. Differences in sonar type will influence detection probability but this was considered in the data analysis (via a random effects structure which codes for vessel type).

The Jenny Lass was equipped with a live view Panoptix sonar and sounder. The live view enabled the mackerel shoal to be monitored in real time whilst also capturing seal interactions below the water line. Other vessels use more conventional sonar systems but qualitative evaluation of recorded images and short video showerd that they were also capable of detecting seals. The fishers have returned images that clearly showed seals under the vessel.

Fishers were routinely monitoring the sonar as part of their daily fishing effort. As is the case for the other response variables (e.g., visual sighting) the potential observation time is given by the start/stop time recorded in the data sheets. Fishers would then either make an entry on the data sheet if a seal was present or no entry if no seal was present (see appendix 2). Fishers could not conduct fishing operations, scan the area continuously for visual sightings and at the same time continuously monitor the sonar screen. Therefore, all these response variables (visual and sonar sightings) have likely underestimated actual seal numbers. However, effort was comparable in treatment and control trials so that this did not affect our evaluation of TAST effects. It was also apparent to an observer (TG) during the pilot trial that fishers had a good grasp of seal activity (most likely because it is relevant to their fishing effort).

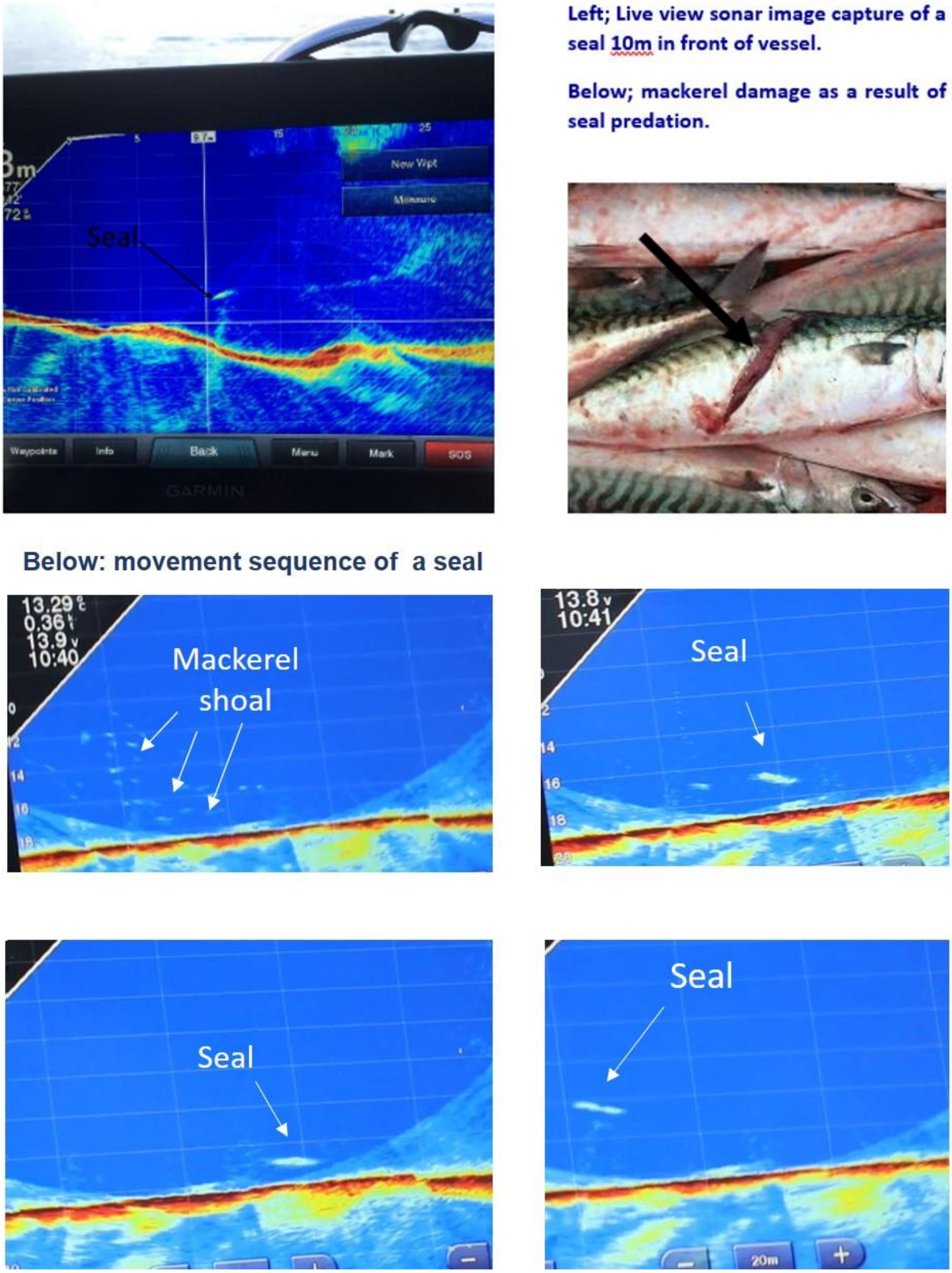


Figure 5. Image of sonar capture with seal visible on screen and evidence of damage to mackerel caused by seal predation (top two panels). The bottom four panels show a movement sequence of a seal and a shoal of mackerel. Initially a shoal of mackerel was present (top left), then a seal appeared on the sonar dispersing the shoal, (top right), continued to move towards the bow (bottom left), turned around and moved away towards the stern (left hand side of bottom left panel).

Dr Thomas Götz made a further visit to Rosehearty with the intention of conducting additional onboard observations and data collection over a three-day period commencing 1st October 2020, however severe weather prevented the boats from fishing and the visit was restricted to meetings with RHIFA fishers during which unclear entries in data sheets were verified with individual fishers. Fishers' subjective opinions and experiences were also anonymously queried during the trial at a meeting during this 2nd trip. All data sheets were collated and checked by RHIFA and then passed on to the University of St Andrews for analysis.

Data analysis

Modelling approach

Generalized linear mixed effects models (GLMMs) were used to estimate the influence of TAST on several response variables related to seal behaviour and metrics of fishing success. GLMMs are designed to accommodate response variables that are not normally distributed, making them well-suited to this dataset. For example, seal sightings were represented as binary observations (presence/pseudo-absence). Mixed models allow a partitioning of variance into fixed effects (primary predictor variables) and random effects (which are additional factors that influence variability). The latter allowed accountability for any consistent differences among fishing vessels or specific trips when estimating direct relationships among variables of interest. Further information regarding the model details is available in Appendix 3.

Analysis of seal sightings

Fishers recorded seal sightings in two ways: visually at the surface and live observations on vessel-mounted sonar devices. Models were fitted separately to investigate the influence of TAST on seal presence for each type of observation. Sonar detections can provide underwater movement data on seals under the vessel while visual sightings are restricted to observing animals at the surface and are likely to be influenced by sea state and light conditions (e.g., a grey seal can easily be missed in overcast conditions in sea state 3). Accordingly, sonar detections were expected to be most relevant for understanding depredation, even though they can suffer from other issues such as reliably classifying seals.

A binomial GLMM with logit link function was fitted to estimate the influence of TAST on seal sightings by sonar (M1). Based on reports from fishers that seals were detected less often later in the season, a second model was fitted that additionally included Julian date (Jan 1st = 1 through December 31st = 366, for leap year) as a predictor (M2). Controlling for the influence of date was also important because, due to logistical constraints, TAST trials tended to occur slightly later in the year than control trials. This allowed the disentanglement of possibly confounding influences of the time-of-year on the relationship between TAST and seal behaviour. A third model was fitted with an interaction term to test whether the influence of the experimental treatment on seal detections was date-dependent, for example, if TAST was more effective at the beginning or end of the study period (M3).

Very similar model structures were then applied to visual sightings (M4-M6). However, the ability to directly spot a seal was confounded by sea state (i.e., with seals being harder to spot in rougher waters). Fishers-supplied reports were converted into a 3-level categorical variable representing calm, moderate and rough sea conditions respectively. This sea state variable was included as an additional predictor in models M4-M6. Initial models based on visual seal sightings showed significant autocorrelation among residuals indicating consecutive data points in a time series (Julian day) were correlated. From a biological point of view such autocorrelation is not unexpected, as the same seal might persist around the vessel for several fishing stops. One method to take this into account is to specify a 1st order auto-regressive correlation structure (AR1) in the model which assumes that consecutive data points are more likely to correlated. Attempts to explicitly model an AR1 autocorrelation structure did not improve diagnostics, so we interpreted coefficients from a thinned model based only on every second fishing event (which may have reduced statistical power).

Analysis of stop durations

Stop duration, indexed by fishing stop, was modelled as a function of TAST use (M7), and secondly as a combined function of TAST and Julian date (M8). These models included regular fishing stops alone, as troll and drift fishing events were expected to have different stop durations which may not be similarly influenced by experimental treatment. Separate models using event durations from these fishing types are not presented, due to small available sample sizes.

Analysis of catch weights

While mackerel catch amounts for entire trips were typically available as weights (kg), catches attributable to each individual stop were measured by the number of standardized plastic baskets filled. After summing up the total number of baskets per trip, a linear regression was fitted to explain overall catch as a function of the number of baskets filled. The slope of this regression was used as a calibrated estimate for the catch weight per basket. The resulting stop-based estimates were then used as a response variable in two models designed to test whether catch weight was influenced by 1) experimental treatment (M9) and 2) experimental treatment while controlling for Julian day (M10). As before, fishing events that were not typical jigging stops were excluded in the models. Moderate but non-significant autocorrelation was detected in the residuals of these stop-based catch weight models. Accordingly, we still interpreted coefficients from the regular models (data not thinned, no specified autocorrelation structure), but interpreted the significance of the results with caution.

