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Cues, creaks, and decoys: using passive acoustic monitoring as a tool for studying sperm whale depredation

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Since 2003, a collaborative effort (SEASWAP) between fishers, scientists, and managers has researched how Alaskan sperm whales locate demersal longline fishing activity and then depredate sablefish from gear. Sperm whales constantly produce relatively low-frequency biosonar signals whenever foraging; therefore, over the past decade, passive acoustic monitoring (PAM) has become a basic tool, used for both measuring depredation activity and accelerating field tests of potential depredation countermeasures. This paper reviews and summarizes past published PAM research on SEASWAP, and then provides a detailed example of how PAM methods are currently being used to test countermeasures. The review covers two major research thrusts: (i) identifying acoustic outputs of fishing vessels that provide long-distance "cues" that attract whales to fishing activity; and (ii) validating whether distinctive "creak" sounds can be used to quantify and measure depredation rates, using both bioacoustic tags and statistical comparisons between visual and acoustic depredation estimates during federal sablefish surveys. The latter part of the paper then provides an example of how PAM is being used to study a particular potential countermeasure: an "acoustic decoy" which transmits fishing vessel acoustic cues to attract animals away from true fishing activity. The results of an initial 2011 field trial are presented to show how PAM was used to design the decoy signals and monitor the efficacy of the deployment. The ability of PAM to detect both whale presence and depredation behaviour has reduced the need to deploy researchers or other specialists on fishing cruises. Instead, volunteer fishers can deploy "user-friendly" acoustic recorders on their gear, greatly facilitating the testing of various deterrents, and providing the industry and regulators a convenient and unobtrusive tool for monitoring both the scale and long-term spread of this behaviour across the Alaskan fishery.

Keywords: acoustic deterrent, commercial fishing, depredation, Gulf of Alaska, longline, marine mammals, passive acoustic monitoring, sablefish, sperm whales.

Introduction

In this paper, we highlight the role that passive acoustic monitoring (PAM) has played over the past 10 years, as part of a collaborative research effort between scientists and fishers to study depredation behaviour of sperm whales off southeast Alaska. The first part of the paper summarizes several previous publications on the topic (Thode et al., 2007, 2014; Mathias et al., 2009, 2012, 2013), to give a broad perspective into how PAM has contributed to this

depredation study. The final part of the paper then provides a previously unpublished case study of how PAM methods are currently being applied to study a potential acoustic deterrent (an acoustic decoy) that would be difficult to evaluate using other methods.

The motivation behind this paper is that acoustics, whenever mentioned at all in the context of marine mammal depredation, is typically associated with acoustic deterrents and harassment devices, a topic with a long and chequered history that is at least 40 years old (Fish and Vania, 1971; Shaughnessy *et al.*, 1981; Jefferson and Curry, 1996). Little to no published research on the use of acoustics to observe or measure depredation behaviour exists before the 21st century (McPherson *et al.*, 2002, 2004; Hernandez-Milian *et al.*, 2008). The reasons are mainly technological; before 2000, passive acoustic recorders were too large and too power-intensive to be deployed autonomously. Instead, they had to be based on vessels, requiring expensive and delicate cables to connect hydrophones to the recording equipment.

This situation was changing by 2004, when passive acoustics began to be applied to the Southeast Alaska Sperm Whale Avoidance Project (SEASWAP). SEASWAP is a collaborative effort between the Alaska Longline Fishermen's Association (ALFA), the University of Alaska Southeast (UAS), the Sitka Sound Science Center (SSSC), and the Scripps Institution of Oceanography (SIO). The programme seeks to determine the scale of depredation by sperm whales on sablefish (*Anoplopoma fimbria*) off demersal (bottom-deployed) longline fisheries operations in southeast Alaska, particularly along the narrow continental shelf off Sitka. A deep-diving species, sperm whales regularly descend to depths >400 m for periods ranging between 30 and 45 min (Watkins *et al.*, 1993; Jaquet *et al.*, 2000; Wahlberg, 2002; Whitehead, 2003). While squid is a primary component of their diet, sperm whales also consume sablefish as natural prey in northern Pacific waters, so it is not surprising that between 124 and 153 individual sperm whales have been identified by SEASWAP as depredators using mark-recapture studies (Straley *et al.*, this issue). A detailed history of SEASWAP is detailed elsewhere in this issue (Straley *et al.* and O'Connell *et al.*); satellite tagging has become another major research tool that is covered elsewhere (Mathias *et al.*, 2013; Straley *et al.*, 2014).

Three aspects of the SEASWAP programme encouraged the rapid adoption and adaption of passive acoustic methods: the emergence of commercial flash-memory passive acoustic recorders, a strong collaborative history between Alaskan fishers and researchers, and the ubiquitous presence and relatively low-frequency content of sperm whale acoustic signals. By 2003, small, compact flash-memory recorders became commercially available, and with a single stroke, the need for cabled hydrophones was eliminated, and the unobtrusive deployment of autonomous acoustic recorders from fishing vessels and even animal tags became possible. The strong working relationship between fishers and programme researchers resulted in the design of practical quick-release attachment systems that made the deployment of the recorders practical during commercial fishing operations.

The way sperm whales use sound also encouraged the extensive use of PAM by SEASWAP. Sperm whales are acoustically active underwater (Figure 1), and during a single dive, one individual can make thousands of impulsive sounds called "clicks" (Worthington and Schevill, 1957; Watkins, 1977; Goold and Jones, 1995). Measurements in other areas of the world have found that ~10–15 min before returning to the surface, an animal typically falls silent (Douglas *et al.*, 2005). Thus, PAM of an animal's vocalizations
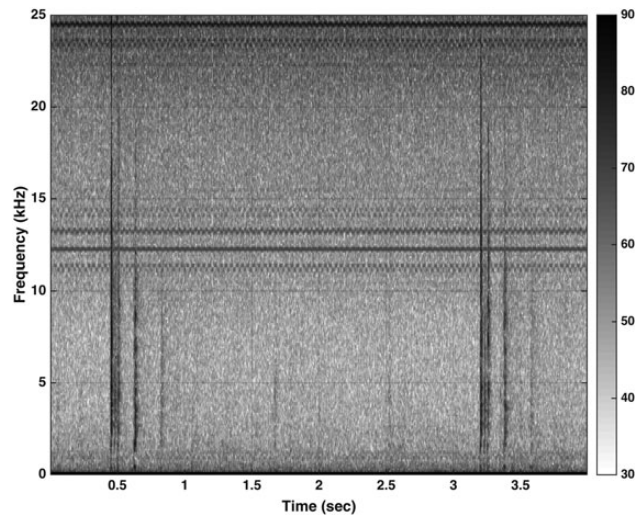
Figure 1. Spectrogram of two typical sperm whale clicks, which appear as thin vertical lines over this time-scale. The ICI for these clicks is ~2.5 s. At least three echoes, or "multipath", are visible within 0.5 s after the arrival of each initial direct-path signal. The various horizontal lines are internal electronic noise contamination.

can yield an estimate of the animal's dive cycle, even if the animal is never observed at the surface. The "inter-click interval", or ICI, of these sounds is typically between 0.5 and 1 s (Figure 1), and the detectable bandwidth of these signals extends from above 15 kHz down to at least 2 kHz, a low-frequency range that is relatively easy to monitor and record on flash memory media. The upper bandwidth of the signals depends on the animals relative orientation to the hydrophone; when the animal's biosonar mechanism is pointed at the hydrophone, frequency components over 15 kHz can be detected, due to the high directivity of the sonar. However, even when the whale is orientated away from the hydrophone, frequency components between 2 and 9 kHz are typically detectable, a fact that makes PAM a practical tool for detecting the presence of sperm whales. Figure 1 also shows that sperm whale clicks often generate detectable echoes, or "multipath arrivals", from the ocean surface and bottom. By measuring the relative arrival times of these multipath, one can occasionally derive the range and depth of the animal, when the animal is <2 km horizontal range (Thode *et al.*, 2002; Tiemann *et al.*, 2006).

The expansion of PAM methods in SEASWAP was evolutionary and incremental, and not pre-planned. Often, casual reviews of acoustic data from deployments opened up serendipitous research avenues. However, when reviewing the past decade of PAM research for SEASWAP, four broad categories of research can be identified: (i) identifying acoustic "cues", (ii) estimating depredation rates by measuring distinctive "creak" echolocation sounds, (iii) testing and evaluating potential countermeasures, and (iv) developing localization and tracking algorithms from fishing gear. This fourth and final category will not be covered in this paper, although three out of the eight peer-reviewed papers produced by SEASWAP have exploited sperm whales' depredation behaviour to develop and demonstrate two- and three-dimensional tracking methods of odontocetes using one to two hydrophones (Tiemann *et al.*, 2006; Thode *et al.*, 2010c; Mathias *et al.*, 2013).

The remaining three categories form both the title and the body of this paper. The "Cues" and "Creaks" sections summarize

previous published research. The acoustic cues section covers the initial use of PAM to quantify the acoustic signatures of fishing activity and to detect the presence or absence of sperm whales around such activity (Thode *et al.*, 2007). The "creaks" section reviews subsequent research into the use of acoustics as a remote measure of depredation effort. Two methodologies have been used to study creaks: bioacoustic tagging studies (Mathias *et al.*, 2012), and comparative measurements between visual and acoustic estimates of depredation rates over 2 years of a federal sablefish longline survey across the Gulf of Alaska (Thode *et al.*, 2014).

The final part of this paper contains previously unpublished material that illustrates how PAM is used to enhance and accelerate the testing of depredation countermeasures, which is the current focus of SEASWAP. While an alternating-hook configuration can be used to test countermeasures that work on a hook-by-hook basis (e.g. weak hooks and fish cages), we contend that passive acoustic methods provide a valuable tool for evaluating deterrents that operate across multiple hooks simultaneously, or try to exploit avoidance as a strategy. The particular countermeasure concept discussed here is one such avoidance strategy: an "acoustic decoy" which broadcasts fishing cues to attract animals away from sites of actual fishing activity. A trial deployment of such a system in 2011 is reviewed here in detail, showing how PAM was used to design the decoy signals and to evaluate the efficacy of the device. The paper concludes by discussing how the techniques used here should be modified when studying depredation by other species in other geographic regions, along with some important caveats when using PAM in the context of fishery depredation studies.

