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Field trials of an acoustic decoy to attract sperm whales away from commercial longline fishing vessels in western Gulf of Alaska

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ABSTRACT

In the Gulf of Alaska, sperm whales (*Physeter macrocephalus*) are known to remove sablefish (*Anoplopoma fimbria*) from commercial longline fishing gear. This removal, called depredation, is economically costly to fishermen, presents risk of injury or mortality to whales, and could lead to unknown removals during the federal sablefish longline survey that contributes to estimation of the annual fishing quota. In 2013 the Southeast Alaska Sperm Whale Avoidance Project (SEASWAP) evaluated the efficacy of an acoustic decoy in reducing encounters between sperm whales and longline fishing gear. The aim of the acoustic decoy was to use fishing vessel sounds to attract whales to an area away from the true fishing haul in order to reduce interactions between commercial fishing vessels and whales. A custom playback device that could be remotely activated via a radio modem was incorporated into an anchored buoy system that could be deployed by the vessel during a two-month trip between June and July 2013. Once activated, the decoy broadcasted vessel-hauling noises known to attract whales, while the vessel performed several true hauls at various ranges from the device. Passive acoustic recorders at both the decoy and true set locations were also deployed to evaluate whale presence. Twenty-six hauls were conducted while a decoy was deployed, yielding fourteen sets with whales present while the decoy was functional. A significant relationship was found between the number of whales present at the true fishing haul and the distance of the haul from the decoy (1–14 km range), with the decoy being most effective at ranges greater than 9 km ($t = -2.06$, $df = 12$, $p = 0.04$). The results suggest that acoustic decoys may be a cost-effective means for reducing longlining depredation from sperm and possibly killer whales under certain circumstances.

1. Introduction

Removal of hooked or netted fish from fishing gear by marine mammals is a worldwide phenomenon known as depredation. Rarely are these interactions positive, often resulting in economic costs for fishers, and risk of bycatch or entanglement for animals (Gilman et al., 2006; Read, 2008; Read et al., 2006). Odontocetes (toothed whales) are particularly attracted to longline fisheries as fish are easily accessible on the lines. In the Hawaiian, Australian, and Fijian pelagic longine fisheries, false killer whales (*Pseudorca crassidens*) routinely remove fish, and may become hooked themselves (Gilman et al., 2006; Hamer et al., 2015; Mooney et al., 2009). Similar occurrences are reported with false killer whales off the coast of Brazil and the Azores archipelago in the Atlantic Ocean (Hernandez-Milian et al., 2008). Sperm and killer whales routinely depredate demersal longline vessels in the Patagonian toothfish fisheries off the Crozet Islands (Guinet et al., 2015; Roche et al., 2007; Tixier et al., 2010), Chile (Moreno et al., 2008), and South Georgia (Purves et al., 2004). The Norwegian demersal longline fleet targeting Greenland halibut, Patagonian toothfish, Atlantic halibut and cod have been experiencing depredation from sperm whales since the mid 1990′s (Dyb, 2006).

Techniques to prevent marine mammals from interacting with fishing operations are known as "deterrents", which are defined as aversive, harmful, fearful, or noxious stimuli that elicit defensive or avoidance responses in animals (Götz and Janik, 2010). These stimuli can be painful, disruptive, threatening, or distracting, and delivered through acoustic, chemosensory, visual, or tactile means (Schakner and Blumstein, 2013). The goal of a deterrent is for the animal's perceived cost of continuing the behavior (e.g. exposure to loud noise) to outweigh the gain from this action (food resource/caloric intake).

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A variety of gear modifications have been tested to reduce depredation effects in longline fisheries (Gilman et al., 2006; Hamer et al., 2012). Wire nets, chains, streamer devices, and net sleeves have been tested on pelagic longline gear as modifications to protect fish as they are hauled to the surface, with some preliminary success (Hamer et al., 2015, 2012; Moreno et al., 2008; Rabearisoa et al., 2015). A primary concern with many of these gear modifications for fishers is often the impracticality of adapting the additional gear to their fishing operation, cost of doing so, and minimal buy-in when depredation persists.

Acoustic deterrents, commonly known as Acoustic Deterrent Devices (ADDs) for marine mammals are designed to emit sounds particularly distracting or annoying to the target animal, such that an aversion to the area is created (Jefferson and Curry, 1996). ADDs designed specifically to disrupt depredation behavior include acoustic playback devices, a specific type of acoustic deterrent that are designed to play pre-recorded sounds from underwater speakers to animals for deterrence purposes. Playback experiments have targeted both cetaceans and pinnipeds, and include a variety of signals such as tonal sounds, frequency modulated sweeps, and windowed pulses (Cummings and Thompson, 1971; Deecke, 2006; Fish and Vania, 1971; Gilman et al., 2006; Kastelein et al., 2006a,b; Mooney et al., 2009; Nowacek et al., 2004; Shaughnessy et al., 1981; Tixier et al., 2014b; Tyack, 2009). Most marine mammal species have been observed to exhibit avoidance and anti-predatory responses to transient killer whales, which has prompted some playback experiments to assess behavioral responses (Cummings and Thompson, 1971; Deecke et al., 2002; Fish and Vania, 1971; Shaughnessy et al., 1981). Testing of playback devices has found that while they show some short-term success, their efficacy vanishes after a few days as animals habituate to the sound and ignore it, suggesting long-term success is likely low (Arangio, 2012; Mooney et al., 2009; Tixier et al., 2014a). In general ADDs can be difficult to design, face regulatory concerns about noise exposure and animal injury, and are vulnerable to animal habituation (Arangio, 2012; Jefferson and Curry, 1996; Mooney et al., 2009; Schakner and Blumstein, 2013; Tixier et al., 2014b; Tyack, 2009).