Lastly, to include observations of fishing trips for which stop-based catches were not known, a global model comparing total catches across all trips was fitted, regardless of fishing type (M11). No time-based measure of fishing effort (e.g., trip time) was included in catch weight models, a decision guided by exploratory visualizations (Figure A4.2). However, possible links between catch weights and the number of jigging machines used were identified (1-3), so the number of jigging machines was controlled for in models M9-M11.

Analysis of stop number

The final set of models focused on stop number within each trip, i.e., whether patterns of seal behaviour were different if it was the vessel’s first vs. last stop of the day. The focus was the possibility that seals may have either habituated or sensitized to the startle exposure, so consideration was given to fitting further models explaining seal sightings as a function of stop number separately for TAST and control trials. However, the relatively small number of data points for TAST trials did not warrant a separate regression for this test. Accordingly, any effects of stop number on seal presence were investigated for control trials only. As before, separate models were fit for sonar (M12) and visual sightings (M13).

Participant survey

Following the study period, four fishers were anonymously surveyed for their views on the effectiveness of the device and possible improvements for future design iterations of TAST. This was done during a meeting with fishers in Rosehearty. Fishers were shown these questions as power point slide on the computer and wrote down their answers on a piece of paper.

Results

Summary of key findings

The analyses revealed a strong deterrent effect of TAST on seal activity directly around fishing vessels. This pattern did not hold for seals in the wider visual range of the vessel. Fishing metrics including stop duration and catch weights were variably influenced by time-of-year effects and TAST. Generally, statistical findings are consistent with reports from fishers in an anonymized survey, supporting the idea that TAST is effective in its primary function of deterring seals.

Data analysed

Analysis included records from 59 separate fishing trips from five vessels and six skippers (Table 1). Catch weights were known for 56 of these trips (43 control, 13 TAST). At a finer scale, these trips were broken down into 425 fishing events comprising 301 jigging stops, 110 drift-fishing sessions, and 14 trolling sessions. Of the 301 jigging stops, calibration of stop-based catches was successful for 172 (155 Control, 17 TAST). Given that only a single TAST device was available for use, there was an imbalance in the number of trips for each treatment (control vs. TAST). This did not create a problem for the statistical models, but the general lack of TAST trials reduced the ability to draw inferences for some secondary questions (e.g., influences on catch weights).

Table 1 – Key details of data included in this analysis, indexed by fishing vessel. Fishing trips sometimes included multiple fishing types.

Data summary						
Vessel	**Date range**	**Trips**	**Jigging stops**	**Trolling events**	**Drift events**	**Total number of events**
1	June 28th – September 10th	11	18	0	13	31
2	July 2nd – October 18th	26	228	6	61	295
3	July 8th – September 29th	12	46	8	10	64
4	June 28th – August 11th	9	2	0	26	28
5	August 18th – August 18th	1	7	0	0	7
Total		59	301	14	110	425

Effect of TAST on seal detections

Seals were spotted on vessel-mounted sonar displays during 51 of 399 fishing events (12.8% overall). Of these 51 detections, 50 occurred during events without the device (Figure 6). Thus, we documented just one instance where a seal was detected via sonar display while TAST was activated. The preferred model based on AIC was model M1, including only the effect of experimental treatment. This model estimated that fishing events with TAST activated were associated with a 97% decrease in the odds of detecting a seal by sonar (Figure 6, Table A3.1).

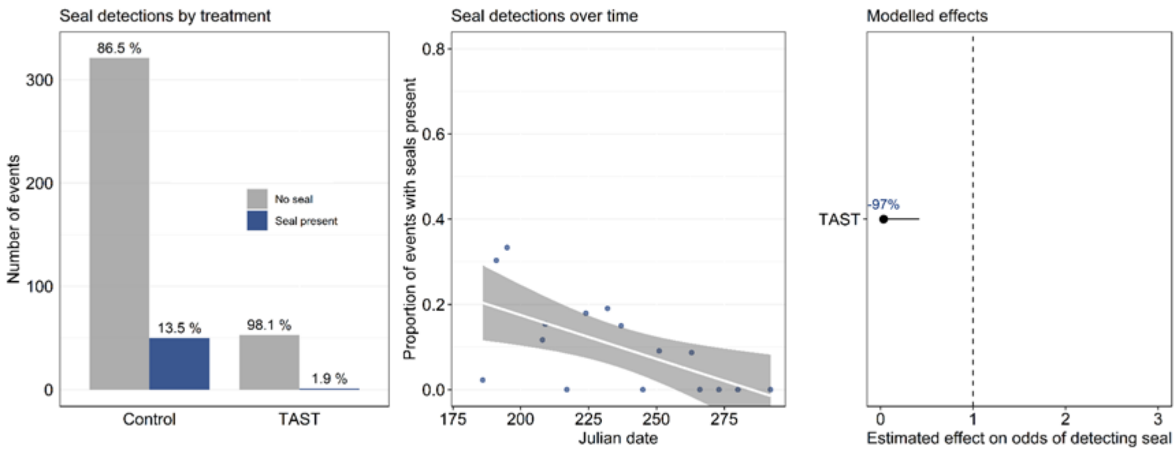


Figure 6 – Proportion of fishing events (stops, trolling or drifting sessions) during which a seal was detected by fishers via hull-mounted sonar (*left*). Overall correlation between seal detections per week by sonar and date during the study period (*center*). Modelled effect of experimental treatment on the odds of spotting a seal by sonar, with the horizontal line showing the 95% confidence interval (M1; *right*). The dashed vertical line reflects no change in odds.

In comparison to sonar sightings, direct visual sightings of seals were generally more common, occurring during 134 of 399 fishing events (33.5% overall). As with sonar observations, visual sightings of seals occurred on a higher proportion of control trials than TAST trials (Figure 7). The preferred model based on AIC differences included Julian date and sea state as predictors (M5; Table A3.2). The model estimated that TAST was associated with a 42% decrease in the odds of visually detecting a seal. We also identified a significant effect of Julian day on visual sightings, a 4% decrease in odds with each successive day in the study period. While sea state had a significant influence on seal sightings in M4, the lack of a significant effect in M5 suggested that this may have been an artefact of collinearity with Julian date, as later dates were generally associated with rougher seas. Thus, our results suggest that date was a more important predictor of visual sightings than sea state.

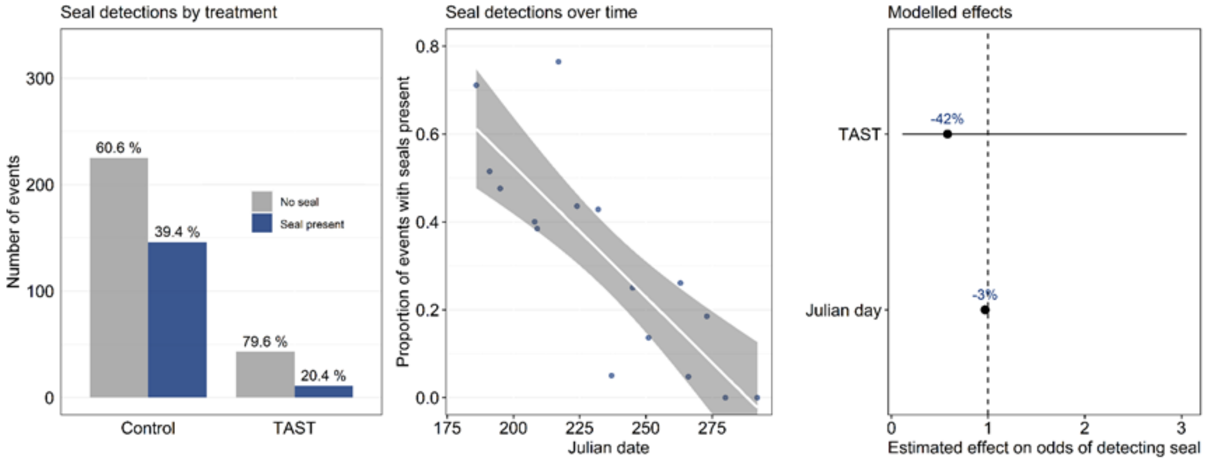


Figure 7 – Proportion of fishing events (stops, trawling or drifting sessions) during which a seal was directly seen by fishers (*left*). Overall correlation between direct seal sightings per week and date during the study period (*center*). Modelled effects of experimental treatment and date during the study period on the odds of spotting a seal visually, with horizontal lines showing 95% confidence intervals (M5; *right*). The dashed vertical line reflects no change in odds.

Effect of TAST on stop duration

Preliminary visualizations (Figure 8) suggested that TAST might have led to longer stop durations than in control trials. This was confirmed by our selected model (M8), which estimated that stop duration was nearly twice as long when TAST was activated. We simultaneously identified a significant influence of Julian date, with a one-day increase in Julian day being associated with an increase in stop duration by a factor of 1.009 (Table A3.3).