A quick review of instrumentation and deployment strategies used during SEASWAP

Over the past decade, the evolution of the acoustic equipment used by SEASWAP has mirrored the rapid development of consumer flash-memory electronics over the same period.

Between 2004 and 2007, autonomous acoustic recorders, designed and built by Greeneridge Sciences Inc. (Burgess, 2000), were used for initial research. Electronically speaking, these instruments were exact copies of the "Bioacoustic probes" produced by the same company, but were placed in small pressure cases instead of encased in epoxy, a change that permitted the flash memory to be swapped out without needing to be downloaded first. These "Bprobes" could sample acoustic data at sampling rates between 100 Hz and 20 kHz, using an HTI-96-MIN/3 V hydrophone (typical sensitivity of 172 dB re 1 μPa V^{-1}) and storing the data to 1 GB of flash memory with 16-bit precision. For the data presented here, the data sampling rates varied between 8.2 and 20.1 kHz. The resulting length and diameter of each recorder was 25 and 5 cm.

In subsequent years, custom-built autonomous acoustic recorders were used, which could be programmed with an internal duty cycle. All recorders have consistently used the HTI-96 min hydrophones with 172 dB re 1 μPa V^{-1} sensitivities during the past decade, but their memory capacity has increased from 1 to 128 Gb, and the recording endurance increased from roughly 12 h to over 30 days.

Figure 2 shows how these instruments have been typically attached to a demersal longline deployment. The longline itself consists of a series of "skates" (100 m long with 45 hooks spaced 2 m apart), which lie along the ocean bottom over a typical distance of several kilometres, typically at depths between 300 and 700 m. At each end of the longline, a 35 kg anchor is used, and from each
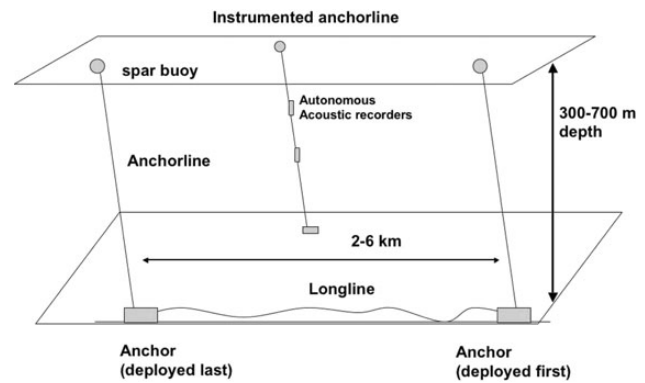
Figure 2. Schematic of a typical demersal longline deployment, indicating where autonomous acoustic recorders are typically placed.

anchor, a "buoy line" rises to the surface, attached to a spar buoy. During a typical instrumented deployment, autonomous recorders are attached by a quick-release clamping mechanism to an existing buoy line, at depths between 100 and 400 m. As the figure shows, often a third buoy line is used, deployed before beginning the actual longline deployment, and recovered once the haul is complete. The third buoy line is generally deployed within 1 km of the expected position of the ground line on the bottom. Given the large scope of the buoy line, the actual deployment depths can vary considerably and must be logged from pressure transducers. Flow noise was an initial concern, but it was found that continuous flow noise was only significant at frequencies below 50 Hz.

Review of research category 1: acoustic cues

One of the first goals of SEASWAP was to determine how a sperm whale both detects and locates fishing activity. Whenever a fishing vessel initially deploys fishing gear shown in Figure 2, it generally feeds the baited ground line through a chute on the stern of the vessel, a process that generally takes around half an hour. Recovering the line is a much slower and more delicate process, taking several hours. The fishing vessel first transits to the up-current buoy, and a deckhand pulls the buoy line over a set of rollers mounted on the side, wrapping the buoy line around a hydraulic winch, which then pulls the anchor and longline off the floor. Once the anchor has been retrieved, the vessel attempts to drift with the current, while continuing to winch the longline aboard. Often the vessel captain has an auxiliary set of steering controls next to the rollers, which he/she will use to engage the engine during a haul to permit fine-scale control of the vessel.

Longliners in the eastern Gulf of Alaska often observed whales arriving after a haul began, raising whether the animals were responding to distinctive visual or acoustic cues inadvertently produced by the activity. An example of a potential visual cue is the flocking of 10s to 100s of seabirds to a fishing haul site, and popular hypotheses for acoustic cues included propeller cavitation, activation of auxiliary hydraulic systems to haul gear, echosounders, and strum noise produced by the vibration of the taut gear line as it is hauled out of the water. Figure 3 shows a spectrogram of several types of acoustic signals detected from a commercial fishing vessel at a couple hundred metres directly underneath the vessel. Signals from the propeller, hydraulic system, and fathometer can all be discerned at these close ranges. Thus, one of the first uses of passive acoustics in SEASWAP was to measure the range at which potential fishing
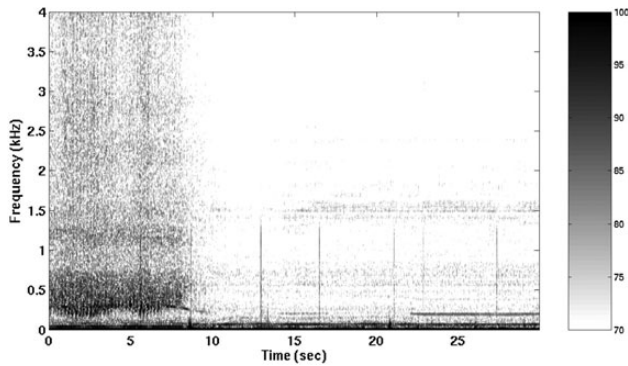
Figure 3. Spectrogram of F/V *Kelly-Marie*, measured at 13:21:14, 7 May 2004, at a depth of ∼100 m directly underneath the hull. The grey scale shows the square modulus of the acoustic pressure in units of power spectral density (dB re 1 μPa^2 Hz^{-1}). Cavitation noise from the propeller is visible between 0 and 10 s, and the hydraulic system to power the hauling winches has been activated at 22 s, generating the 190 Hz tone visible in the spectrogram. The thin vertical lines between 0 and 1.25 kHz are not sperm whale clicks, but the vessel's fathometer.

cues could be detected. This research is detailed in Thode *et al.* (2007), but the major points are reiterated here.

Figure 4b displays some measurements from the first acoustic deployment around a hauling vessel that was depredated by two sperm whales. Two continuous curves are plotted: the rms acoustic pressure detected across a bandwidth associated with the hydraulic system (150–250 Hz: dotted line), and the pressure measured over a more broadband frequency range (250–1000 Hz: solid line). Note that the hydraulic system curve has been shifted −10 dB for visual clarity. The exact time that the hydraulic system was switched on was not noted, but it was ∼9:00 a.m., a few minutes before the first buoy line retrieval, and the system remained on until the end of the haul. A careful review of Figure 4b around 9:00 a.m. confirms the absence of any sustained hydraulic signature at 1.6 km detection range (the transient increase just before 9 a.m. cannot be associated with the hydraulics, as the hydraulic system runs continuously once activated during the entire haul).

However, an interesting feature in the acoustic signal appears as the vessel begins to haul the buoy line at 9:04. The 250 Hz–1 kHz curve in Figure 4b displays a series of short-duration peaks that change the rms pressure by 3–5 dB between 9:05 and 9:20. The short-term peaks beginning at 9:05 arise from a particular method of handling the vessel to keep the winched longline vertical. Generally, a longliner tries to keep the engine in neutral and drift with the current while hauling the line. Often, however, due to snags, currents, or delays in gaffing fish, the line will begin to angle underneath the hull of the vessel. Under this circumstance, the engine is briefly engaged for 5–10 s to swivel the vessel around the line, the result being a cavitation bubble cloud. Figure 5 shows an example of how a spectrogram of this signal appears, taken at 9:53, or 34 min after substantial sperm whale activity began, and when the vessel is 900 m from the instrumented buoy line. Figure 4a and b uses vertical dashed lines to mark discrete times when this activity occurs while hauling the buoy line, to give an impression of the long-term temporal pattern generated by this hauling behaviour.

From this very first acoustic deployment, it was apparent that the cavitation noise generated by changes in the propeller rotation speed produced a significant broadband acoustic signature that could be

detected kilometres away, and that the output of the hydraulic system was not apparent at ranges >1 km. These cavitations occur via engaging the engine from neutral, or to a lesser extent via changes in vessel shaft speed. Over three subsequent field deployments conducted between 2004 and 2005, SEASWAP determined that engaging the propeller from a neutral state increased the vessel rms acoustic intensity by 6–10 dB between 250 and 1000 Hz and produced a detectable signal with a signal-to-noise ratio (SNR) of at least 6–10 dB at 1–2 km range. The bulk of the energy of this signal generally lies below 6 kHz, but frequencies above 10 kHz can be detected, though at levels 20 dB below the lower-frequency content. Continuous engine noise is often detectable below 1 kHz. Generally, cavitation signals were detected reliably to 5 km range in 600–700 m deep water, but detection ranges out to 10 km have been observed on calm days.

By 2005, SEASWAP had demonstrated that deliberately manipulating the vessel controls to produce cavitation noise caused sperm whales to appear within 4 min and within 50 m of the vessel, although no real haul was taking place, and the vessel was over 1 km from the nearest buoy line. The research also suggested that engaging the engine to move the vessel from a drifting state produced an acoustic signature that is perceptually salient to sperm whales, in that when a drifting vessel engaged its propeller during the night, the dive cycle of a sperm whale foraging in the area was disrupted.

The cumulative conclusion of both Thode *et al.* (2007) and subsequent SEASWAP fieldwork is that fishing vessels loitering in the immediate area of a fishing deployment attract sperm whales, particularly whenever a vessel repeatedly engages its propeller to stay near a buoy. If a vessel can transit to shallow water or anchor, then that provides the best chance of avoiding depredation. When conducting a haul, speed is of the essence, because there is no way to mask or suppress the distinctive cavitation sounds of a hauling vessel. Although not emphasized in the original 2007 paper, SEASWAP has since noted that the intensity of sperm whale clicks recorded near depredating vessels can be greater than the vessel sounds themselves, suggesting that sperm whales may (inadvertently or not) alert other whales to the presence of fishing vessels over a much wider region than that ensonified the original hauling cues themselves. This observation seems borne out by fishers' logs, which report that when one whale appears next to their vessel during hauls, inevitably other whales eventually appear as well.