In Alaska demersal longline fishermen have been experiencing removal of sablefish (*Anoplopoma fimbria*) by sperm whales (*Physeter macrocephalus*) and killer whales (*Orcinus orca*) since the 1970s (Dahlheim, 1988; Hill et al., 1999; Peterson et al., 2013; Sigler et al., 2008; Straley et al., 2015; Yano and Dahlheim, 1995). Reports of depredation have increased in Alaskan waters after implementation of the catch-share program in the mid-1990s (Hanselman et al., 2014; Hill et al., 1999). In addition to increased reports, documentation of depredation on the federal longline sablefish survey has experienced an accelerative pattern of increase over time, and fits predictions of social transmission of this behavior (Schakner et al., 2014).

Since 1995 the sablefish fishery in Alaska has been managed under an Individual Fishing Quota (IFQ) program by the National Marine Fisheries Service (NMFS) with a season of roughly 8 months, from mid-March to mid-November. In 2012 there were 838 individuals that fished quota shares for sablefish in Alaska, from just over 600 vessels (NOAA Fisheries Service, 2013). Vessels are classed into size categories of A (freezer vessel any length), B (> 60 ft), and C (≤60 ft), with median vessel length increasing from 49 ft in 1995–56 ft in 2012 (NOAA Fisheries Service, 2013). The total fishery value for 2016 was estimated to be over $189 million (NOAA, 2017). While pot gear and demersal longline gear have both been legal in the Bering Sea region since the IFQ program began, the Gulf of Alaska (GOA) has restricted the gear to demersal longline gear from 1989 to 2017, when pots were first allowed again in the GOA (NOAA, 2017). The GOA has four management areas (Western Gulf, Central Gulf, West Yakutat, and Southeast), in addition to the Bering Sea (BS) and Aleutian Islands (AI) regions.

In 2003, as a response to economic costs of depredation and entanglement risks to whales, the Southeast Alaska Sperm Whale Avoidance Project (SEASWAP, www.seaswap.info) was formed. SEASWAP is a collaborative effort between fishermen, scientists, and fisheries managers, working cooperatively towards the common goal of investigating and documenting the occurrence of sperm whales in association with longline fishing to develop strategies to minimize this interaction. Within the SEASWAP project in the GOA, a variety of deterrence strategies have been tested including changing fishing practices, gear modifications, and acoustic playbacks of frequency modulated upsweeps, white noise, and transient killer whale vocalizations (O'Connell et al., 2015; Thode et al., 2010, 2009). However, none of these strategies has provided a significant reduction in depredation rates (O'Connell et al., 2015; Straley et al., 2015; Thode et al., 2010, 2009).

One of the first major findings from SEASWAP gave insight into how sperm whales were able to detect and locate longline fishing activity in the vast offshore habitat of the GOA. SEASWAP found that fishing vessels make a distinct sound as fishermen engage and disengage the engine to stay on top of their gear as they haul their long lines to the surface. This sound, arising from propeller cavitation, creates a distinctive pattern that can be measured at distances of 4–8 km (Thode et al., 2007). Anecdotal evidence has revealed that whales were observed abruptly changing direction and making a beeline for a fishing vessel that began hauling gear 18.5 km from a tagging vessel (Straley pers. comm.). Whales have learned that this 'acoustic cue' is a signal that longline hauling is occurring (Thode et al., 2007).

During the first few years of acoustic SEASWAP studies (Thode et al., 2009, 2006), fishing vessels would often drop extra buoylines that contained passive acoustic instruments, in addition to their actual groundline deployments. Sperm whales would often loiter around the instrumented buoylines as the vessel departed the area, and would be present when the vessel returned to haul both the true and instrumented gear. A review of sperm whale sounds on the acoustic instruments demonstrated that the animals remained in the vicinity of the instrumented gear all night (Thode et al., 2006), revealing that animals were willing to wait near an anchored buoyline that contained no real fishing gear. Anchored buoylines appear to act as a decoy, distracting whales from the true fishing set.

The discovery of acoustic cues that alert and attract sperm whales suggested that acoustic playbacks could be combined with the passive decoy strategy to create an "acoustic decoy" (Thode et al., 2015). Here the "passive decoy" represents a buoy deployment, not attached to true fishing gear, that is used to delay and/or distract marine mammals from true fishing activity, but does not generate any sound. The acoustic playback component adds a device emitting vessel hauling sounds, the attractant for sperm whales to detect fishing activity, to this anchored buoyline. The idea of using acoustic playbacks to attract animals *away* from a region is not nearly as common in the scientific literature as the use of playbacks to drive animals out of a region (Gilman et al., 2006; O'Connell-Rodwell et al., 2011; Schakner and Blumstein, 2013).

An initial engineering trial of the decoy concept was performed off Sitka in August 2011, during which pre-recorded sounds of a fishing vessel hauling longline gear were played back from an underwater speaker. Both visual and acoustic observations suggested that animals did converge to the decoy, delaying their response to an actual fishing haul (Thode et al., 2015). Based on that trial, this study was designed to test the efficacy of an acoustic decoy device in attracting sperm whales away from fishing activity and reducing the effects of depredation on longline fishermen in Alaska. The basic premise of the acoustic decoy device was to deploy it away from the vicinity of the true fishing gear, where it would play recordings of vessels hauling gear, thereby attracting whales away from the fishing gear. Thus the fishers could haul their fishing gear without whales present, with fewer numbers of whales present, or with increased time delay for whales to leave the decoy and travel to their gear.