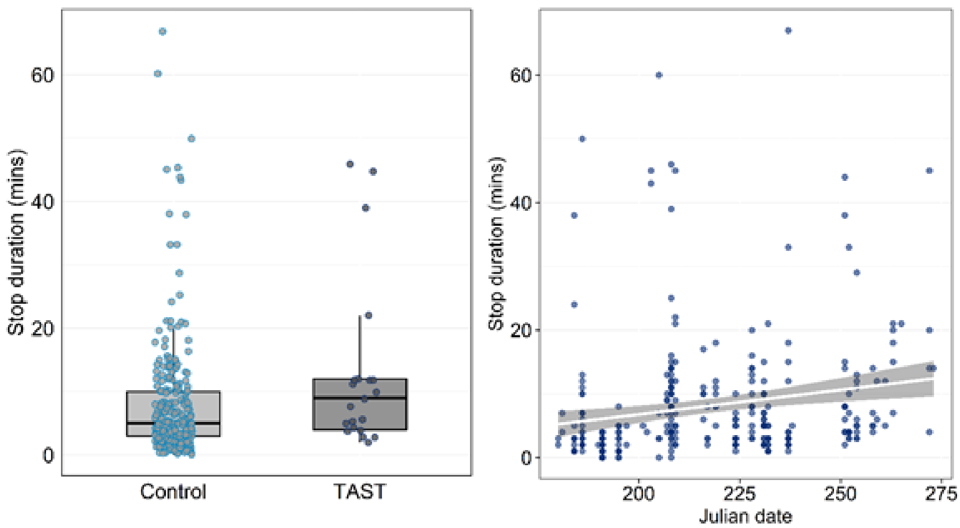


Figure 8 – Boxplots with individual data points showing distribution of fishing stop durations, grouped by experimental treatment (*left*). Simple regression showing a slight increase in stop duration across the study period (*right*; $n_{control} = 278$, $n_{TAST} = 21$).

Effect of TAST on catch weight

Based on the empirical calibration, each full basket contained approximately 37.4 kg of mackerel (Figure A4.1). Exploratory visualizations suggested that fishing stops with TAST activated had a slightly higher catch and that catch weight might have decreased slightly over the course of the study period (Figure 9). However, while the selected model also showed a trend towards larger catches (85% increase) when TAST was activated in M9, the effect was not significant (Table A3.4). As with the stop duration model, we suspect that the limited number of fishing stops with the device activated resulted in limited power to detect effects of the device on fishing metrics. More data is required to draw definitive conclusions on whether TAST can increase fish yields. The model based on all trips which included all fishing types revealed no clear effect of TAST on mackerel catch mass (M11; Table A3.5). This analysis is less reliable than the 'per stop' model as it suffered from the shortcoming that some TAST treatment days (n=6) also included individual stops during which TAST was not deployed (controls). These mixed treatment days reduced the power to detect an effect.

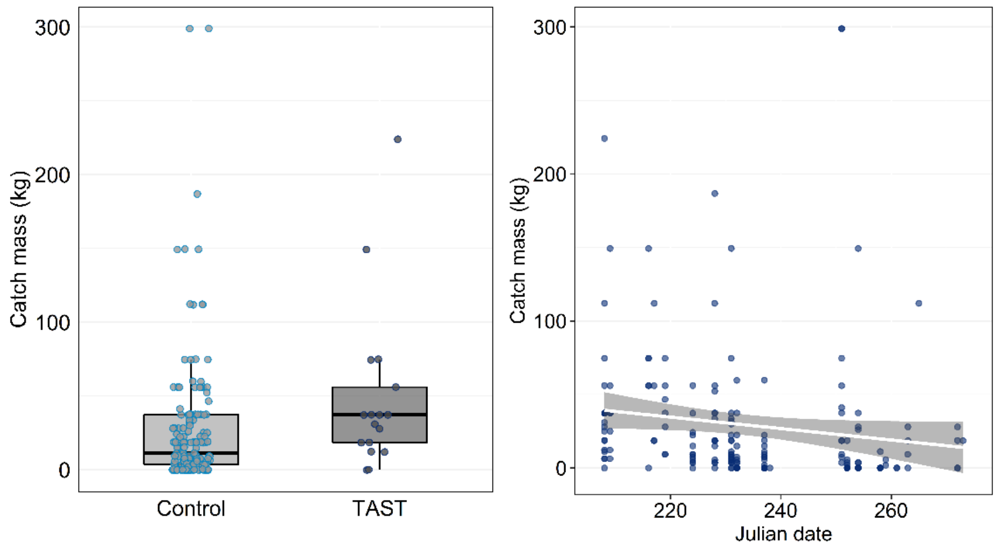


Figure 9– Boxplots with individual data points showing distribution of mackerel catch masses for individual stops, grouped by experimental treatment (*left*). Simple regression showing a slight decrease in catch masses across the study period (*right;* $n_{control} = 155$, $n_{TAST} = 17$).

Effect of stop number on seal sightings

Both models linking seal sightings to stop number (M12, M13) calculated positive coefficients, as expected if seals found and then remained near vessels over the course of a trip. However, both estimates were non-significant, which means that no conclusive evidence was found for changes in seal behaviour as a function of stop number. Despite being non-significant, the p-value for the estimate of change in visual detections was small (0.062; Table A3.7), suggesting that a significant effect *may* emerge with more data. Additional TAST trials are required to fit models to test whether seals are more likely to be associated with later stops and whether seals might habituate or sensitize to the sound stimulus.

Results of participant survey

In an anonymous survey, two of four fishers indicated that they believed TAST was effective in keeping seals away from under their vessels, the others indicating that they were unsure (none stated that it was ineffective). Three of four fishers indicated that they were not sure whether TAST had an influence on overall fishing success, with one respondent reporting he thought TAST had a positive influence. He also expressed a desire for more data to answer the question more clearly. All fishers indicated that they did not believe there was any effect of the device on the presence of mackerel under their vessels. The fishers generally agreed that subsequent versions of the device could be made easier to use, namely by mounting the transducer on the hull of the vessel (three respondents), making it smaller (one respondent), and by having it operable by switch (one respondent).

Fishers were keen to highlight their observations on seal behaviour during the mackerel fishing season. There was a general view that seal interactions were highest during the first half of the season and when the shoals were more prevalent on the grounds. Seal presence was perceived to decrease during September as the fish shoals became more dispersed and moved farther from shore.

Fishers reported that seals frequently stay at the surface watching the fishing operation and dive when they see fish coming up on the lines. The seals are often felt pulling the fish from the lines and can sometimes be seen following the lines of fish up to the surface of the water adjacent to the boat. On occasion a seal can become entangled in a line of hooks eventually parting the line and making off with a significant number of hooks.

The fishers reported that they felt the TAST did deter the seals, however would like to trial the equipment during the times when the shoals and seals are more prevalent, typically during June and July. The equipment, in its current form, is not ideally suited for deployment from a small fishing vessel due to the bulky nature of the component parts. The fishers indicated that an ideal solution would be a permanently installed unit, connected via a switch to the vessels electrical system and with a small transducer mounted to the hull of the boat. This would enable TAST to be used whist the vessels are underway and enable use with all of the four main fishing methods utilised. Any solution would also need to be demonstrably cost effective.

Discussion

The primary predator problem in the inshore mackerel jigging fishery is related to seals dispersing mackerel shoals by diving under the fishing vessels, therefore reducing fishing time. Shoal dispersal can regularly be observed on vessel sonar that allows clear identification of seals, seal movement patterns and shoal movement (Video - https://rifg.scot/region/north-east-coast). In the most extreme cases, seals following vessels can make the fishery unviable by causing immediate shoal dispersal. Direct predation of hooked fish can also occur but is considered a minor nuisance by fishers. However, it is considered a safety hazard when handlining lines and can cause injury to seals. This study showed that TAST succeeded regarding the primary objective relevant to this particular inshore fishery to keep seals away from the vessels and therefore mitigate seals causing mackerel shoal dispersal. This is supported by several pieces of evidence. First, there was a 97% reduction in the odds of detecting a seal (Figure 6) on the fishing vessel's sonar when TAST was operational. Second, fishers were able to run roughly two times longer fishing stops when TAST was operated (Figure 8). There was also a trend towards lower rates of visual detections of seals on the water surface in the wider area around the vessel (42% reduction), though this estimate is associated with a high degree of uncertainty (Figure 7).

Fisher-reported sonar detections and visual sightings of seals will have missed some of the seals that were present. One potential reason for this is due to vessels being operated either single-handedly or with a single crew member. Continuous sonar detection of seals requires a person to be present in the wheelhouse while continuous visual detections require focussed observation effort. Ideally, the study would have been conducted blind to experimental treatment but this was not possible even if additional observers had been placed on the vessels as the sound from TAST is audible in air. However, the data analysis controlled for some of these key influences and biases by including random effects of vessel ID and fishing trip when possible. There is no obvious reason to assume a systematic observer bias that would lead to an over-interpretation of efficacy as at least some fishers voiced initially critical opinions on the potential efficacy of acoustic deterrence methods. The appearance of a seal on the sonar is a noteworthy event for a fisherman and fishermen are experienced in separating bait fish, mackerel shoals and other objects on their sonar. Hence, observation effort for sonar is likely to be greater than for visual detections as fishers have an obvious interest in monitoring shoal presence by sonar throughout the fishing operation. Often sonar targets can then be confirmed when a seal surfaces consecutively. On the other hand, it needs to be acknowledged that classification accuracy will be lower for sonar detections, i.e., targets may have occasionally been misinterpreted as seals when they were not and vice versa. Sonar-based seal detection rates on the same vessel primarily depend on the sonar beam width and frequency and can therefore be assumed to be consistent within the same vessel and across treatments (while vessel differences were controlled for in the model). This is consistent with fishers' reports of sometimes seeing shoal responses ('being flighty') before the seal became visible on the sonar. We did not ask fishers to estimate or measures a distance between the seal and the vessel. Hence, some seals that were visually detected on the water surface may have been further away than the expected deterrence range of TAST (between 50m and 250m, Götz & Janik, 2015 & 2016). In addition, sound exposure around the vessel may have caused seals to spend more time with their heads above the water surface making them more likely to be detected visually. There is some evidence for reduced dive times after startle elicitation from captive studies (Götz & Janik, 2011). This effect also constitutes a possible explanation for only weak effects on visual detections in some field studies (Götz & Janik, 2016, see also Götz & Janik, 2015 for stronger effects). Importantly, seals swimming at the water surface at >50 m do not constitute a problem for fishers if they do not dive and disperse shoals or predate on hook lines.