Review of research category 2: using creaks to remotely measure depredation rates
Motivation

Beginning in 2006, SEASWAP started investigating potential countermeasures to reduce depredation during the location and terminal stages, but eventually realized that the key problem was not generating ideas for countermeasures, but testing these ideas quickly and cost-effectively. One of the biggest problems was accurately measuring depredation rates. Originally depredation rates were estimated using visual counts of damaged or partially eaten fish remains appearing on the longline. This approach required either substantial note-taking by fisher collaborators or the presence of a researcher on board, situations that were often not practical.

Underwater video recordings cast further doubt into the reliability of measuring depredation rates by tabulating damaged remains on hooks. The presence of acoustic multipath sometimes permitted the range and depth of the whale relative to the monitoring hydrophone to be derived, assuming a flat bathymetry surrounding the
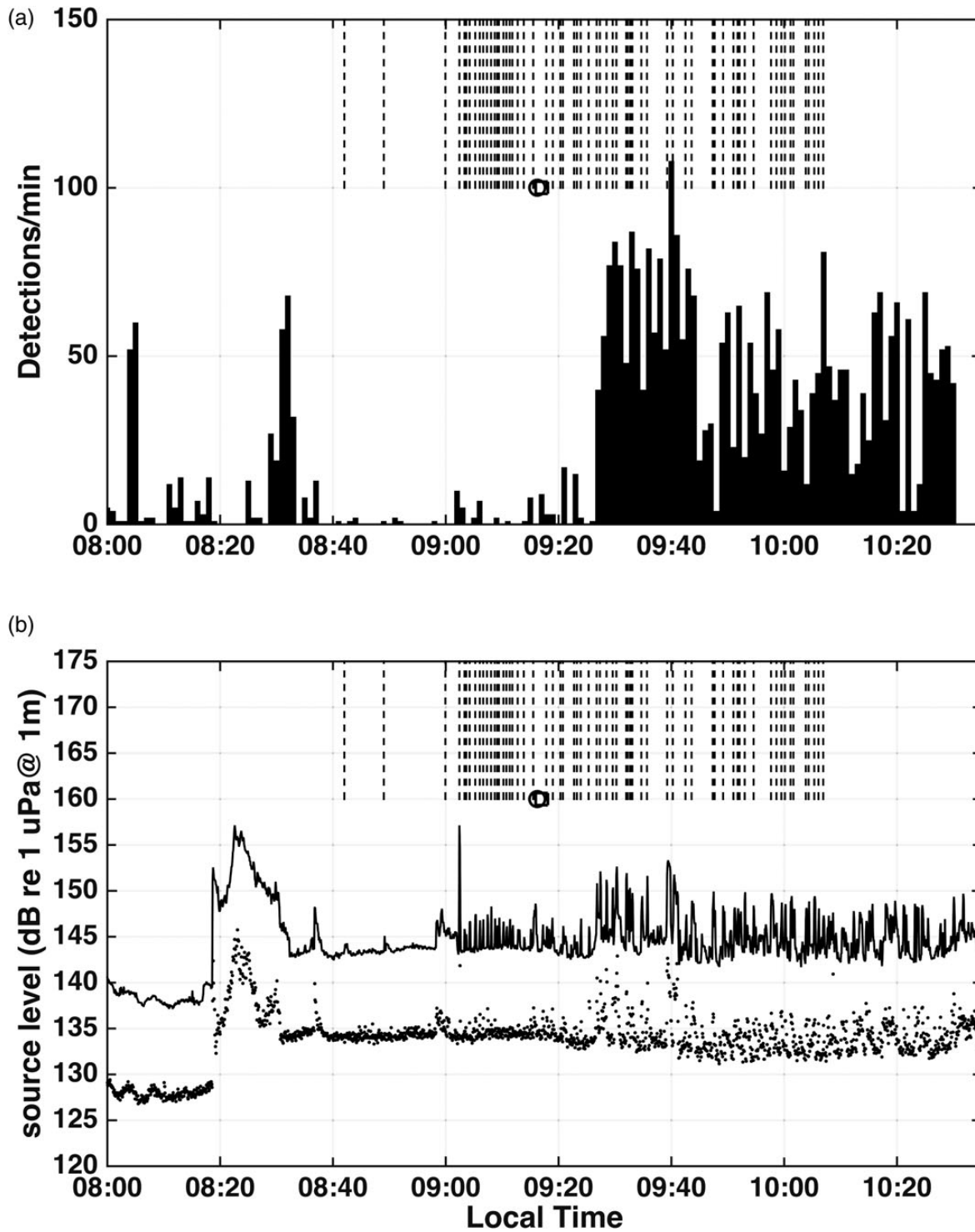
Figure 4. Example of fishing vessel cues generated during depredation, between 8:00 a.m. and 10:30 a.m. (a) Histogram of sperm whale click and multipath sounds detected per minute. Vertical dashed lines indicate the presence of acoustic signatures of an engine engaging and disengaging the propeller. The circle indicates time at which an anchor is dropped on deck (anchorline on board), and the square indicates the start of substantial sperm whale acoustic activity at 09:17:01; (b) source level (rms) in units of dB re 1 μPa @ 1 m, averaged over 5 s intervals, integrated between 250 and 1000 Hz (solid line) and 150 and 250 Hz, a band associated with the vessel's hydraulic system (dashed line, shifted − 10 dB for clarity). Received levels have been adjusted by measured vessel slant range to produce effective source levels at 1 m range.

hydrophone. By late 2005, SEASWAP noted that depredating whales sometimes seemed to forage closer to the surface than under regular conditions—as shallow as 50 m. Enough ambient light exists at

these depths for video recording without artificial lighting, so in May 2006, an Sony HVR-1AU videocamera housed in a Gates Underwater Products HC1/A1U underwater housing was deployed
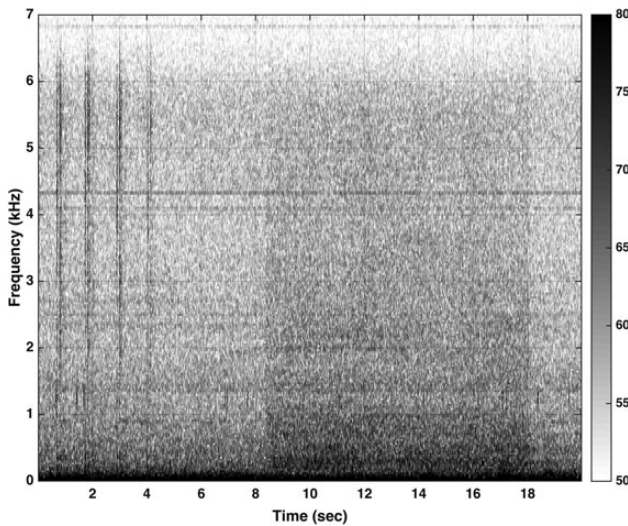
Figure 5. Example of "engine cycling" as fishing vessel fine-tunes its position relative to the longline, during a time (9:53) that the vessel is closest to the acoustic recorder during the haul (900 m range). The engine is engaged at 8 s and disengaged at 18 s, generating broadband cavitation noise visible up to 6 kHz. Sperm whale clicks are visible between 1 and 6 kHz between 0 and 4 s.

during an active longline haul by the F/V Cobra. The resulting video and audio (Mathias *et al.*, 2009) revealed that a sperm whale could remove a fish from a longline without leaving any visual evidence behind, other than an empty hook. Unfortunately, empty hooks are a fairly common occurrence during longlining, as fish can shake, or "spin off", the line relatively easily.

Tabulating visual evidence of partial fish remains was thus found to be both inconvenient and inaccurate (i.e. likely undercounting depredation activity). However, the same video that revealed this problem also suggested a potential solution: the whale was generating sound while depredating the fish, even under good visual conditions.

The sound produced by the depredating sperm whale in the video is well known: it is a "creak" (or "buzz") sound, a sequence of pulses produced at a rate of 10 s^{-1} or faster (Madsen *et al.*, 2002), and often characterized by a decrease in the pulse interval and (occasionally) amplitude over the 5–10 s duration of the sound (Whitehead and Weilgart, 1990; Whitehead, 2003). Bioacoustic tagging work on sperm whales has shown that most creaks occur at foraging depths and are often associated with changes in the orientation of the animal (Miller *et al.*, 2004; Watwood *et al.*, 2006). Creaks are sometimes followed by a few seconds of silence before the animal resumes "usual" clicking (Madsen *et al.*, 2002), defined here as a "creak-pause" event. This cumulative circumstantial evidence suggested that creak and creak-pause events were associated with an animal's use of biosonar to acquire individual prey, similar to analogous sounds produced by bats (Surlykke *et al.*, 2003), deep-diving beaked whales (Johnson *et al.*, 2009), and porpoises (DeRuiter *et al.*, 2009). Both Surlykke *et al.* (2003) and DeRuiter *et al.* (2009) also noted that short periods of silence occurred after an echolocation sound, whenever prey were captured and consumed.

The idea thus arose that PAM for creak sounds might provide a complementary measurement of depredation activity by sperm whales. It was further hypothesized that "creak-pause" events may be evidence of a successful prey capture (as opposed to just a prey

attempt), and thus creak-pause detection rates should correlate better with underlying depredation rates than raw creak counts. Other interpretations of a creak-pause event are possible, but the interpretation of a creak-pause event as prey capture did yield at least one testable hypothesis. The rest of this section summarizes two papers (Mathias *et al.*, 2012; Thode *et al.*, 2014) that used two very different methodologies in search of a common goal: evaluating whether creak rates are a good predictor of true depredation rates, and if so, whether a creak-pause event is a better measure of depredation than a more inclusive creak rate estimate, a conclusion that would provide circumstantial evidence that creak-pause events are associated with prey capture.

### Bioacoustic tagging evidence

The first evidence that creak detection rates were correlated from depredation activity arose from bioacoustic tagging studies on depredating sperm whales (Mathias *et al.*, 2012). "Bprobe" tags with a 4 kHz sampling rate were deployed on sperm whales during two field efforts in July 2007 and June 2009. Several animals displayed both "natural" and "depredation" foraging behaviour on the same tag record, and various behavioural metrics were derived, including animal depth, pitch inflection rate, click rate, mean ICI, and creak rate.