The goal of this experiment was to determine how the distance between the decoy and the true fishing haul affected depredation and whale interactions with fishing operations. The distance variable was chosen because the efficacy of the system was strongly suspected to be a function of the distance between the decoy and the true haul – once a whale realizes that the decoy is not an actual fishing vessel, it needs to decide whether it is worth the trouble to swim toward another fishing vessel sound. With a complex issue such as depredation, fishers would like to eliminate whale interactions completely, but even reducing the number of whales that arrive at their boat, or delaying the arrival of whales to their boat would be beneficial in reducing the economic cost of depredation. However, the cost of reducing depredation effects must not outweigh the benefits, and setting an acoustic decoy miles away from their fishing gear adds time and fuel costs to the fishing operation. As such, the experiment was designed to address this cost-benefit complexity of setting an acoustic decoy. Given that whales are attracted to fishing vessel hauling sounds and recordings of hauling sounds (Thode et al., 2015, 2007), this study seeks to assess how the distance between the decoy and the fishing haul affects depredation predictors. Specific objectives of the decoy experiment were to assess how the distance between the fishing haul and the acoustic decoy influenced: 1) the presence/absence of sperm whales at a fishing haul; 2) the number of sperm whales at a fishing haul; and 3) the timing in the arrival of sperm whales at a fishing haul.

2. Methods

2.1. Equipment

The acoustic playback device used for this study was custom built and able to play pre-recorded digitized sounds sampled at 100 kHz, stored on a micro-SDHC flash memory card and played through an underwater speaker (Lubell Labs LL9162T). The device was designed to broadcast sounds between 0.5–30 kHz, at source levels of up to 190 dB re 1 μPa @ 1 m pk–pk (rms). It was buoy-mounted at the base of a 4 m aluminum flagpole (Fig. 1), with a salt-water switch that prevented the device from activating when not submerged in salt water. The speaker was suspended 3–4 m below the controller, and was capable of broadcasting sounds for over 11 h continuously in the field. A UHF modem antenna was mounted at the top of the flagpole for the decoy controller and contained a spread-spectrum radio modem (Digi XTend RF module) operating in the ISM 900 MHz license-free segment of spectrum.

A deck box on the fishing vessel was used to turn the decoy device playback sound on and off via radio communication. An N-type coaxial connector on the deck box was connected to a second externally-mounted UHF antenna, which was placed on a high point of the fishing vessel. This box also confirmed that the decoy was playing sound by flashing a green light. The line-of-sight distance between the controller buoy antenna and the boat-mounted antenna determined the range at which the decoy device could be controlled. The higher each antenna could be, the longer the distance. In practice, the maximum activation distance was found to be about 10–15 km.

Fig. 1. Photograph of the acoustic decoy controller (left), mounted at the base of a spar buoy. The blue playback speaker is in the water on the right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A custom-built autonomous acoustic recorder was attached below the decoy at 100 m depth to confirm decoy activation, and to monitor the presence of sperm whales over time. In addition, an autonomous acoustic recorder was attached to the end of a true fishing set, to monitor the potential presence of sperm whales near the true sets over time. Recorders are custom-built by SEASWAP to be programmed with an internal duty cycle, sample at 100 kHz, and use a HTI–96 min hydrophone with 172 dB re 1 μPa V^{-1} sensitivity. Each recorder has a 128 Gb memory capacity, and can record continuously for 30 days. These devices can detect the presence of sperm whale 'click' sounds before, during and after a fishing haul.

2.2. Acoustic decoy playback signal

The field experiment used acoustic recordings of SEASWAP-member fishing vessels hauling gear and engaging in engine cycling patterns, as described in detail by Thode et al. (2015, 2007). The bulk of the energy in recordings of fishing vessel engines hauling gear is below 7 kHz (Fig. 2), but the true frequency range of the signal is between 500 Hz–13 kHz. Cavitation signals from the engines signal can be detected reliably from a minimum of 5 km away in water 600–700 m deep, but on calm days detections can be made out to 10 km (Thode et al., 2015). Several 3-min recordings were selected from vessel recordings, which were programmed to continuously cycle for hours at a time. Fig. 2 shows a spectrogram of the signal received 100 m away from a broadcast of the decoy signal. Original recordings were edited to remove sperm whale clicks and any other biological sounds, as we only wanted to test the effect of vessel engine hauling sounds in attracting sperm whales. Electronic self-noise at 9.3, 12.8, and 13.1 kHz was also removed using notch filters, and the signal was then amplified until it spanned the maximum dynamic playback range of the device. Finally, a gentle fade-in/fade-out was added to the start and end of a continuous three-minute data sample. This three-minute segment could be played in a continuous loop for several hours until the battery discharged.