This study also found clear evidence for an effect of season (Julian day since start of study) on several response variables (Figure 7 to Figure 9). There was a significant negative correlation between Julian day and visual detection rates of seals and a positive correlation with fishing stop duration. While there may be some collinearity between Julian day and sea state, these results still suggest that seals associate less frequently with fishing vessels later in the season. This may be mediated by a lower abundance of mackerel shoals or by mackerel moving offshore, which may in turn have caused a reduction in fishing efficacy or a change of fishing strategy towards the end of the season. Fishers felt that the visual detection rate of only 13.5% for control stops across the whole study period was much lower than what they normally experience during the peak predation season. One fisherman even stated that if seal-vessel interactions were generally that rare they would not have initiated the study. Hence, the study would have ideally started earlier and included the peak of the predation season (June to August). The delay in our study was due to Covid-19 restrictions and funding delays. Due to the University of St Andrews' Health and Safety policy during the pandemic and delays in the funding we were also not able to conduct dedicated sonar observations of seal-vessel interactions from a secondary research vessel.

The significant effect of TAST on fishing stop duration (~2 times longer) can most likely be explained by the absence of seals diving under the vessel and displacing mackerel shoals. Fishers typically finish the 'fishing stop' and move on if a shoal dissipates. A fisher's decision to stay at a location (rather than stop and move on) is primarily driven by two factors, a) the continued presence of shoals of mackerel on the sonar screen and b) fish being caught on hook lines (when the jigging machines operate continuously). Therefore, TAST seems to have allowed fishers to remain with the shoal for longer, resulting in increased fishing stop duration. However, we cannot fully rule out that some form of conscious and sub-conscious bias may have also influenced fishers' decisions to remain at a spot. The increased stop duration does suggest that TAST did not adversely impact mackerel or cause shoal displacement or dispersal. Mackerel shoal behaviour on the sonar was also monitored by an observer during the pilot trial which revealed no noticeable change during TAST deployment.

Median catch weight per fishing stop was higher when TAST was on. The model for catch weight per fishing stop points towards an increase in catch weight when TAST was on, but this effect was not statistically significant. There were several factors in this study which mean that statistical power for the 'catch weight per fishing stop' analysis ended up being low. One reason is that the 'baskets per stop' measures was only fully implemented after the pilot study in early August. In addition, some fishers did not always return entries for 'baskets caught' for each fishing stop leading to a much more limited data set compared to other data sets in the study. Most importantly, there was also an imbalance between the two treatment levels for stops with known catches (153 controls to 17 TAST stops for stops with known catches and number of jigging machines). Similarly, the low sample size of the study caused the catch weight per day analysis to be unreliable. Fishers believe that catch weight is influenced by a variety of factors such as behavioural state of the fish (e.g., "flightiness"), sun radiation ("fish stick to the bottom on sunny days"), time of day and depth. None of these variables were included in our study as it would have required sophisticated analysis of vessel tracks and quantification of environmental variables. This was beyond the scope of this study.

One fisherman reported a potential bycatch interaction event during the study period, i.e., a seal biting the hook line, getting tangled and then eventually breaking free. This happened during a control trip and no such events were observed when TAST was operational. Another fisherman reported similar events occurring in previous years. While no firm conclusions can be drawn from these isolated observations, the fact that TAST displaces seals from the immediate vicinity of the vessel would make such events potentially less likely.

TAST was specifically designed with two goals in mind: a) implementing scientific research on the physiological mechanisms mediating aversiveness of sound to develop an effective deterrence method (Götz & Janik, 2010, 2011, 2013), b) mitigating any potential adverse behavioural and auditory effects on target and non-target species while reducing noise pollution

(Götz & Janik, 2013, 2015 & 2016, MMO, 2020). The results of this study are consistent with previous studies on TAST on fish farms (Götz & Janik, 2015 & 2016), in fisheries (Gosch et al. 2017, MMO, 20230) and on salmon runs (Williams et al. 2021). The TAST signal has been improved to reduce adverse effects on non-target species since the early studies by Götz & Janik (2015 & 2016). Acoustic properties based on empirical recordings of TAST signals were submitted to NatureScot who approved this study (see also appendix 5).

The statistical results from this study are also consistent with fishers' subjective impressions after the trial. Fishers were unsure about any direct benefit on catch weight but most were under the impression that TAST kept seals away from under the vessel. Fishers reported challenges with deploying TAST while operating a vessel single-handedly. They mentioned a preference for hull-mounted transducer solutions with a simple switch on mechanism. Genuswave ltd. is currently conducting R&D work on adjusting TAST for wild capture fisheries applications which includes the jigging fishery. Despite the challenges posed by the Covid-19 pandemic, participation of fishers in the study was exemplary. This was highlighted by the large number of data sheets returned for control observation days during which fishers could not expect any benefits for fishing but were facing the additional workload caused by having to fill in data sheets. This commitment reflects Rosehearty fishers' dedication to engage with scientists, governmental organisations and the private sector to find non-lethal solutions for mitigating seal-vessel interactions.

The sonar methods proved to be highly efficient at detecting seals and observing shoal dispersals in this study. This opens additional opportunities for studying seal vessel interactions in more detail in future studies. This could be done from a secondary vessel using a multi-beam or side scan sonar. The results could provide suggestions for potential modifications to the sound exposure protocol to further reduce the noise dose, influence seal behaviour more effectively and avoid habituation while encouraging sensitisation processes. Such results would contribute to mitigating a seal-fisheries conflict while minimising noise exposure. Continuing data collection next year would also allow to further explore possible effects of TAST on catch weight.

Conclusions

The results revealed a strong deterrence effect of TAST on seal activity directly around and under fishing vessels (based on sonar detections). This statistical effect did not hold for seals beyond the immediate vicinity of the vessel, even though less seals were observed generally when TAST was operational. Fishing metrics including stop duration and catch weights were variably influenced by time-of-year (seasonality). However, fishing stop duration was almost twice as long when TAST was operational compared to controls, which may be the result of a reduction in shoal dispersal by seals. The statistical findings for sonar detections were consistent with reports from fishers in an anonymized survey, supporting the idea that TAST was effective in its primary function of deterring seals and preventing shoal dispersal by seals. From a practical point of view, fishers highlighted current transducer size, deploying equipment from a drifting vessel and inability to deploy from a vessel under way as challenges associated with TAST use and expressed interest in a hull-mounted option with a simple switch. Genuswave is currently in the process of developing a prototype that would allow such an installation and may potentially be available for tests in the summer of 2021.

Acknowledgements

The project team wishes to express their gratitude to the following people and organisations for helping make this trial possible;

- Skipper and crew members of the fishing vessels operating from Rosehearty Harbour; Relentless FR477, Amanda Jane FR1060, Oystercatcher FR12, Tranquility FR1039 & Jenny Lass FR980; for implementing the fishing trial and data collection.
- Members of RHIFA for their involvement in discussions whilst setting up and implementing the trial.
- Genuswave - Steven Alvey, Alan Sragow and JJ Brandler for provision of the Targeted Acoustic Startle Technology (TAST) equipment, resources and for participation within the project steering group.
- NatureScot – for their input, helpful comments and assistance in applying for the research licence for the project.
- Marine Scotland - Marine Planning and Policy and MSS: Renewable Energy Environmental Advice (REEA) for guidance on acoustic deterrent devices and their use in Scottish waters.