Figure 6 shows an example of time-series of these metrics, computed from an animal displaying particularly aggressive depredation around a large fishing vessel, the F/V Ocean Prowler. The shaded regions in the plots indicate times when the animal was depredating the vessel. One sees that during aggressive depredation, the animal is extremely shallow (subplot A), changing orientation rapidly (subplot B), and generating many clicks at a rapid rate (subplots C and D). One also sees in subplot E that the creak rates are quite high, often over 30 creaks an hour. To provide some context to these rates, Miller *et al.* (2004) reported creak rates close to 15 h^{-1} for animals foraging naturally, while Watwood *et al.* (2006) reported that 37 sperm whales in the Atlantic Ocean, the Gulf of Mexico, and the Ligurian Sea made an average of 22 ± 8.0 creaks h^{-1}.

The SEASWAP tagging work reveals considerable variation in depredation techniques, ranging from the aggressive, or "shallow" depredation shown in Figure 6, to apparent depredation behaviours that initially seemed identical with natural foraging. These latter behaviours, dubbed "deep depredation", were intriguing, for although these animals were clearly associating with vessels, often surfacing within 20 m of the vessel between dives, the dive depths, dive durations, and orientation rates of the animals were statistically indistinguishable from natural foraging dives. However, consistent differences in acoustic behaviour were noted between deep depredation and natural foraging behaviour (Figure 7). Roughly speaking, when compared with natural foraging, sperm whales conducting either deep or shallow depredation began generating biosonar clicks sooner after the start of a dive, had lower ICIs, and had higher creak rates. For example, the median creak rate of 30 creaks h^{-1} during shallow depredation was more than three times higher than natural median creak rate. The spread in creak rate values was also very high during shallow depredation: the 25th and 75th percentiles lie between 10 and 50 creaks h^{-1}, respectively, while the spread was much narrower for natural dives. Similar, but slighter, increases in creak rates are visible for deep-depredating animals.

There was much less dramatic change in the median percentage of creak-pause events (fraction of total creaks detected that were followed by pauses) during shallow depredation; even so, in three-quarters of shallow-depredation, dives over 60% of creak events
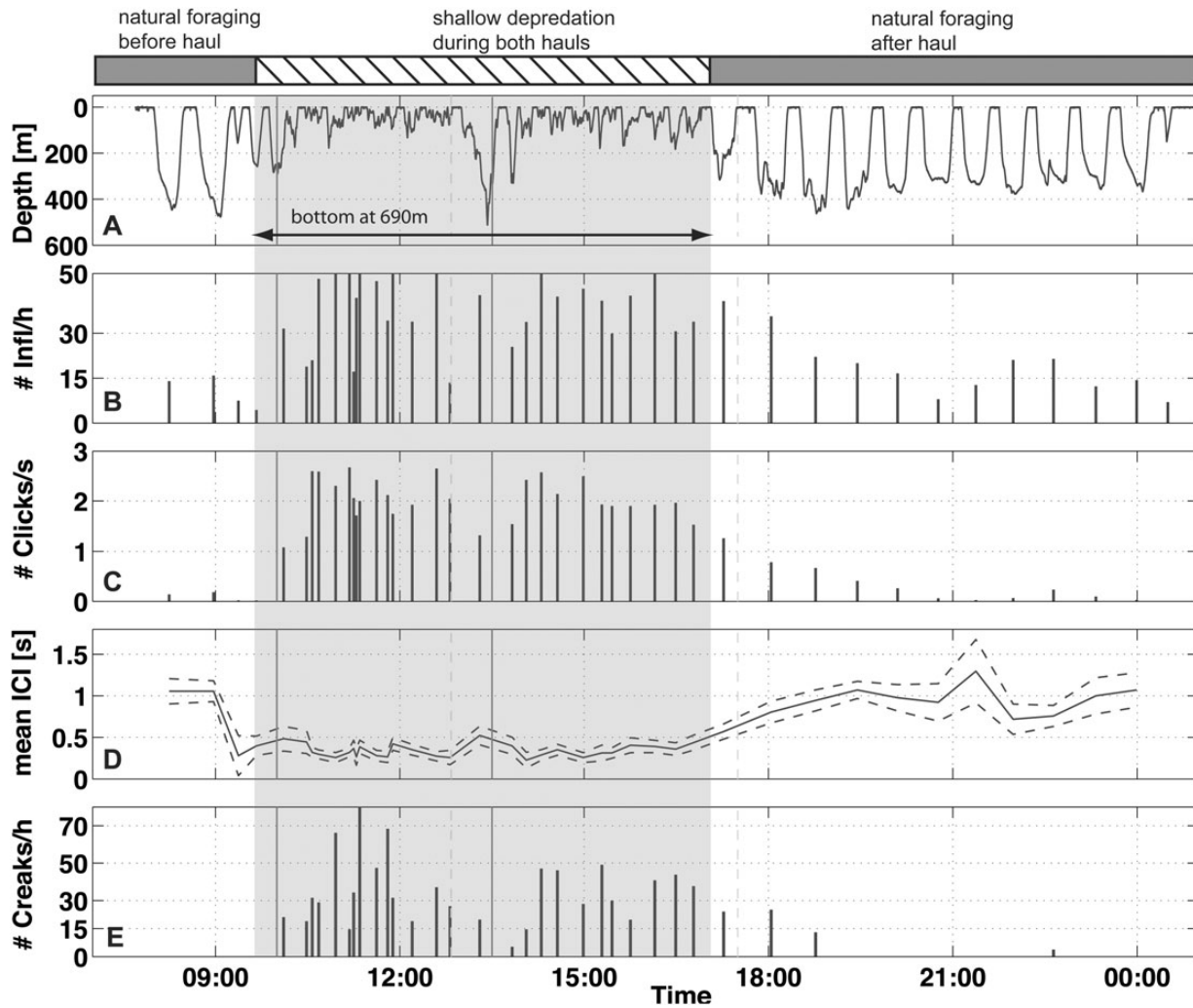
Figure 6. Selected dive and acoustic parameters of a whale displaying natural foraging and shallow depredation behaviour on 17 July 2007: (a) dive profile; (b) normalized dive inflection rate per hour, *Infl*, with each bar representing a distinct dive; (c) click rate per second; (d) mean ICI per dive, with dotted lines corresponding to 1 s.d.; and (e) normalized creak rate per hour, combining *creak-only* and *creak-pause* events. The start and end times of the fishing hauls are indicated by the solid and dotted vertical lines, respectively. The shaded areas indicate when the tagged whale was visually sighted surfacing within 400 m of the F/V Prowler after every dive.

detected were followed by a pause, while only 40% of natural foraging dives had creak-pauses. These differences, however, did not turn out to be statistically significant when a Kolmogorov–Smirnov test was applied.

One additional interesting contrast in creak-pause rates did appear: the relative fraction of creaks that were followed by pauses (a "creak-pause fraction") was quite low in the Gulf of Alaska tagging sample, when compared with published reports from the Gulf of Mexico and Ligurian Sea (Figure 7e). One (of several) possible interpretations is that Alaskan whales generally had lower prey acquisition success rates than whales in the Gulf of Mexico or Ligurian Sea; i.e. the Alaskan whales required more creaks per capture, perhaps because Alaskan whales include fish as a natural part of their diet, whereas sperm whales elsewhere are assumed to feed mainly on squid (Whitehead, 2003).

Thus, the bioacoustic results indicated that passive acoustic measurements of creak rates might correspond to depredation rates, but were ambivalent whether creak-pause rates were any better

depredation metric than general creak rates. The results also provided some of the first data into the energetic benefits generated by depredation for any marine mammal species.

Comparing visual vs. acoustic depredation estimates during the federal sablefish survey

Since 1987, the National Oceanographic and Atmospheric Administrations (NOAA) Alaska Fisheries Science Centre has conducted annual longline surveys of sablefish along the upper continental slope, referred to as domestic longline surveys. In 2011, the F/V Ocean Prowler and in 2012 the F/V Alaskan Leader were chartered to deploy demersal longline sets at a total of 65 "stations", or geographic locations. At each station, two "sets" of gear were deployed, roughly in tandem. Each 8 km set consisted of 80 skates of gear. For every hauled skate, a 100% hook census logged the number of baited hooks, damaged hooks, lip remains, and the number of undamaged and depredated fish, enumerated by species.
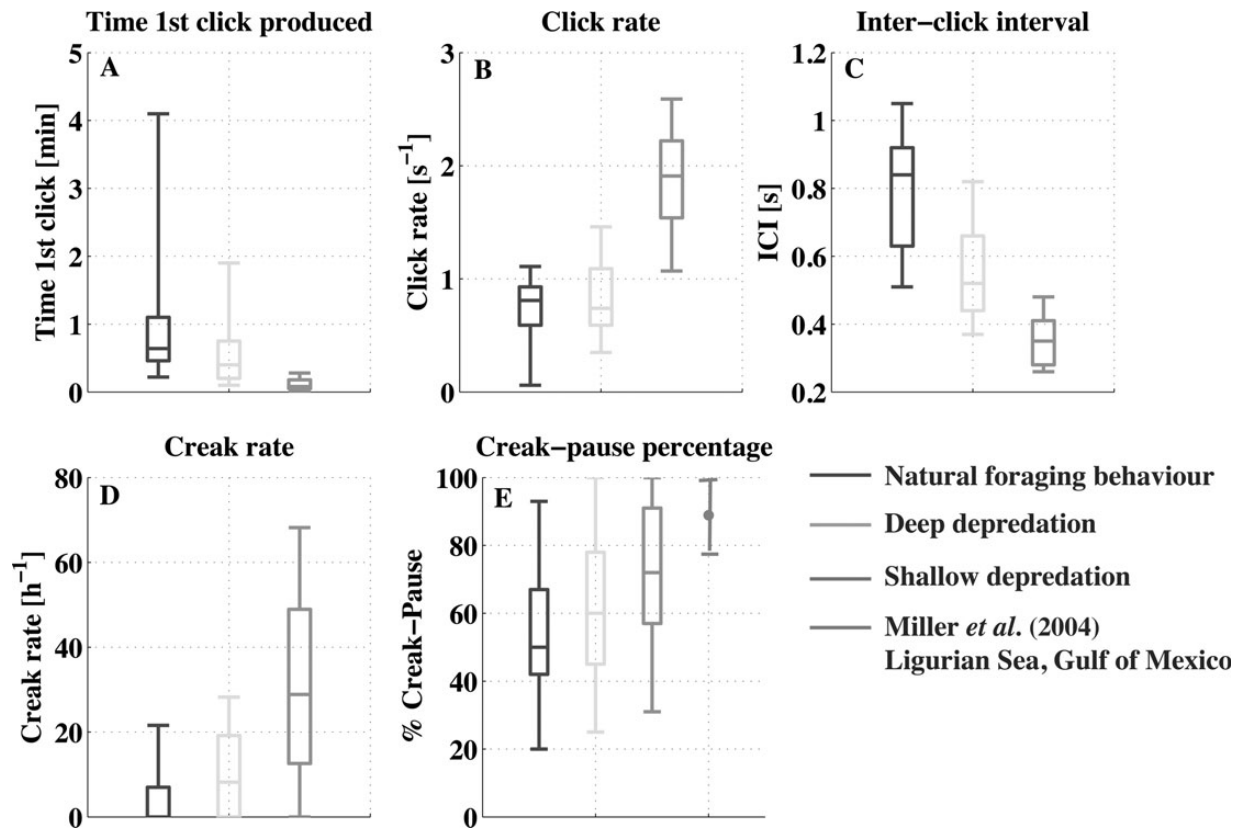
Figure 7. Boxplots of five bioacoustic tag parameter distributions, using tag records that display both natural and depredation behaviour. For each parameter, distributions are shown for deep and shallow depredation states, along with the distributions for the natural foraging states preceding/following a given depredation behaviour: (a) time of first click produced (min), relative to start of dive; (b) click rate per second; (c) ICI (s); (d) normalized creak rate per hour (for all creak events); and (e) creak-pause percentage. The box plots show the 5th, 25th, 50th, 75th, and 95th percentile values of the distributions.