2.3. Sablefish fishing

Sablefish fishing predominantly occurs in water depths between 400 and 1000 m. A true fishing set, as is standard for demersal longline

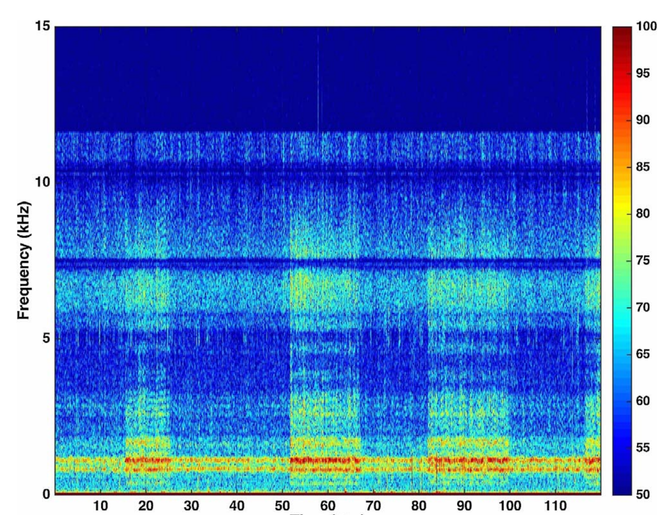

Fig. 2. Spectrogram of decoy playback signal, as received by an autonomous acoustic recorder at 100 m below the playback device, 2013 July 14, 10:26:00, 2048 FFT size (100 kHz sampling rate). Note significant energy exists up to 11 kHz.

fishing gear in Alaska, consists of two anchored buoylines connected by baited hooks on a groundline. The groundline consists of 200 m sections called “skates” tied together, the total length of which is highly variable depending upon vessel size, fishermen preference, and unpredictable factors such as current and sea state. However fishery-wide, longline sets average 7 km length with hook spacing averaging 1.2 m, which is equal to 7500 hooks per set (NOAA, 2017). Fishers typically fish multiple sets per trip, depending on weather and how many pounds they aim to catch, and after deploying the set, allow it to “soak” for 6–24 h to allow fish to strike the hooks. Setting, soaking, and hauling gear occurs at all hours of the day, though many fishermen prefer to set and haul their gear during daylight hours, and allow it to soak overnight.

2.4. Experimental design

Between June and July of 2013 skipper Stephen Rhoads of the F/V Magia transported the decoy, along with three autonomous recording devices, to the western Gulf of Alaska in order to fish for sablefish (Fig. 4). The F/V Magia is a 58 ft. steel longline fishing vessel, which targets sablefish and halibut. Hooks are spaced 46” apart and longline sets average 3 miles in length. For each trial the skipper deployed both the acoustic decoy configuration and a true fishing set (Fig. 3). Each trial followed the same sequence. First the fisherman would deploy his fishing sets for the day. On the true fishing sets, a recorder was deployed at 100 m depth on the buoyline end of the set that was to be hauled last, so as to allow the recorder to remain in the water during the entire duration of the fishing haul to monitor whale activity in the area. After deploying the fishing sets, the vessel moved 1–14 km away to deploy the decoy buoy. An additional autonomous recorder was attached at 100 m depth below the decoy. Here, there were distinct distances for the device to be set (1–14 km), but the skipper randomly selected the distance. This range of distances was chosen for a variety of reasons. First, input and consultation with fishermen revealed they would not want to travel more than 14 km away from their fishing set to deploy the device. This suited the study as detection of vessel hauling sounds by sperm whales falls off after 8–10 km (Thode et al., 2007), and we wanted the maximum distance of the device to be at the edge of the audible range for whales to detect another fishing haul. Finally, differing distances create different levels of distracting noise intensity, as well as longer distances for whales to swim between the decoy and the fishing haul.

The skipper was instructed to record the location and depth of each anchored buoyline from the ends of the true fishing sets, as well as of the decoy buoy configuration itself. In addition he/she was instructed to record the date and time of each gear deployment, time of decoy activation and deactivation, and date/time of retrieval of gear.

After the decoy and fishing sets were deployed, fishing vessels were instructed to travel to shallow water, away from sperm whale habitat and where acoustic detection and tracking of vessels is more difficult (Møhl et al., 2000; Thode et al., 2015; Watwood et al., 2006; Whitehead, 2003). This reduced the ‘saturation’ of vessel noise on the fishing grounds for whale detection. While in shallow water, the skipper allowed the gear to soak and fish to bite hooks, as is standard in commercial longline fishing operations. Once the vessel was ready to haul the fishing gear, the fisherman would remotely activate the decoy device, wait an hour to give animals that might be present in the area time to move to the decoy, and then approach the actual fishing gear to begin a true haul. During the fishing haul the skipper recorded the time of all sperm whale interactions, and estimated the number of whales during each encounter. Sperm whale presence at the fishing haul was defined as visual sighting, reduced catch, bent/straightened hooks, and/or visual evidence of depredation as reported by fishermen in all instances. The acoustic recorder placed on the true fishing set confirmed sperm whale presence in inclement weather where visual observations may not have been easy to make. Sperm whale presence/absence at the haul was represented numerically with a 1 for presence and 0 for absence. After recovering the true gear, the vessel could leave the decoy buoy in the water, but remotely deactivate it. The vessel could then perform another complete deployment and recovery of additional sets. This approach minimized the inconvenience of deploying and recovering the decoy buoy. Alternatively, the fishermen could opt to bring the decoy back aboard the vessel and move to another area before re-deploying the configuration.

2.5. Post-processing

Once the vessel returned to shore, the acoustic data were preprocessed to determine whether a particular haul would be included as a sample in the statistical analysis. The two requirements for a particular haul to be included in the analysis were as follows:

(1) The acoustic decoy had to be broadcasting during a particular haul.
(2) Sperm whales had to be acoustically detected on the decoy buoy acoustic recorder.