References

- Brooks, M. E., Kristensen, K., van Benthem, K. J., Magnusson, A., Berg, C. W., Nielsen, A., … Bolker, B. M. (2017). glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *R Journal*, *9*(2), 378–400. https://doi.org/10.32614/rj-2017-066
- Gosch, M., Luck ,C., Cosgrove, R., Goetz, T., Tyndall, P., Cronin, M. (2017): Development of an acoustic deterrent device to mitigate seal fisheries interactions. Interim report. Board Iascaigh Mhara (Irish Fisheries Board). http://inshoreforums.ie/wp-content/uploads/2016/06/BIM-Seal-Deterrent-Interim-Report-2017.pdf
- Götz, T. & Janik, V. M. (2010). Aversiveness of Sounds in Phocid Seals: Psycho-Physiological Factors, Learning Processes and Motivation. Journal of Experimental Biology. 213, 1536-48. *doi*: *10.1242/jeb.035535* https://jeb.biologists.org/content/213/9/1536.long
- 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). doi: 10.1186/1471-2202-12-30 https://doi.org/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. https://doi.org/10.3354/meps10482
- Götz, T., & Janik, V.M. (2015). Target-specific acoustic predator deterrence in the marine environment. Animal Conservation, 18(1), 102-111. https://doi.org/10.1111/acv.12141
- Götz, T & Janik, V. M. (2016). Non-lethal management of carnivore predation: long-term tests with a startle reflex-based deterrence system on a fish farm. Animal Conservation, 19(3), 212-221. https://doi.org/10.1111/acv.12248

- Götz T, Pacini AF, Nachtigall PE, Janik VM (2020) The startle reflex in echolocating odontocetes: basic physiology and practical implications. J. Exp. Biol. 223, jeb208470.
- Hartig, F. (2018). DHARMa: residual diagnostics for hierarchical (multi-level/mixed) regression models. Retrieved from https://cran.r-project.org/web/packages/DHARMa/vignettes/DHARMa.html
- MMO (2020). Assessing Non-Lethal Seal Deterrent Options: Fishing Trials Technical Report. A report produced for the Marine Management Organisation. MMO Project to: 1131, February 2020, 41pp. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/873280/MMO1131_Trials_Tech_Report_PubCopy_200203.pdf
- Yeomans, J. S., Li, L., Scott, B. W., Frankland, P. W. (2002). Tactile, acoustic and vestibular systems sum to elicit the startle reflex. Neuroscience and Biobehavioural Reviews 26(1): 1-11.
- R Core Development Team. (2020). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.
- Seal conflict with under 10m summer Handline Mackerel Fishery *(David D Whyte February 2020).*
- Russell, D J F, Jones E L, Morris, C D (2017) Updated Seal Usage Maps: The Estimated at-sea Distribution of Grey and Harbour Seals. Scottish Marine and Freshwater Science Vol 8 No 25, 25pp. DOI: 10.7489/2027-1
- Seal deterrent project; Progress summary report August 2020 (David D Whyte August 2020).
- Thomas L, Russell DJF, Duck CD,et al. (2019) Modelling the population size and dynamics of the Britishgrey seal.Aquatic Conserv: Mar Freshw Ecosyst. 29:6–23.
- Tixier P, Lea M-A, Hindell MA, et al. (2021) When large marine predators feed on fisheries catches: Global patterns of the depredation conflict and directions for coexistence. Fish Fish. 22: 31–53.
- Todd, V.L.G., Williamson L.D, Jiang, J. , Cox, S.E., Todd, I.B., Ruffert, M. (2021) Prediction of marine mammal auditory-impact risk from Acoustic Deterrent Devices used in Scottish aquaculture. Marine Pollution Bulletin: 165. https://doi.org/10.1016/j.marpolbul.2021.112171.

Supplementary Material

Jenny Lass FR980 11th August 2018 - Panoptix – Live view of seal dispersing a Mackerel shoal during handline fishing; https://youtu.be/ibamj7-pKqs

Note; ctrl+click then change the settings in youtube to 360p for improved quality.

Appendix 1 – RHIFA Seal Conflict with under 10m summer Handline Mackerel Fishery Report.

R.H.I.F.A

Rosehearty Harbour and Inshore Fisherman's Association

Seal conflict with under 10m summer Handline Mackerel Fishery

Rev 0 (issue); 25 February 2020

David D Whyte (Chairman RHIFA)

Purpose

To document relevant information associated with seal interference and/or conflict with the inshore commercial handline mackerel fishery in the North East coast of Scotland (specifically within a radius of 15 miles of Rosehearty Harbour) and to outline potential options with a view to finding a long-term solution to the issue.

Background

Rosehearty Harbour is host to a fleet of 15 registered under 10m fishing boats. There are two main commercial fishing opportunities available to the boats within a reasonable sea distance (15 miles) of their home port. These are creel fishing (for lobster and velvet crab), and handline fishing for mackerel. Whilst some brown crab is landed at this port, realistically boat size is limited by the harbour facility and therefore the boats here tend to be too small to work pots in deep water, hence landings of brown crab are relatively small.

The handline mackerel season in the area usually presents sometime between May and June and persists to sometime in October each year, and provides a significant source of income for many of the commercial fishers in the village. This seasonal fishery allows the opportunity to boost the income of local fishers, and the diversification means there is less effort targeted towards fishing crab and lobster stocks in the area.

Fishers have observed a steady increase in seal numbers around our local coast since shooting of predatory seals ceased when the local salmon netting station closed many years ago.

For a number of years now (at least 16) the handline fishers have been reporting problems with seals hindering the mackerel fishery. Such “problems” have been increasing year on year causing extreme frustration to the industry and the locals who rely on it for their income.

Problem

It is now frustratingly difficult for the fishers to catch their allowance of mackerel because of the hindering interference of seals. It is vitally important to our local industry that the best fishing effort can be made of short-term seasonal opportunities.

Our observations indicate seals are extremely intelligent mammals that follow each boat, sometimes in large numbers, until the skipper finds a shoal of fish. The seals wait outside the harbour from early morning or evening (just before dawn, around 3.00 am at the height of summer) and tag on to each boat as they depart.

Once a shoal of fish is located the seal will dive to feed on the fish from the lines. This (depredation) is not the problem, however when the seal peruses the feeding fish it ‘spooks’ the mark leading to the shoal rapidly dispersing. At times it can take several hours for the fish to school again and be located by the fishing vessels. On many occasions a seal will remain on the surface, watching the fishing operation and dive when it sees the fish coming aboard the boat. It appears that the seals find it easier to catch fish whilst the mackerel are attempting to “feed” on the deployed sets of hooks/flies. This behaviour is repeated until the fishing vessel returns to port. It is nigh on impossible to evade them, even when cruising at full speed for a number of miles. Under 10m boats tend to have an average top speed of 6-7 knots.

During inclement weather, the seals are not always visible however their presence is felt by the tugging of a handline and/or the shoal of fish disappears quickly. Seals are often visible following the boat on the surface of the water and around the boat during fishing. The seal(s) often wait until they see fish coming out of the water on the hooks before diving down towards the shoal and lines. It is suspected that some seals remain in the vicinity of the shoal and feed on an easy meal when the boats find the fish and commences fishing.

Young seals can occasionally be seen alongside the larger mature seals following the boat indicating that the young seal is learning skills from the mature seal.

Fishers are not so concerned at losing a number of fish whilst fishing but are extremely frustrated and hampered by the shoal being spooked soon after being located, often after hours of searching by a number of boats.

Location

Rosehearty fishing boats have a particular problem within an area extending from Rattray Head along the coast to Macduff. Seal interference is at its worst within one mile of the coast, however the problem persists, to a lesser degree, when fishing farther offshore *(up to 5 + miles).* The problem does not appear to be restricted to the Rosehearty area as fishers from other locations have also reported similar issues with seal interference.

Magnitude

Seal interference is not necessarily constant throughout the duration of the fishery season (May/June to October). It appears that interference from seals is at its highest during July to September when seals are present constantly, even after a number of days of no fishing activity when the fleet is for example confined to harbour due to bad weather. Seal interference appears to decrease during September.

Grey seals appear to make up the majority of the population in the Rosehearty area. Juvenile seals are occasionally present with mature seals whilst following the fishing boats and it is therefore assumed that they are learning to participate in this “easy meal” approach from their mothers. This being the case the problem will only increase year on year.

Seal avoidance Techniques

Seals appear to recognise specific boats that target the seasonal mackerel fishery the most. It is believed that they do this by recognising the boat characteristics and/or by tuning into engine noise and following fishing activity in general.

Over many years’ skippers have attempted to evade the problem seals by moving significant distances at speed, working farther offshore and by attempting to “offload” a seal or seals on a boat that is pursuing other activities e.g. sport or creel fishing. These techniques have limited success and are becoming even less effective as the population of seals increase.

Outcome

Seal harassment during the mackerel fishery creates the following issues for skippers…

- Frequently return to port with insufficient quantity of fish to land.

- Inability to catch allocated quota.
- More time at sea.
- Increased fuel consumption.
- Loss of earnings.
- Significant frustration.
- Injury to seals by entanglement in fishing lines.

Legal framework.

Seals are a protected species under Marine (Scotland) Act 2010 - Part 6 'Conservation of seals'. The Act does not prohibit the killing of seals however it promotes non-lethal seal management measures such as "acoustic deterrent" (and others) as a first option. A seal management license may be granted to shoot seals for the prevention of damage to fisheries. It is recognised that Acoustic Deterrent Devices (ADD's) are not always effective in deterring seals.

There are no Special Areas of Conservation (SAC) for Grey and Common seals within 60 miles of the Rosehearty fishers's operating area. The nearest being the Dornoch Firth area.

The Protection of seals (Designated Sea Haul-out Sites) (Scotland) Order 2014 introduced additional protection for seals at 194 designated haul-out sites: locations on land where seals come ashore to rest, moult or breed. Harassing a seal (intentionally or recklessly) at a haul-out site is an offence. The nearest haul out site to the Rosehearty fisherman's area of operation is located at the Ythan estuary approximately 25 miles from Rattray head and approximately 40 miles by sea from Rosehearty.

Under the Conservation of Seals Act 1970 and the Marine (Scotland) Act 2010, the Natural Environment Research Council (NERC) has a duty to provide scientific advice to government on matters related to the management of seal populations. NERC has appointed the Special Committee on Seals (SCOS) to formulate this advice

Occasionally a seal gets caught up in fishing tackle and after a period snaps the line and departs with the tackle embedded in their skin. It has proved impossible for a snagged seal to be unsnagged by a fisherman, whilst at sea.