NOAA provided support for deploying sets of acoustic recorders during the sablefish survey (Thode *et al.*, 2014). Over 2 years, 87 acoustic deployments documented 60 depredated hauls, which yielded over 170 h of raw data to review.

Figure 8 shows a graph that compares visual counts of lips/partial fish with various acoustic metrics. In the top subplot, the raw acoustic counts are used; while in the bottom subplot, background noise-adjusted values are plotted (Thode *et al.*, 2014). Only hauls with two or fewer sperm whales present are plotted here. Applying a noise-correction factor was found to increase the correlation with visual and acoustic metrics always, and a Poisson regression model that used visual survey data as predictor coefficients only obtained significant values when noise-adjusted metrics were used as the dependent variable.

Pearson correlation and Poisson regression analyses also provided significant support for the idea that counting creak-pauses, instead of all creaks, is a better acoustic metric of depredation activity, and that noise-adjusted creak-pause rates are the best overall acoustic depredation metric. For example, if all hauls that took place in the presence of whales were analysed, the number of noise-adjusted "creak-pauses" was found to be significantly correlated with survey counts of lips [$r(43) = 0.49$, $p = 0.03$] and sablefish damage [$r(43) = 0.29$, $p = 0.05$] in 2011, and significantly correlated with lip counts in 2012 [$r(10) = 0.89$, $p = 0.001$]. These results, in our opinion, provide the best evidence to date that creak-

pause events measured during depredation activities off Alaska are measurements of successful prey-capture attempts, and thus can provide insight into depredation rates.

However, several challenges were observed when trying to apply acoustics to depredation rate estimation. First, detecting creaks (and particularly creak-pauses) in the data becomes more difficult as more whales are present, and whenever more than two animals are present the visual evidence of depredation changed relatively little, while the number of creaks detected grows large, destroying the linear correlation between the two depredation metrics. Another challenge facing an acoustic depredation approach is the translation of acoustic depredation metrics into estimates of absolute depredation rates.

Despite the above caveats, the idea of using passive acoustics to measure depredation rates has been borne out by the experimental field data to date. As the cost of passive acoustic recorders continues to fall and their convenience continues to increase, we suspect further opportunities will arise to verify these conclusions.

Research category 3: using passive acoustics to test an acoustic decoy

The purpose of this final section is to illustrate how passive acoustics has been used to enhance the rapid evaluation of potential depredation countermeasures, a topic that is also the focus of O'Connell
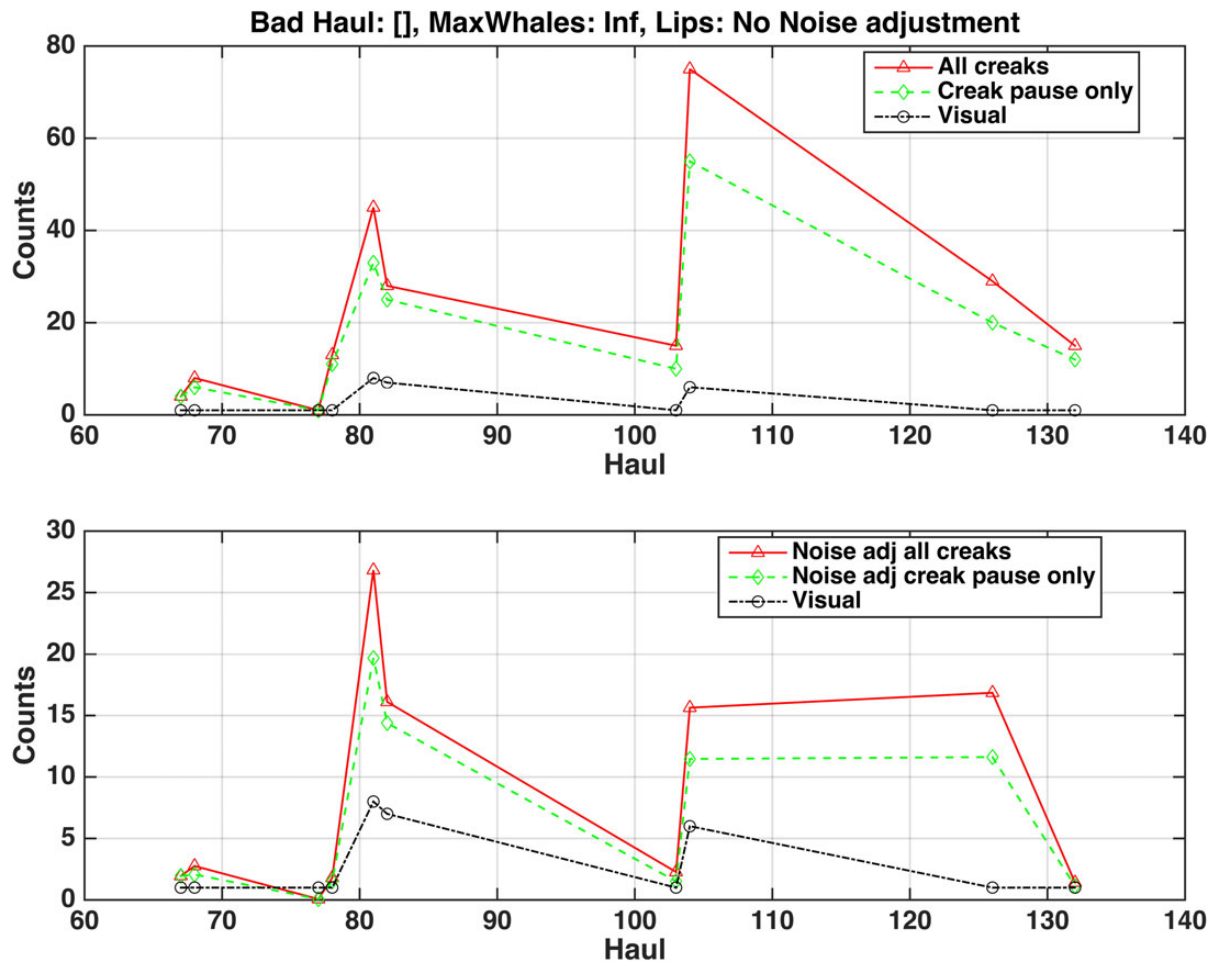
Figure 8. Plots of 2012 time-series of "lips" depredation count from federal survey database, vs. four candidate acoustic depredation measurements. (Top) Raw acoustic counts of creak and creak-pause events vs. lips records. (Bottom) Noise-adjusted acoustic counts vs. lips records.

et al. (this issue). This section varies from the two previous sections, in that it describes previously unpublished material. As a result, this section devotes considerably more detail to various procedural topics such as equipment, signal design, deployment configuration, and data analysis.

The concept of an acoustic decoy (Gilman *et al.*, 2007) was inspired by the passive acoustic discoveries reviewed here, and is currently being tested in field trials by SEASWAP. This section presents the initial proof-of-concept field trial of the technique in 2011, which illustrates the central role passive acoustics has assumed in evaluating the effectiveness of countermeasures for SEASWAP.

Acoustic playbacks, of course, are not a new deterrent concept, but the emphasis of these playbacks has always been on driving animals away from a fishing site during the terminal phase, either by broadcasting high-intensity signals that cause physical discomfort, broadcasting biologically meaningful sounds (e.g. transient killer whale sounds) that generate an avoidance response in the target species, or generating sounds intended to "jam" the biosonar of a species. Specific types of signals that have been used in depredation and related "alerting" studies include narrowband pulses (Carlstrom *et al.*, 2002; Johnston, 2002; Morton and Symonds, 2002), tonals (Kastelein *et al.*, 2001, 2006a, b; Nowacek *et al.*, 2004), FM sweeps (Nowacek *et al.*, 2004), or various types of killer whale sounds (Cummings and Thompson, 1971; Fish and Vania,

1971; Shaughnessy *et al.*, 1981; Deecke *et al.*, 2002). In general, a high-intensity sound strategy suffers from habituation and regulatory concerns, and behavioural strategies suffer from difficulties with signal fidelity, habituation, and pseudo-replication (Kroodsma, 1990; Jefferson and Curry, 1996; Deecke, 2006).

Visual decoys have also occasionally been proposed as deterrents. The idea has a long history among Alaskan fishers. Early studies of killer whale depredation (Dahlheim, 1988, 2006) found "limited success" in the use of dummy buoys in reducing killer whale depredation in the Bering Sea, as opposed to no success for other ideas. SEASWAP noticed that sperm whales would often loiter around the instrumented buoy lines illustrated in Figure 2, although no fishing gear was attached to the bottom.