A sighting or acoustic detection of sperm whales at the true haul was not required, in order to account for a situation where whales stayed in the vicinity of the decoy but did not travel to the location of a true haul. Requirement 2 ensured that a particular haul would not be rejected if no sperm whales were present at the true haul.

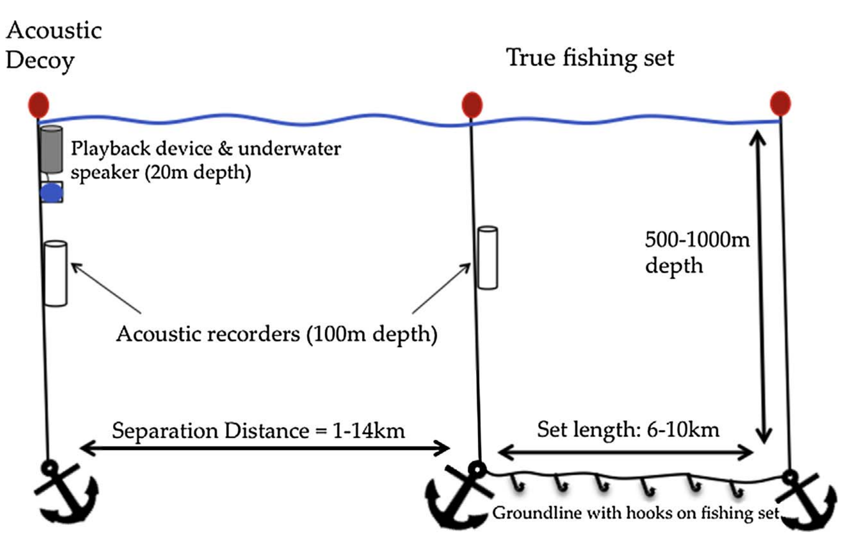

Fig. 3. Schematic of an acoustic decoy trial deployment.

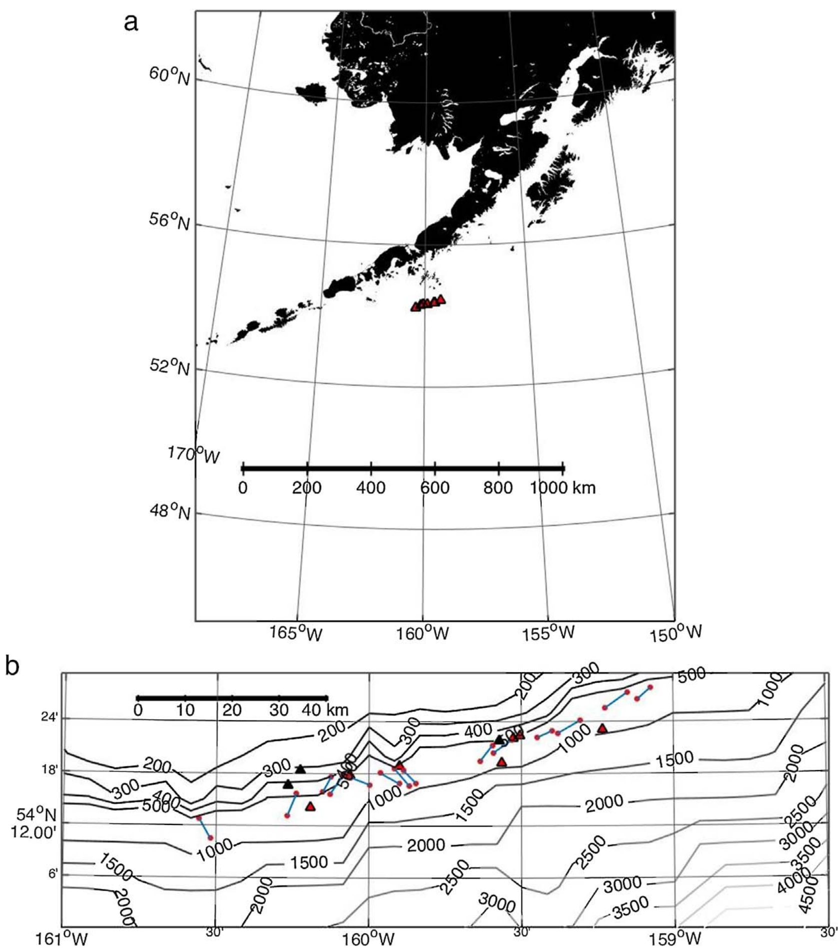

Fig. 4. Locations of 2013 acoustic decoy deployments by the F/V Magia off the Aleutian Islands between June 20 and July 16. Red triangles indicate locations of decoy buoy, and red dots connected by blue lines indicate sets used in the statistical analysis. Black triangles are decoy buoy deployments that were discarded from final analysis. Depths of contours are in meters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To address Requirement 1 the power spectral densities of the decoy buoy recorder data were computed by taking a series of 512-point Fast Fourier Transforms of the entire data stream, with 75% overlap. These densities were integrated between 500 and 9000 Hz to yield a broadband measure of the acoustic intensity in the environment, and every 10 s the percentile distributions of this intensity were computed. These percentiles were plotted vs. time; whenever the decoy was actually activated, a sudden jump in the acoustic intensity across all percentiles would occur.

Requirement 2 was checked by taking the same set of power spectral densities, averaging them for 1–2 s, and then creating a series of images that displayed this average power spectral density over time. Sperm whale clicks produce distinctive signatures (Goold and Jones, 1995) in these images that can be quickly identified by manually reviewing these images. The sperm whale signatures were detectable even when the decoy was active, because at distances within about 5 km of the decoy, sperm whale clicks have energy above 11 kHz, the maximum spectral component of the decoy signal. In addition, sperm whale clicks could typically be recognized at lower frequencies, even when masked by the decoy signal.