Considerations

RHIFA are well aware of the sensitivities associated with the removal of seals through licensed shooting and do not wish to consider this option in the first (if any) instance.

RHIFA, and others, wish to deploy **Targeted Acoustic Startle technology (TAST), Acoustic Deterrent Devices (ADD's) or another non-lethal deterrent option** in an attempt to minimise the interference of seals within this important fishery. We are aware that there are certain considerations than need addressed should we endeavour to proceed with the deployment of TAST/ADD's e.g.

- Potential for fishing fleet use of ADD's requiring a license. *Lynda Blackadder of Marine Scotland (MS) Science has attempted to determine whether there are any licensing requirements. To date, MS has indicated that there is currently no requirement for* *licensing of ADD's for general deployment in a commercial fishery. We await confirmation in writing.*

- There may be a requirement to obtain a license to carry out a study/trial.
- The potential for damage to seal hearing due to long term exposure to noise will need considered. Options for TAST using a "startle" technique would minimise this potential.
- Effect on other sea mammals will require consideration when choosing the sound frequency and type of the ADD/TAST. Toothed Whales e.g. *Minke Whales, Harbour Porpoise and Bottlenose Dolphins can also be present in the area at times.*
- The effect of ADD/TAST on mackerel.
- Public perception.
- The potential for seals to become accustomed to an ADD *(habituation)* and the potential for the ADD to act as a "dinner bell".
- Effectiveness of the ADD/TAST in providing a long-term sustainable solution after taking all other issues into consideration.
- An initial indication of costs to purchase an ADD in the UK have ranged from £5,000 to £10,000 depending on supplier and device.
- A company in Macduff are looking into the potential purchase of ADD units from a company in America. Costs are quoted in the region of £400 per unit. These ADD's appear to be proven as effective with fishers from Maine USA.

RHIFA Proposals

- To engage with relevant parties and organisations with a view to tabling a relevant question to the Special Committee on Seals (SCOS).
- To acquire sufficient funding to finance the formulation and implementation of a study into the potential use of ADD's/TAST technology.
- To formulate a sea trial aimed at identifying a suitable & sustainable means of preventing seal interference with the handline mackerel fishery.
- To implement a scientifically based, trial in the sea area around Rosehearty or other suitable location.
- To provide a cost-effective long-term solution, easily implemented and maintained by under 10m fishing boat skippers whilst minimising the impact on seals and other marine life in the vicinity of fishing activity.
- Ensure that public perception and environmental considerations are addressed.

Support and Guidance

Sea Mammal Research Unit at St Andrew's University (SMRU)

- Dr Bernie McConnell – Deputy director. Via email. Telephone and a meeting on the 14th August 2019.
- Professor Aillsa Hall - Director. Meeting on the 14th August 2019.
- Rob Harris – Field researcher – via email and Telephone.
- Dr Thomas Goetz – Research fellow – email via Lynda Blackadder (Marine Scotland Science).

Aberdeenshire council

- Councillor Mark Findlater (Troup ward) – meetings & email.
- Councillor Ross Cassie (Troup ward) – meeting & email.
- Derek McDonald Industry Support Executive (Rural & Maritime) – email.
- Fisheries working group – harbour meeting 11th September 2019.

Parliamentary

- David Duguid MP (Banff & Buchan) – Meeting 18th October 2019.
- Stewart Stevenson MSP (Banff & Buchan) – telephone and letter.

Literature review

- Scottish Government / Marine Scotland (Marine and Fisheries) website.
- Marine Management Organisation; Assessing NON-Lethal Seal Deterrent Options; Literature & Data Review (MMO1131).
- T. Götz & V. M. Janik 2016; Non-lethal management of carnivore predation: long-term tests with a startle reflex-based deterrence system on a fish farm. SMRU, School of Biology, University of St Andrews, Animal Conservation. Print ISSN 1367-9430
- T. Götz & V. M. Janik 2015; Target-specific acoustic predator deterrence in the marine environment. SMRU, School of Biology, University of St Andrews, Animal Conservation. Print ISSN 1367-9430
- T. Götz (Summary) - The targeted acoustic startle technology (TAST): a sustainable approach to management of seal predation on fish farms.
- SCOS report 2018.

Devices

Many different devices are on the market. Further research is required to identify the most suitable and cost-effective device available. The following companies have been contacted to provide some general information in the first instance;

- Ocean Science (ADD's) – www.OSC.co.uk
- Genus Wave (TAST) - www.Genuswave.com

The following extract from a Thomas Götz - summary document titled *"The targeted acoustic startle technology (TAST): a sustainable approach to management of seal predation on fish farms"* dated 13/11/19, explains the benefits and limitations of ADD and TAST technology.

ADD's Conventional high-power acoustic deterrent devices (ADDs) are widely used to keep seals away from fish farms in Scotland. These devices intend to deter seals by emitting sound at very high source levels and duty cycles, i.e. the percentage of time that sound is produced (Götz & Janik 2013). The long-term success of these devices is often limited and habituation, a decrease in responsiveness to the signal, can be a significant problem in contexts where food motivation is involved (Götz & Janik 2010). ADDs have also been highlighted as a conservation concern as they cause large-scale habitat exclusion in non-target species such as harbour porpoise and dolphins. Furthermore, ADDs have some potential to cause hearing damage in target and non-target species, particularly when noise pollution is almost continuous because farmers use many speakers (Götz & Janik 2013).

TAST An alternative can be found by harnessing the autonomous acoustic startle reflex, which caused flight and avoidance behaviour without a decrease in responsiveness over time in the majority of tested seals (Götz and Janik 2011). This approach only requires low noise doses by using brief, isolated sound pulses emitted at low duty cycles. Target-specificity can be achieved by choosing a frequency band where hearing sensitivity in the target-species is higher than in non-target species. This method has been shown to be successful in deterring seals from a fish farm while not adversely affecting the behaviour and distribution of harbour porpoise (Götz and Janik 2015). In a consecutive study, a startle-reflex based system reduced seal predation by ~91-97% on a fish farm over the course of one year while operating at a duty cycle of less than 1% using a noise dose that is more than one order of magnitude lower than in ADDs (Janik & Götz 2016). Additional short-term tests at different sites confirmed this result. As the device emits much lower noise doses than ADDs and operates in a frequency band where porpoises have lower auditory sensitivity than seals there is no risk of hearing damage in target or non-target species (Götz and Janik 2015).

The targeted acoustic startle technology (TAST) has been implemented in an industrial prototype and product development is nearing completion. These acoustic startle devices (ASD) are different from ADDs in that they emit significantly lower noise doses and their environmental compliance has been assessed (Götz and Janik 2015). The technology for fish farms is available as 'TAST-ASD', 'ASD' or 'SalmonSafe' through Genuswave ltd. (www.Genuswave.com).

Appendix 2 – Data Sheets completed by fishers

Copy of the recording sheet completed by fishers participating in the trial.

Data sheet: Mackerel Jigging & Handline **Date:** 18/08/20

Vessel name:

Sea state (morning): CALM

Number of operational jigging machines: 1

Sea state (afternoon):

Number of Handlines: 1

Sea State (evening):

Skipper:

Sea surface temperature: 54

Time BST	Action F: fishing started S: fishing stopped	Treat-ment C: Control T: TAST (sound) Verify TAST is playing sound	Catch per stop (no of baskets or % of basket if less than one	Way point #	Seals G - Grey C - Common *Annotate – V = visual S = Sonar Note number of seals* Predation H: heads S: scratches J: pull on lines	Notes D: dolphins P: porpoise M: minke whale	No Fish Stops (tick)
Control ☒		TAST ☐					
0500	F						
0515	S		10%	57°42.2'N 002°06'W	2×G ✓		
0525	F						
05 30	S		20%	57°42.5'N 002°06.5'W	2×6 ✓		
05 40	F						
05 50	S		20%	57°43'N 002°07'W	2×G ✓		
0600	F						
06 05	S		15%	57°43.2'N 002°06.8'W	2×G ✓		
06 20	F						
06 30	S		10%	57°43.1'N 002°06.5'W	2×G ✓		
06 40	F						
06 50	S		15%	57°42.9'N 002°06.3'W	2×G ✓		
07 05	F						
07 10	S		10%	57°42.8'N 002°06'W	2×G ✓		
	Catch weight (based on sale from fish 1 form) 40 KG						

Appendix 3. – Model details and full results

Modelling details

GLMMs with seal sightings as the response variable were fit with binomial families and logit link functions, while models with catch mass or stop duration as the response were fit with negative binomial families and log link functions. For each model, we fit a nested random effects structure that included random intercepts for fishing trips within vessel-level groupings. Based on diagnostic visualization of the resulting distribution of best linear unbiased predictors (BLUPs), this structure was either retained or simplified to just a vessel-level grouping (random intercept for vessel). Before consideration of estimated relationships, all models were diagnostically examined for evidence of misspecification and poor fit, using the DHARMa package.

We also tested models for evidence of temporal autocorrelation. When significant autocorrelation was detected, we applied and assessed two strategies to correct it: 1) fit new models including AR1 autocorrelation structures, and 2) re-calculated the original models using a subset of data, “thinned” by excluding odd stop numbers so that subsequent observations were not unduly similar. All models were fit using the glmmTMB package (Brooks et al., 2017) implemented in R version 4.0.3 (R Core Development Team, 2020). We calculated the Akaike information criterion (AIC) to aid in model selection of fixed effects, only choosing to interpret estimates from more complex models when there was a decrease in AIC of 2 or more.