The discovery of acoustic cues that alert and attract whales to fishing hauls suggested that acoustic playback and decoy strategies could be merged into an "acoustic decoy" concept. Acoustic decoys are very common in submarine warfare tactics, but the use of acoustic playbacks to attract animals *towards* a decoy (Gilman *et al.*, 2007) is not nearly as common in the scientific literature as the use of playbacks to drive animals *away* from a region. However, one study has found that the playback of female elephant oestrus calls can attract adult male elephants experiencing a hormonal state called musth, and thus "may serve as an effective tool in non-invasive male elephant/human conflict mitigation" (O'Connell-Rodwell *et al.*, 2011).

An acoustic decoy in principle sidesteps several issues that plague deterrent playbacks. Sound intensity levels do not need to be as high as generally required for a deterrent playback, thus reducing logistic issues and mitigating regulatory concerns. Because distant animals are the targets of the playback, signal fidelity becomes less of a concern, since the animals will be detecting low SNRs anyway. Habituation and pseudoreplication issues become less problematic, in that acoustic cues are highly diverse and relatively convenient to record, creating opportunities for a large potential pool of decoy playback signals that can be played back randomly. Finally (and most speculatively), in principle, associated learning concepts (Pearce and Bouton, 2001) could be applied to the technique. For example, broadcasts from moored buoys could be used to reduce the association the animals make between hauling noises and fishing activity, and thereby over the long term cause a delay in the animals' response to actual hauling activity.

Equipment

An autonomous acoustic playback device (Thode *et al.*, 2010b) was developed to broadcast a random selection of arbitrary signals between 0.5 and 30 kHz, at broadband source levels up to 190 dB re 1 μPa @ 1 m (rms), using a Lubell LL9816 clam-shell transducer. The device can be programmed to activate after a set delay, and can then broadcast for hours before running down the batteries. The fidelity of the Lubell transducer is excellent, with a flat response between 50 Hz and 20 kHz, but due to its air-filled design, its deployment depth is restricted to 20 m or less. As the noise production by hauling fishing vessels occurs at the surface, the depth restriction on these playbacks was not an issue.

Decoy signal design

The cavitation hauling cues shown in Figure 5 are natural candidates for an acoustic decoy playback signal. Fortunately, SEASWAP has collected substantial amounts of acoustic data from multiple fishing vessels at various slant ranges. Several records also exist wherein the fishing vessel approached a recording buoy and then deliberately produced a sequence of cavitation sounds by cycling the engine while drifting within 100 m of the recorder.

A portion of one such sequence, recorded on 2 June 2011 from the *F/V Myriad* at 50 m range and 20 m depth, is shown as a spectrogram in Figure 9a. To generate a decoy playback signal, the original recording was edited to remove sperm whale clicks and
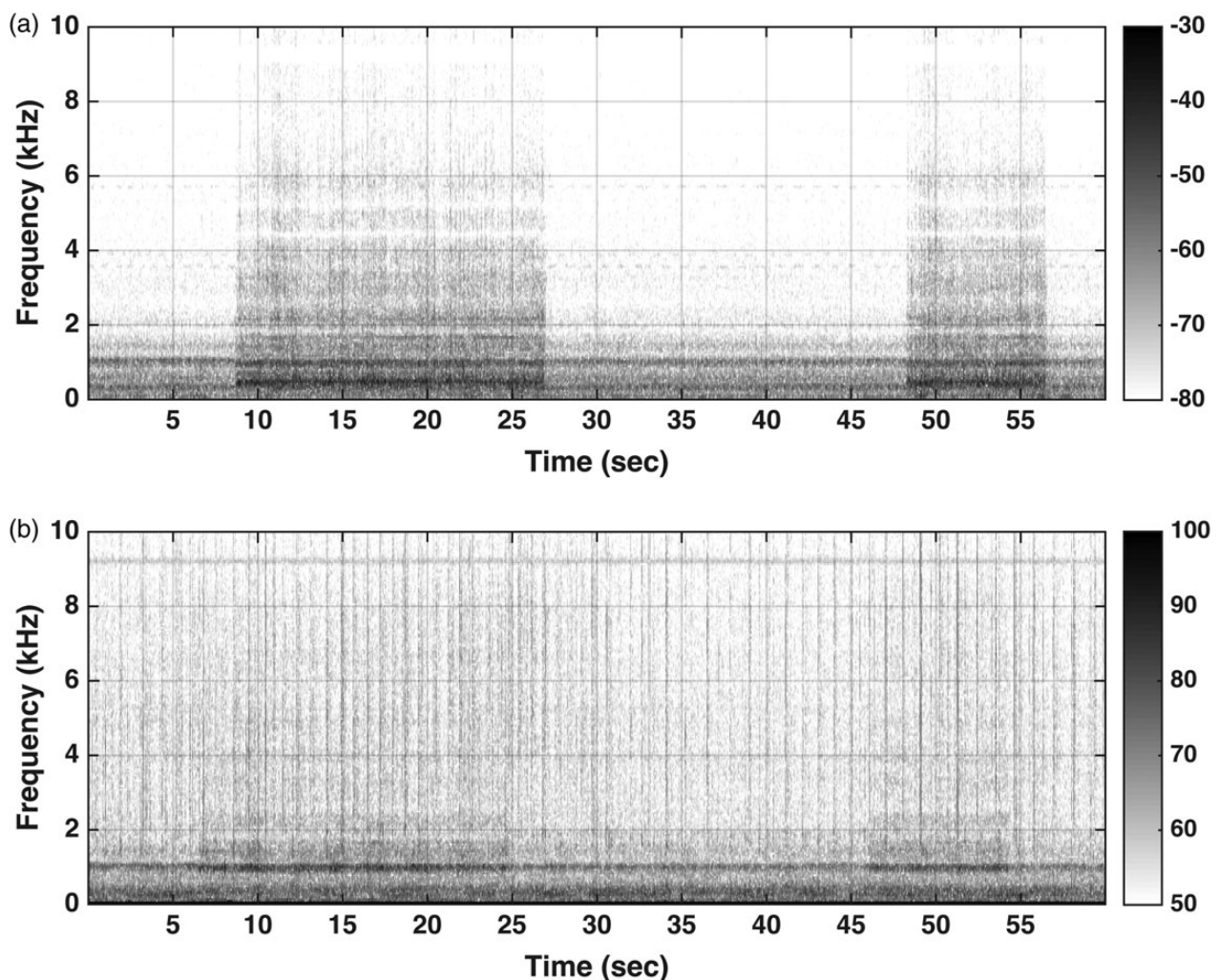
Figure 9. Spectrograms of a portion of a 3-min acoustic decoy signal. (a) Original playback signal; (b) same signal received 340 m below playback device during trial 2011 deployment. The numerous vertical lines visible between 2 and 10 kHz on the bottom image are sperm whale clicks.

thumping of the deployment rope against the recorder. Electronic self-noise at 9.3, 12.8, and 13.1 kHz was then removed using notch filters, and the resulting signal was then amplified until it spanned the maximum dynamic range of the A/D converter in the playback device. The original 50 kHz sampling rate of the data was upsampled to generate a 100 kHz signal compatible with the playback device. Finally, a gentle fade-in/fade-out was added to the beginning and end of a continuous 3-min data sample. The use of a long continuous data sample was judged critical: the intervals of silence between the engaging/disengaging of the propeller may prove essential to the playback's verisimilitude.

Deployment configuration and procedure

The deployment geometry for the acoustic decoy trial consisted of two sets of longline gear spaced 9.2 km apart. One set, the "true" set, connected the buoy lines with a bottom groundline with baited hooked gear, while the other "decoy" set had no ground line. Instead, the autonomous acoustic playback device was attached at 20 m depth to the decoy buoy line closest to the true haul (the "playback" buoy). An autonomous acoustic recorder (Unit 2) was also deployed at a depth of 365 m on the same buoy line. The second ("initial") decoy buoy line also had an autonomous recorder (Unit 5) attached at the same depth, to log acoustic activity at both decoy locations.

The deployment sequence consisted of a fishing vessel (F/V Cobra) approaching a 600-m deep location where whales had been reported a few days earlier, to deploy the decoy set first. After deploying the "initial" buoy, the vessel transited away from the buoy in a manner indicative of an actual ground line deployment, although no ground line was actually deployed. After travelling 4.2 km, the second "playback" buoy was dropped, with both the playback device and recorder pre-attached. The playback device was programmed to activate 14 h after its deployment. The Cobra

then departed inshore several kilometres to water depths of 200 m or less, before travelling to the location of the true set, which it deployed in a conventional manner. Figure 10a illustrates the relative position of all setup deployments, along with the vessel GPS track in green. There are two reasons to transit in shallow water: first, sperm whales in our study area do not usually follow boats inshore; second, vessel sounds do not propagate as far in shallower water, because sound radiating from the vessel has more substantial interaction with the sound-absorbing seabed. The goal of the trial was for the vessel to begin hauling the true set shortly after the decoy playback began. As discussed below, the actual deployment trial captured this essential sequence, but did not achieve the ideal timing between the decoy's activation and the start of the true haul.

Visual and acoustic analysis procedures

A visual observer was present on the vessel during the trial deployment, and noted the times of surfacing animals, except during night-time hours. Animal distances from the vessel were also estimated or measured using laser rangefinders. GPS waypoints and times of the beginning and end of all deployments and hauls were recorded. Whenever possible, photo-ID shots of diving whales' flukes were taken and later compared with the SEASWAP fluke catalogue, to consistently identify the locations of particular individuals throughout the trial.