2.6. Statistical analysis

The objective of the study was to assess how the decoy-haul separation distance related to depredation. While some analyses use the calculation of catch-per-unit-effort (CPUE) as a proxy for depredation, this has been shown to be difficult acquire, and can be a poor predictor of depredation rates (Roche et al., 2007; Straley et al., 2015). Thus three variables were chosen as separate proxies for depredation, as follows: 1) A simple presence/absence predictor of whales as an indicator of depredation, which assessed how the distance between the decoy and fishing set related to the probability of encountering a sperm whale; 2) The number of whales, which allowed for multiple whales to arrive at the decoy, but not all of them to make the decision to leave and swim to the true fishing haul; 3) The time delay between when the fishing haul started and when whales arrived at the fishing haul. This response tested if the decoy could distract whales long enough to delay them from arriving at the fishing set so the fisherman could retrieve most of their gear before whales arrived.

Any fishing hauls that passed the two criteria in the previous section were then included in the final statistical analysis, which consisted of three generalized linear models (GLMs). All three models used the same predictor variable, which was the distance between the decoy buoy and the nearest end of the set ("decoy-haul separation distance"). The input to the link function in all cases was of the form:

$$y = b_1 + b_2 r \qquad (1)$$

where r is the decoy-haul separation in km, y is the input to the link function, and b_2 represents the coefficient that expresses a connection between decoy-haul separation and the dependent variable. The three GLMs were as follows:

(1) The first model used a binary variable for whale *presence* at the true haul as the response variable. This allowed testing of whether or not increased distances reduced the likelihood a whale would be present at the fishing haul. A binominal distribution was fitted to the data, with the logit function as the link function.
(2) The second model used the *count* of the animals sighted at a true haul as the response variable (including zero, if sperm whale activity had been detected at the decoy buoy, even if no animals were

present during the haul). We used a Poisson model since the domain of the dependent variable is a set of nonnegative integers, and can be interpreted as a rate (whales sighted/haul).

(3) The response variable for the final model used the *time delay* between the time the decoy was activated and the time a whale's presence was noted at the true haul. A standard linear regression model with normally distributed errors was used for this approach. Whale arrival times at the true fishing haul was determined by acoustic detection; however, if no recorder was available at the haul, then the visual logs of the fishermen were used.

After fitting the appropriate model, a *t*-test was conducted to check whether the value of b_2 differed significantly from zero. A t-statistic that yielded a *p*-value of 0.05 or less was deemed a significant result. Assumptions of independence, correct specification of the variance structure, correct distribution of the residuals, and linear relationships between the response and linear predictor were all tested.

3. Results

All deployments took place off the continental shelf break between 400 and 1000 m depth from June 20 to July 16, with the exception of June 22–25, June 29–July 4 and July 10–11, when the vessel was in port selling fish. This resulted in a total of 14 days of deployments. Each day, two sets were deployed and hauled around a single decoy deployment, and the decoy was turned on and off twice during the day, in order to reduce the logistical inconvenience of re-deploying the decoy. On one day, July 16, 2013, three fishing sets were hauled rather than two, and on July 12 only one set was hauled. A total of 28 hauls were conducted while the decoy buoy was also deployed, and preliminary acoustic analysis was conducted to confirm whether decoy activation occurred (Fig. 5) and whether sperm whales were present at the decoy or haul. From this preliminary analysis 12 hauls had no whales at the decoy or the fishing haul; one haul was missing an acoustic recorder, had no information about the location of the fishing set, and had no haul time listed; and one haul had the decoy fail to activate. These sets were discarded. The remaining 14 hauls were selected for detailed statistical analysis (Table 1). Fig. 5 shows an example of how the autonomous recorder mounted on the decoy confirms the decoy activated twice during July 13, 2013.

The acoustic data collected on the fishing hauls was used to verify arrival times of whales at the true fishing haul noted by the fisherman. On two occasions the fisherman had not written down a time of arrival for whales, just that they had arrived and begun depredating. For those two occasions, we omitted the two data points for the model assessing the time delay of the whales' arrival at the true fishing haul, model 3.

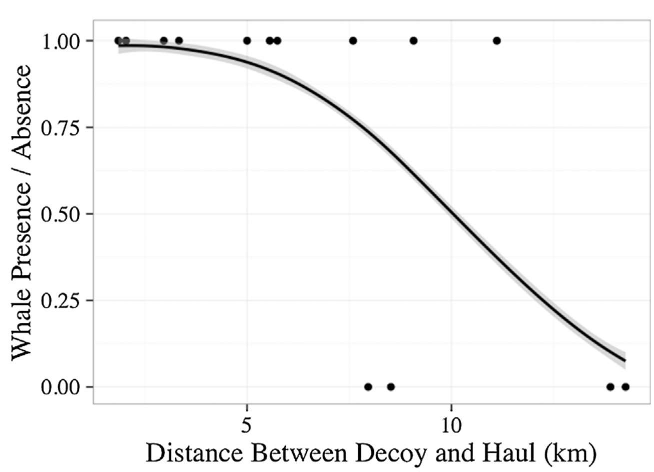

Fig. 5. Binomial GLM fit showing the raw data points of whale presence (1) and absence (0) with respect to the decoy-haul separation distance.