Table A3.1 – Parameter estimates of generalized linear mixed effects models (GLMMs) testing whether TAST influenced the probability of spotting a seal via hull-mounted sonar display ($n_{control}$ = 371, n_{TAST} = 54). Coefficients for fixed effects have been back-transformed, so that they represent multiplicative influences on the response (e.g., an estimate smaller than 1 implies a reduction in the probability of detecting a seal). Upper and lower bounds demarcate the 95% confidence interval of the estimate.

Effect of TAST on seal sightings by SONAR				
	Estimate	Lower	Upper	
M1. $Seal_{SONAR}$ ~ treatment + (1|vessel/trip)				
Intercept	0.006	5.101×10^{-6}	6.01	0.145
Treatment: TAST	0.033	2.662×10^{-3}	0.416	0.008
Trip (Variance)	1.239			
Vessel (Variance)	14.839			
AIC	**267.1**			
M2. $Seal_{SONAR}$ ~ treatment + julianDay + (1|vessel/trip)				
Intercept	0.067	2.050×10^{-5}	222.177	0.514
Treatment: TAST	0.051	0.004	0.646	0.022
Julian day	0.989	0.968	1.011	0.332
Trip (Variance)	1.126			
Vessel (Variance)	13.426			
AIC	268.2			
M3. $Seal_{SONAR}$ ~ treatment * julianDay + (1|vessel/trip)				
Intercept	0.088	2.658×10^{-5}	292.703	0.557
Treatment: TAST	2.148×10^{-5}	8.679×10^{-18}	5.314×10^{-7}	0.46
Julian day	0.988	0.967	1.010	0.294
TAST-julian day interaction	1.032	0.923	1.154	0.581
Trip (Variance)	1.116			
Vessel (Variance)	13.236			
AIC	269.9			

Table A3.2 – Parameter estimates of generalized linear mixed effects models (GLMMs) testing whether TAST influenced the probability of spotting a seal by direct visual observation ($n_{control}$ = 157, n_{TAST} = 20). Coefficients for fixed effects have been back-transformed, so that they represent multiplicative influences on the response (e.g., an estimate smaller than 1 implies a reduction in the probability of detecting a seal). Upper and lower bounds demarcate the 95% confidence interval of the estimate.

Effect of TAST on visual seal detections				
	Estimate	Lower	Upper	
M4. $Seal_{VISUAL}$ ~ treatment + seaState + (1|vessel/trip)				
Intercept	9.969	0.705	140.923	0.089
Treatment: TAST	0.301	0.052	1.735	0.179
Sea State	0.418	0.182	0.964	0.041
Trip (Variance)	1.808			
Vessel (Variance)	3.976			
AIC	198.6			
M5. $Seal_{VISUAL}$ ~ treatment + julianDay + seaState + (1|vessel/trip)				
Intercept	5585.895	34.903	8.940×10^{5}	< 0.001
Treatment: TAST	0.58	0.11	3.054	0.52
Julian day	0.968	0.948	0.989	0.003
Sea State	0.67	0.3	1.497	0.329
Trip (Variance)	0.996			
Vessel (Variance)	2.913			
AIC	**191.8**			
M6. $Seal_{VISUAL}$ ~ treatment * julianDay + seaState + (1|vessel/trip)				
Intercept	2701.943	67.849	1.076×10^{7}	< 0.001
Treatment: TAST	3.505×10^{-6}	1.206×10^{-12}	10.18	0.098
Julian day	0.964	0.939	0.986	0.002
Sea state	0.605	0.259	1.413	0.246
TAST-julian day interaction	1.053	0.990	1.12	0.104
Trip (Variance)	1.12			
Vessel (Variance)	3.67			
AIC	191.1			

Table A3.3 – Parameter estimates of generalized linear mixed effects models (GLMMs) testing whether TAST influenced the duration of fishing stops ($n_{control}$ = 278, n_{TAST} = 21). Coefficients for fixed effects have been back-transformed, so that they represent multiplicative influences on the response (e.g., an estimate smaller than 1 implies a reduction in the probability of detecting a seal). Upper and lower bounds demarcate the 95% confidence interval of the estimate.

Effect of TAST on fishing stop duration				
	Estimate	Lower	Upper	
M7. StopDuration ~ treatment + (1|vessel)				
Intercept	9.269	5.132	16.739	< 0.001
Treatment: TAST	1.77	1.19	2.633	0.005
Vessel (Variance)	0.37			
AIC	1867.7			
M8. StopDuration ~ treatment + julianDay + (1|vessel)				
Intercept	1.205	0.399	3.639	0.74
Treatment: TAST	1.921	1.304	2.828	0.001
Julian day	1.009	1.005	1.014	< 0.001
Vessel (Variance)	0.382			
AIC	**1851.5**			

Table A3.4 – Parameter estimates of generalized linear mixed effects models (GLMMs) testing whether TAST influenced stop-indexed mackerel catch masses ($n_{control}$ = 153, n_{TAST} = 17). Coefficients for fixed effects have been back-transformed, so that they represent multiplicative influences on the response (e.g., an estimate smaller than 1 implies a reduction in catch mass). Upper and lower bounds demarcate the 95% confidence interval of the estimate.

Effect of TAST on fishing catch weight by stop				
	Estimate	Lower	Upper	
M9. catchWeight ~ treatment + jiggingMachines + (1|vessel)				
Intercept	17.259	4.135	72.033	< 0.001
Treatment: TAST	1.853	0.853	4.025	0.119
Number of jigging machines	1.178	0.707	1.963	0.529
Vessel (Variance)	3.057×10^{-9}			
AIC	**1423.7**			
M10. catchWeight ~ treatment + julianDay + jiggingMachines + (1|vessel)				
Intercept	130.759	4.376	3906.831	0.005
Treatment: TAST	1.504	0.648	3.49	0.342
Julian day	0.991	0.977	1.005	0.192
Number of jigging machines	1.244	0.744	2.078	0.405
Vessel (Variance)	2.681×10^{-9}			
AIC	1424.1			

Table A3.5 – Parameter estimates of generalized linear mixed effects models (GLMMs) testing whether TAST influenced trip-based mackerel catch masses ($n_{control}$ = 42, n_{TAST} = 13). Coefficients for fixed effects have been back-transformed, so that they represent multiplicative influences on the response (e.g., an estimate smaller than 1 implies a reduction in catch mass). Upper and lower bounds demarcate the 95% confidence interval of the estimate.

Effect of TAST on fishing catch weight by trip				
	Estimate	Lower	Upper	
M11. catchWeight ~ treatment + jiggingMachines+ (1|vessel)				
Intercept	108.203	25.647	456.5	< 0.001
Treatment: TAST	0.634	0.319	1.262	0.195
Number of jigging machines	1.447	0.812	2.581	0.21
Vessel (Variance)	2.123×10^{-9}			

Table A3.6 – Parameter estimates of generalized linear mixed effects models (GLMMs) testing whether fishing stop number (ordered by trip) influenced the probability of spotting a seal via hull-mounted sonar display (n = 248). Coefficients for fixed effects have been back-transformed, so that they represent multiplicative influences on the response (e.g., an estimate smaller than 1 implies a reduction in the probability of detecting a seal). Upper and lower bounds demarcate the 95% confidence interval of the estimate.

Effect of stop number on seal sightings by SONAR [control trials only]				
	Estimate	Lower	Upper	
M12. $Seal_{SONAR}$ ~ stopID + (1|vessel/trip)				
Intercept	0.025	3.993×10^{-4}	1.529	0.079
Stop number	1.044	0.964	1.131	0.286
Trip (Variance)	1.239			
Vessel (Variance)	6.803			

Table A3.7 – Parameter estimates of generalized linear mixed effects models (GLMMs) testing whether fishing stop number (ordered by trip) influenced the probability of spotting a seal by direct visual observation (n = 248). Coefficients for fixed effects have been back-transformed, so that they represent multiplicative influences on the response (e.g., an estimate smaller than 1 implies a reduction in the probability of detecting a seal). Upper and lower bounds demarcate the 95% confidence interval of the estimate.