The acoustic data were first analysed by constructing long-term averaged spectrograms of the entire deployment, to confirm the times that the playback device was active, and when it began to either fail and fall silent. The averaged spectrograms were also useful as a gauge of relative sperm whale activity at both the decoy and initial buoys, and for checking for the presence of other vessels in the region. A simple automated event detector (Thode *et al.*, 2010a) was used to identify the presence of sperm whale clicks in the data. Along with the start time and duration, each
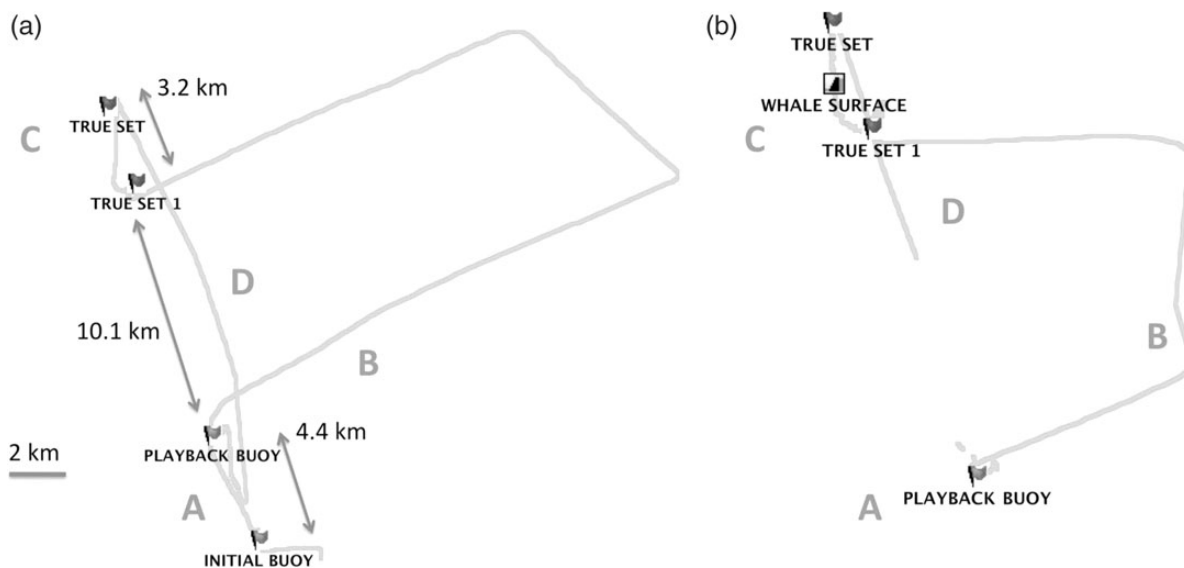
Figure 10. (a) Map of locations of decoy and true haul buoys, plus GPS track line (green) of F/V Cobra between 19:30 17 August and 07:00 18 August, before start of acoustic playback. (A) Deployment of decoy between 19:30 and 20:15; (B) inshore track taken to deploy true set; (C) deployment of true set between 23:45 and 1:10; (D) return track to decoy site, where vessel cut engines near initial buoy by 2:23. (b) Map of locations of decoy and true haul buoys, plus GPS track line (green) of F/V Cobra between 07:00 and 15:00 18 August, during acoustic decoy trial. (A) Departure of Cobra from playback buoy at 7:51; (B) inshore jog to approach true set; (C) hauling of true set between 10:30 and 12:58, with one whale surfacing at 11:55; (D) vessel track returning to playback buoy.

click's peak power spectral density was also logged, to provide a measure of the sound's intensity. Both the "raw" and "reduced" click detection rate were calculated, with the latter being a click detection rate with multipath arrivals removed. The reduced click rate was generated by rejecting click detections that occurred <0.5 s after a previous detection—a typical arrival time for multipath, as can be seen in Figure 1. The reduced detection rate was expected to be less sensitive to the range of the animals from the buoy, and more representative of the number of whales present (if the mean ICI of a given animal remains stationary over time). A large discrepancy between the raw and reduced click detection rates is a sign of the presence of substantial acoustic multipath, which in turn means that the animals are relatively close to the recorder.

Both types of detections were then assigned into three different categories, depending on the status of the vessel and playback device at the time: (1) "vessel present" (VP), when the fishing vessel was present within 2 km of the recorder; (2) "vessel-absent-playback-absent" (VAPA), when the acoustic playback device was silent, the fishing vessel was >2 km from the recorder, but the animals were believed to still be near the buoy; and (3) "vessel-absent-playback-present" (VAPP), when the fishing vessel was absent and the acoustic playback device was active. The range of 2 km was chosen because typically, whenever the vessel was 2 km or less from the decoy buoy, it was drifting or otherwise manoeuvring in such a fashion to attract animals close to the vessel and/or the decoy. Thus, the VP situation provided a baseline indication of sperm whale acoustic activity at close ranges to the buoy.

The raw and reduced detection rate per minute was computed for every minute in each category, and the autocovariance of the VAPA sequences was used to determine a time-scale T over which these rates became effectively uncorrelated. A normalized threshold of 0.2 was selected, because random sequences of clicks generated days apart could yield autocovariance values that attain, but do not exceed, this value. The VAPA sequences were chosen because they effectively provided the "control" data for the null hypothesis discussed below. Histograms of both the raw and reduced detection rates per minute were computed for the entire deployment by averaging over T minute intervals, thus ensuring that adjacent histogram bins were statistically uncorrelated. The raw histograms were useful as a combined indicator of both the number of animals and their range, as closer animals tended to produce more multipath. The reduced histograms were expected to be a better indicator of the relative number of animals present, regardless of their range.

The final analysis step was to subject the distributions of the raw and reduced detection rates from the three status categories to both a two-sample Kolmogorov–Smirnov goodness-of-fit hypothesis test, and a Mann–Whitney U-test. Both tests are non-parametric, since the distributions involved are non-normal and skewed. The distributions of the received power spectral densities of the detections from each category were also evaluated using the same tests. The null hypothesis always was that the underlying distributions of the VAPP and VAPA were the same, i.e. the activation of the acoustic decoy caused no shift in acoustic behaviour of sperm whales.

Qualitative description of proof-of-concept deployment

On 17 August 2011, the first test of an "acoustic" decoy began just offshore of Sitka, AK, at 56.59° N, 135.88° W. A volunteer fishing vessel (*F/V Cobra*) first deployed the decoy set in the presence of three sperm whales, including one individual (GOA-026, aka "Jack"), who is a known serial depredator across multiple years. Figure 10a shows the relative locations of the buoy deployments

and the track line of the vessel before the playback decoy activated on 18 August. The initial and playback buoys were deployed at 19:30 and 20:12, respectively (Figure 10a, leg "A"). The *Cobra* then departed inshore (Figure 10a, leg "B"), travelled to the northwest in 200 m depth water, and headed towards deep water again, arriving at the true deployment site at 23:45. After deploying 16 skates (3.2 km) of a true halibut set (Figure 10a, leg "C"), the *Cobra* began driving directly back to the decoy site at 1:09 on 18 August (Figure 10a, leg "D"), passing by the playback buoy at 2:05 and cutting its engines at 2:23, within 1.5 km of the initial buoy. The arrival of the *Cobra* near the initial buoy triggered intense bouts of sperm whale acoustic activity that were detected on the initial buoy recorder (Unit 5) until both recorders shut down between 4:47 and 7:25 to transfer data to hard disk. Acoustic data collected between 02:00 and 4:30 on Unit 5 (on the decoy line) were subsequently used in the "VP" category analysis. While the crew rested, the Cobra drifted northwest until 7:10 the following morning, at which point it was within 0.7 km from the playback buoy.

Figure 10b illustrates the GPS waypoints and vessel track line during the acoustic decoy playback trial. At 07:00, three whales were sighted loitering around the *Cobra* and the decoy buoy, and subsequent photo-ID efforts revealed that they were the same individuals who had witnessed the decoy set deployment the previous night. At 07:12, the *Cobra* engaged its engines to drive next to the decoy buoy, sparking a flurry of intense sperm whale acoustic activity around the decoy that also provided additional data for the "VP" category. At 07:51, the *Cobra* headed inshore (Figure 10b, leg "B") to discourage whales from following. The departure generated a final bout of sperm whale activity around the playback buoy, which was also assigned to the "VP" category. At 8:40, the decoy activated, and a sample of the signal as detected by Unit 2, 340 m below the playback device, is illustrated in Figure 9b.

At 9:22, the *Cobra* arrived at the true haul site; meanwhile, a sperm whale approached the decoy buoy and interrogated the decoy at 9:38 with a creak. Unfortunately, due to mechanical issues, the *Cobra* did not begin hauling until 10:30 (Figure 10b, leg "C"). As luck would have it, around 10:25, the acoustic playback began to fail by dropping the signal for a couple of minutes at a time.

Ninety minutes later, "Jack" surfaced at 11:55 next to the true haul (Figure 10b), but only after 75% of the true haul had been completed. At 12:58, the *Cobra* finished hauling and began returning to the decoy set (Figure 10b, leg "D"), with Jack following.

Quantitative statistical analysis of acoustic record

An autocorrelation of the 1-min detection counts under VAPA conditions found that they became effectively decorrelated over $T = 15$ min. Thus, click detection rates collected over 15 min intervals were used to construct empirical distributions of several acoustic parameters, sorted under the three situational categories: VP, VAPA, and VAPP. The VP data were taken on Unit 5 between 02:00 and 04:30 on 18 August, and on Unit 2 between 07:12 and 8:10 that same morning, and between 14:30 and 16:30 later that day. The VAPA data were collected on Unit 2 between 20:30 on 17 August and 02:00 on 18 August, between 8:00 and 8:40 on 18 August, and between 10:25 and 14:30 later that same day. The playback time (VAPP) was taken between 8:40 and 10:25 on 18 August, before the playback began to fail and drop samples.