However, we were able to keep those two data points for the other analysis of presence/absence and number of whales, as acoustic detections of the whales from the acoustic recorder on the fishing set confirmed presence and number of whales.

One outlier was found, where the decoy did not correctly de-activate when the skipper thought he had turned it off. For this record, on July 14, 2013 the decoy was activated at 10:24am, as the skipper went to haul his first set, and de-activation failed after the first set. Instead, the device stayed on, and had been running for 9 h and 31 min by the time the second haul began (Set 13, Table 1). As such, the second haul is considered an outlier data point where the longer 9.5 h activation of the decoy could be influencing whale activity differently than intended with a 1 h activation target prior to hauling the fishing set. Due to a small sample size, we left this data point in for each model, and then re-ran the model omitting the outlier to assess its potential effect on our results.

3.1. Binominal model

Distance between the decoy and the true fishing haul was a not a significant predictor of whale presence at the haul ($t = -1.85$, $df = 12$, $p = 0.06$) (Fig. 6). When the outlier was omitted (Set 13, Table 1), the decoy effect was also non-significant ($t = -1.8$, $df = 11$, $p = 0.07$).

3.2. Poisson model

The Poisson GLM showed significance at the 5% level between the decoy-haul separation distance and the number of whales that arrived at the fishing haul ($t = -2.06$, $df = 12$, $p = 0.04$) (Fig. 6). The coefficient for the response of -0.1648 ± 0.08 whales per km separation indicated that every 6 km increase in separation distance would result in 1 fewer whales arriving at the fishing haul. Discarding the outlier data point in the analysis only slightly changed the significance ($t = -2.19$, $df = 10$, $p = 0.03$) and the coefficient (-0.172 ± 0.087). The variance of the residuals is consistent with those of an actual Poisson distribution, with the dispersion parameter (the ratio of measured variance to expected Poisson variance) being 0.88 when all samples are used, and 0.68 when the outlier was rejected.

3.3. Linear model to delay time

For this model, only eight data points were available, as four sets had no whales present at the haul and could not be included, and two sets did not have the time of whale arrival logged by the fisherman. A linear regression between decoy-haul separation distance and the time delay between decoy activation and sighting of first whale at the true haul, or "decoy-haul delay" showed significance at the 5% level ($t = 2.5$, $df = 7$, $p = 0.046$; Fig. 7).

This reduced data set included the influential outlier, which caused the time difference between the decoy activation and the second fishing haul of the day on the 14th of July (Set 13, Table 1) to be accidentally long. If this influential data point is eliminated, the seven remaining data points reveal no significant correlation between the distance from the decoy to the fishing haul and the delay time from decoy activation to the time the first whale was sighted at the fishing haul ($t = 0.848$, $df = 6$, $p = 0.435$; Fig. 7).

4. Discussion

The prospect of delaying, reducing, or even preventing whale presence at a fishing haul is highly attractive for longline fishermen. Using an acoustic decoy as an attractant to lure whales to an area away from the fishing haul has shown promise in this analysis, which we hope can represent a preliminary study upon which to build future experiments. We believe these positive results are the first analysis of an acoustic

Table 1
Summary of fourteen fishing hauls used in statistical analysis, arranged by date.

Set #	Date	Distance from Decoy (km)	Time Decoy On	Time Haul Start	Time Decoy Off	Number Whales at Haul
1	20-Jun-13	7.4	15:01	16:03	21:00	0
2	21-Jun-13	1.77	04:41	06:00	09:39	1
3	27-Jun-13	4.35	07:17	07:32	11:54	1
4	27-Jun-13	4.99	14:18	14:45	17:40	1
5	05-Jul-13	6.92	08:03	09:00	12:17	0
6	08-Jul-13	12.07	06:35	07:40	12:09	0
7	09-Jul-13	2.9	07:39	08:30	10:07	3
8	09-Jul-13	6.6	15:02	16:00	18:58	1
9	12-Jul-13	9.66	14:07	19:48	21:40	2
10	13-Jul-13	7.89	10:03	11:01	11:49	1
11	13-Jul-13	4.83	20:40	20:45	22:40	1
12	14-Jul-13	12.39	10:24	15:40	21:56	0
13[a]	14-Jul-13	1.61	10:24	19:55	21:56	2
14	16-Jul-13	2.57	21:21	21:30	00:32	3

[a] Indicates the outlier where the decoy did not correctly de-activate between sets 12 and 13, thus by the time the skipper began hauling his second set at 19:55, the decoy had been on since 10:24 that morning, potentially influencing whale responses.

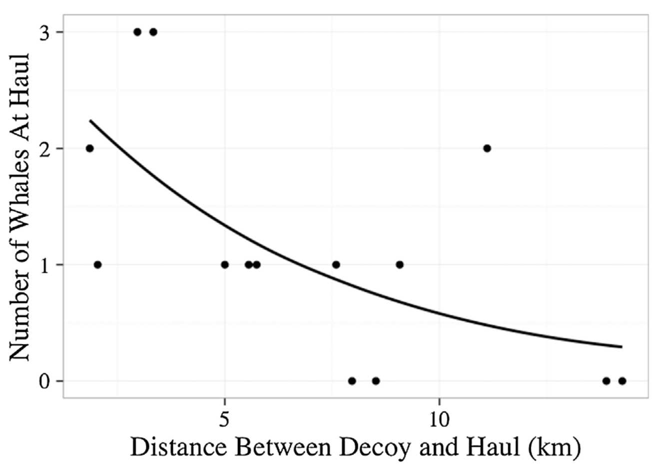

Fig. 6. Poisson GLM fit to the number of whales present at the haul with respect to the decoy-haul separation distance, using all 14 data points.

decoy test on marine mammals, and one of the first effective countermeasures ever tested by SEASWAP.