Effect of stop number on visual seal detections [control trials only]				
	Estimate	Lower	Upper	
M13. $Seal_{VISUAL}$ ~ stopID + (1|vessel/trip)				
Intercept	1.68	0.261	10.795	0.585
Stop number	1.067	0.997	1.143	0.062
Trip (Variance)	1.475			
Vessel (Variance)	2.03			

Appendix 4. – Supplementary figures

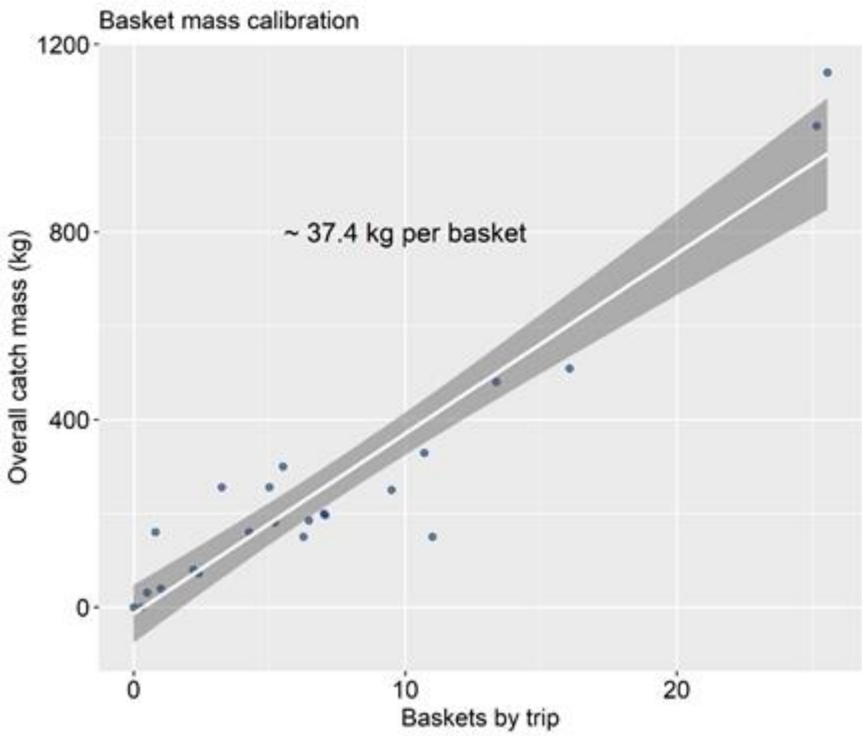
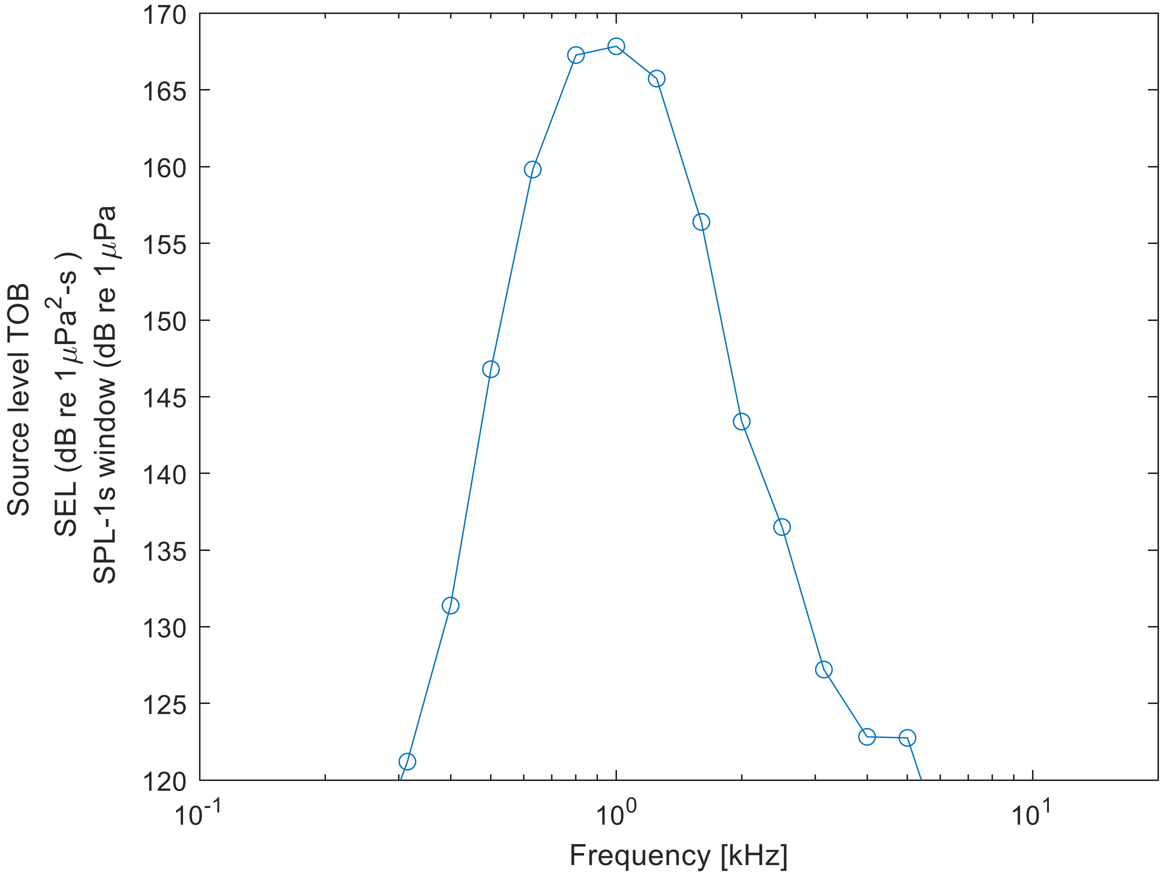


Figure A4.1 – Estimated relationship between the number of full baskets reported and overall catch mass, by trip (n = 24 trips for which both overall and stop-based catches were known). The slope of the linear fit represents an approximate value of 37.4 kg/basket.

Figure A4.2 – Estimated relationships between total trip duration (minutes between departure and return to port) and overall catch mass, displayed according to fishing type of the trip. Mixed trips consisted of combinations with up to all three fishing types.

Appendix 5: Acoustic properties of the TAST system used in this study.

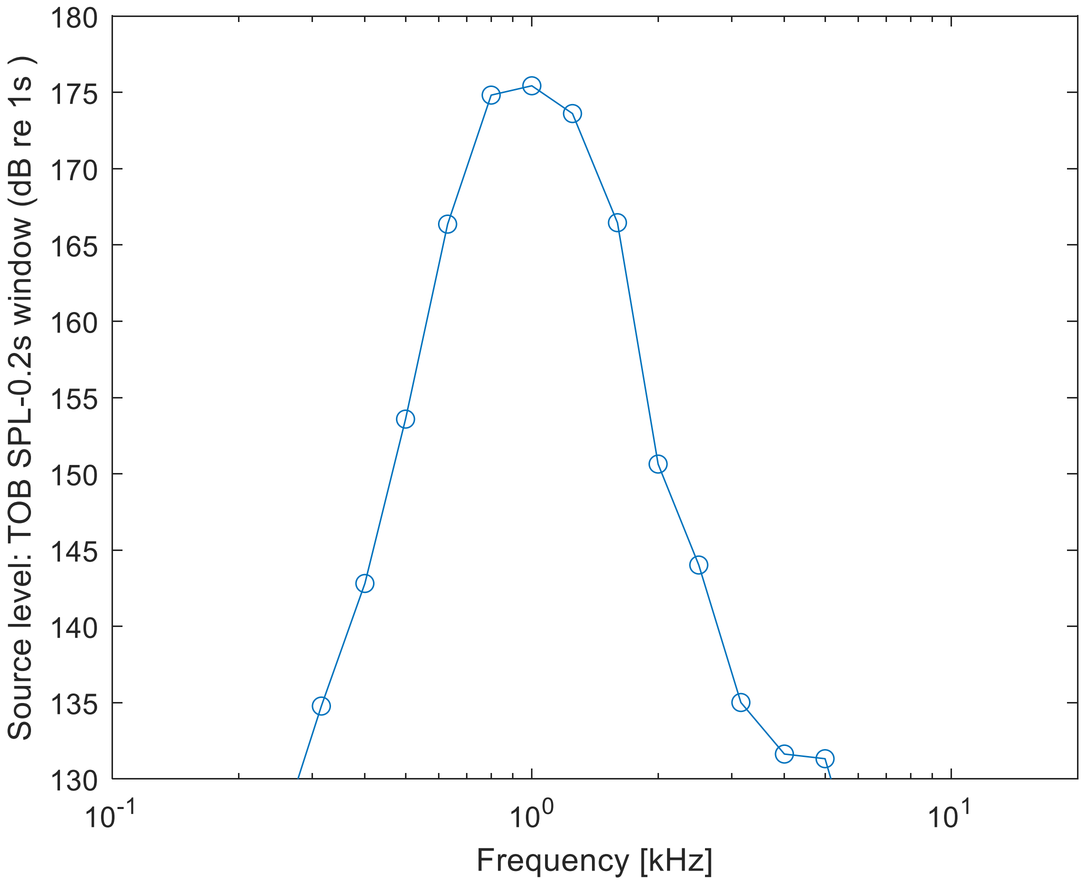
Source level (rms): 1 second integration window (SEL)



The mammalian auditory system processes sound within one third octave bands (TOB). The source level of the TAST unit was calculated using TOBs which is the same method that Lepper et al. 2014 set as a standard (see their Fig. 25-30) when they assessed the acoustic properties of conventional acoustic deterrent devices. The graph above shows the sound exposure level (SEL) which is equivalent to the sound pressure level (SPL, rms) calculated over a 1s integration window. The highest value in this graph represents an **SEL of 167.8 dB re 1 μPa^2-s** or sound pressure level (**SPL**, rms) of **167.8 dB re 1μPa** (1s window). The graph also shows the frequency range of the signal which is centred at 1kHz.

Source level (rms): 200ms integration window

The graph below shows the source level in units of sound pressure level calculated over a 0.2 (200ms) integration window (corresponding to the signal duration) in one third octave bands (TOB). The highest value in this graph represents a SPL of **175.4 dB re 1μPa.** The graph also shows the frequency range of the signal which is centred at 1kHz.


180
175
170
165
160
155
150
145
140
135
130
Source level: TOB SPL-0.2s window (dB re 1s)
10^{-1}
10^{0}
10^{1}
Frequency [kHz]