Figure 11 shows the resulting quantile distributions for the three categories for five acoustic parameters: raw detection rate, reduced detection rate, and mean, median, and maximum power spectral density detected over 15 min intervals. Figure 11a suggests that
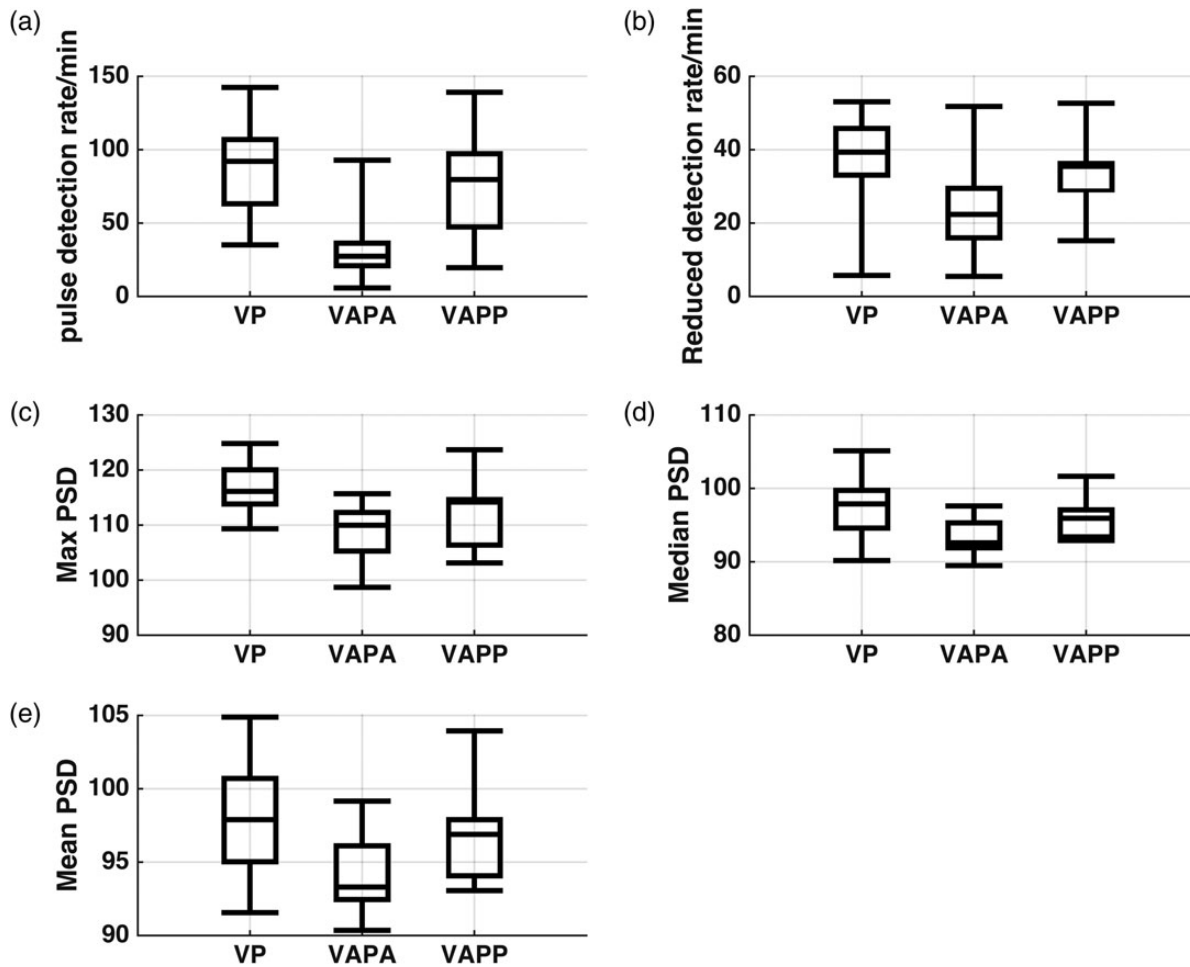
Figure 11. Box and whisker plot of distributions of various sperm whale acoustic parameters, averaged over 15 min intervals, and sorted by category. VP, vessel present within 2 km of recorder (22 15-min samples); VAPA, vessel-absent, no playback (40 samples); VAPP, vessel-absent, playback active (7 samples). (a) Raw detection rate per minute; (b) reduced detection rate per minute; (c) maximum, (d) median, and (e) mean power spectral density (dB re 1 $\mu Pa^2\ Hz^{-1}$) measured over 15 min interval.

Table 1. Hypothesis testing of VAPA vs. VAPP situations on five parameters measured over 15-min intervals

	Mean raw detection rate (ES: 41%)	Mean reduced detection rate (ES: 3%)	Mean power spectral density (ES: 3%)	Median power spectral density (ES: 3%)	Maximum power spectral density (ES: 3%)
Kolmogorov–Smirnov	**$p = 0.0057$**	$p = 0.043$	$p = 0.09$	$p = 0.03$	$p = 0.10$
Wilcox–Mann–Whitney	**$p = 0.0057$**	$p = 0.058$	$p = 0.02$	**$p = 0.01$**	$p = 0.26$

Boldface *p*-values are those deemed statistically significant, applying an FDR criteria of 0.05, using the Benjamini–Hochberg procedure. ES stands for relative effect size in terms of percentage change from VAPA. There are not enough data to test whether VP and VAPP distributions are equivalent.

the median value of the click detection rate during the playbacks (75 min^{-1} during VAPP) was higher than the median rate during times when the playback was either absent or failing (25 min^{-1} during VAPA). However, the sample size of the VAPP playback distribution (7 samples) is much less than the VAPA no-playback situation (40 samples), so the visual indications can be misleading.

Thus, the non-parametric Wilcox–Mann–Whitney (WMW) two-sample rank sum and two-sample Kolmogorov–Smirnov goodness-of-fit hypothesis tests were applied to the VAPA and VAPP distributions, with results shown in Table 1. Note that there

is not a large enough sample size in the data to determine whether the VP and VAPP come from similar distributions; in other words, one cannot determine whether the whales were as acoustically active during the playbacks as they were when a fishing vessel was actually present. A power analysis of the WMW test found that a statistical power of 0.8 could only be achieved if the actual difference in the mean raw detection rates of the VAPP and VP distributions was >50 detections min^{-1}.

Table 1 shows that the mean raw detection rate was significantly different between the VAPA and VAPP situations (with an effect size

of 40 clicks min^{-1}), but not the reduced click rate or click intensity. Statistical significance for these multi-hypothesis tests was determined by setting the false discovery rate (FDR) to 0.05, and employing the Benjamini–Hochberg controlling procedure to a sorted list of *p*-values from Table 1 (Benjamini and Hochberg, 1995). As discussed previously, the reduced click rate can be interpreted as a relative metric of the number of whales present, regardless of range, while the raw click rate will generate more detections when whales are closer to the receiver, generating more multipath. Thus, one interpretation of these results is that the activation of the playback did not significantly change the number of whales present (*p = 0.058* result for WMW in Table 1, column 2), but it did cause a significant change in the range of the whales relative to the receiver, generating significant increases in multipath data detected (*p = 0.0057*, column 1).

Interpretation of visual observations of Jack

Once the acoustic playback began to fail at 10:25, the detection rates dropped sharply within 10 min, down to levels that had previously been detected when the fishing vessel was absent. One interpretation of this result is that once the decoy began to fail, the animals either departed for the true haul or moved away to resume natural foraging. The visual observations are consistent with this interpretation, in that Jack (GOA-26) was sighted at 11:55 next to the true haul, 11.6 km distant from the playback buoy. The last previous sighting of this animal had been next to the decoy buoy at 7:30 that morning. Both SEASWAP observations and published literature (Whitehead, 2003) find that sperm whales generally travel at 5 knots, or 2.6 km h^{-1}. Thus, if one assumes that Jack swam directly from the decoy to the true haul, then it would have taken him ~1 h and 15 min to cover the distance, suggesting that he would have departed the playback buoy at around 10:40, or only 15 min after the acoustic decoy began failing to produce the hauling sounds with good fidelity.

Summary of acoustic decoy field trial

Visual observations, qualitative reviews of the acoustic record, an analysis of the timing of arrival of "Jack" at the true haul, and a statistical analysis of the click rates and intensities all suggest the same conclusion: the acoustic decoy did cause a change in the acoustic behaviour of the whales, and kept them near the playback buoy, at least until the playback began to fail, after which "Jack" departed for the true haul.

The results of this single trial deployment are promising, in that it demonstrates how the acoustic data can determine whether whales remain near a playback device without requiring visual observations. This work has also demonstrated how a relatively simple acoustic analysis can be performed without localizing the sounds, during situations when both the weather and number of animals present remain consistent over the course of the trial. Additional trials with new decoy designs are currently in progress. The use of such a system may not be practical when multiple vessels are fishing an area, but could be a viable strategy when a vessel is planning to fish alone in a region of known sperm whale depredation. In principle, the effectiveness and convenience of the decoy approach would be increased using automated moored playback systems, but the power requirements and maintenance needs of such a system would be substantial, and broadcasting the signals from a fixed location may increase the likelihood of habituation.

Conclusion

This paper has shown how PAM has been used to identify acoustic cues that attract the animals to the gear; to estimate depredation rates using "creak" sounds; and to evaluate the performance of acoustic countermeasures, with the acoustic decoy provided here as a specific example. Although not presented in detail here, SEASWAP passive acoustic research has also provided insight into the energetic benefits of depredation, and provided data for testing several new passive acoustic tracking methods. One such tracking method has yielded measurements on the maximum detection range of a male sperm whale as a function of sea state (Mathias *et al.*, 2013), data that will be essential if passive acoustics is used to estimate population density of these animals.

From a practical point of view, SEASWAP's developments in passive acoustics have effectively removed the need for researchers or other specialists to travel with fishers to test deterrents, and placed very little note taking burden on fishers as they focus on their essential tasks. The newest generation of passive acoustic recorders used by SEASWAP were designed to be "fisher friendly", in that they are simple to activate and attach to gear. The cumulative impact of these efforts is that SEASWAP researchers are finding it easier to collaborate with SEASWAP fishers (and *vice versa*!). PAM is no substitute for healthy collaborative working relationships between researchers and fishers, but SEASWAP's experience has been that PAM has lowered the inconveniences required for both groups to work together.

A natural follow-on question is whether PAM would be useful for studying depredation by other marine mammal species that may be less vocally active than sperm whales. Two obstacles exist when applying PAM to other species. First, there is little to no information about how species like killer whale or false killer whales locate fishing gear, and whether they use sound to acquire hooked prey during daytime and night-time. Second, the frequency range of other odontocete species can be considerably greater than that of the sperm whale; killer whale sonar signals have a *minimum* frequency of 40–50 kHz, which requires sampling rates at least double or triple of what SEASWAP currently uses. High-frequency signals not only place higher burdens on recording gear, but the signals are more quickly absorbed by seawater, and thus attenuate more quickly with range. Thus, applying these methods to pelagic longlines for species like the false killer whale will likely require the use of many more acoustic recorders per deployment than is currently required by demersal longline sperm whale research. SEASWAP has tentatively begun deploying recorders with fishers in the Bering Sea, to gain some basic information on whether PAM would be suitable for studying killer whale depredation.

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