The time delay of arrival of whales showed a significant relationship only if the outlier was included. Here the farther the decoy-haul separation distance, the longer it took whales to arrive at the fishing gear. In the reduced model without the outlier, the b_2 coefficient for the delay was a 30.3 ± 12.12 min per km separation between the decoy and haul, which has an inverse coefficient of 0.033 km/min swim speed for a sperm whale, or 1.9 km/hr. This is much slower than the typical swimming speed of 9.26 km/h (5 knots) for a sperm whale (Wahlberg, 2002). This suggests whales were not always arriving at the true haul from the decoy, and could have been coming from other directions. Analysis of the simple binomial fit of whale presence/absence yielded a close but not-significant p-value of 0.07. As the decoy-haul separation distance increased, likelihood of whale presence at the fishing haul decreased, but not significantly so. However, the distance between the decoy and the haul was shown here to be a key factor in significantly reducing the number of whales that arrive at the true fishing haul. As the distance between the decoy and the true haul increased, fewer whales arrived at the true haul.

Together these results suggest that the decoy can be effective in reducing interactions of whales with longline fishing vessels, but only if the distance between the decoy and true hauls is sufficiently great. The transition point of the binominal fit (y-value: 0.5) suggests that the hauls should be at least 10 km from the decoy in order for the technique to be effective. Given sperm whale average swim speeds of 9.26 km/h (Wahlberg, 2002), this corresponds to an estimated swimming time of

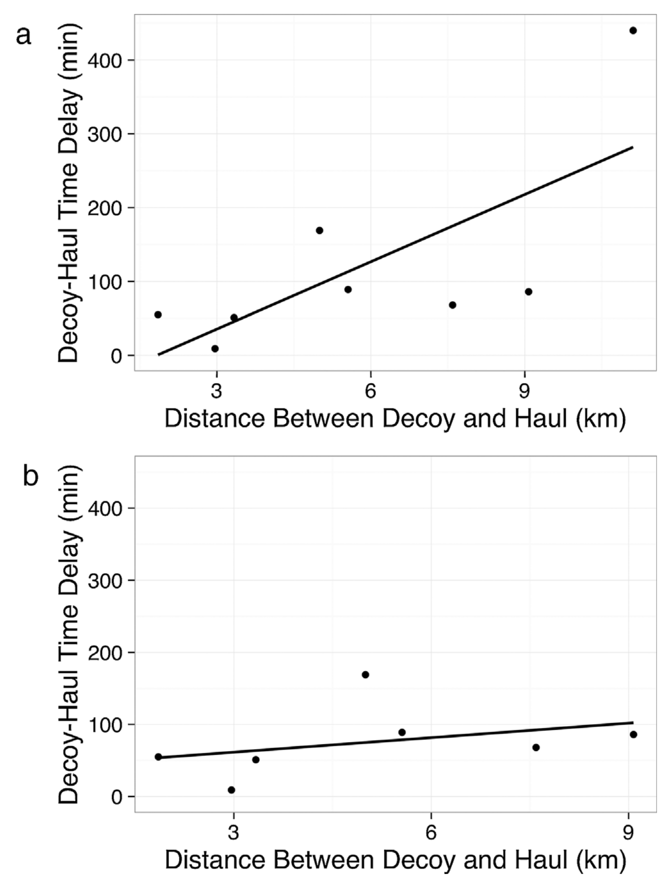

Fig. 7. Linear regressions showing the time delay between the decoy activation and the first whale sighting at the fishing haul with respect to the distance between the decoy and the haul. The top plot shows the full eight data points with the fitted regression, while the bottom plot shows the seven data points eliminating the influential outlier and fitted regression.

one hour for a whale traveling from decoy to the true haul. Therefore, even if whales attracted to the decoy departed as soon as they heard the true fishing haul begin, the fisherman could theoretically retrieve an hour's worth of gear before whales arrived. While the range of fishing haul times varies drastically amongst longline fishermen in Alaska, anecdotal information from many small-boat fishermen that work out of the SEASWAP study area suggest an average of 3-h fishing hauls. At this rate, deploying a decoy could allow a fisherman to haul a minimum of 1/3 of his catch before depredation affected the catch. While it is difficult to know the detection range of the acoustic decoy for sperm whales, previous work by SEASWAP has documented a minimum of 4–8 km detection range of fishing vessel activity (Thode et al., 2007), with anecdotal evidence from researchers suggesting whales can detect fishing activity in calm weather conditions at upwards of 18 km (Straley pers. comm.). Sperm whale echolocation signals themselves can occupy an acoustic space of over 60 km^2 so their ability to detect a fishing vessel from a 10 km distance at the surface is likely not that far-fetched.

The capability of detecting sperm whales at the decoy using passive acoustics, even when no whales were sighted at the true haul, was a crucial factor in the analysis, as four data points confirmed whales were present at the decoy, while no whales were sighted that day at the true fishing haul. This implies that at least some of the time, whales would approach the decoy and loiter in the area, but choose not to swim to the true fishing haul that they could undoubtedly hear in the distance. Whales either decided the distance was not worth the effort to swim, perhaps if the decoy was already in an optimal foraging area, or vessel hauling sounds playing from the device masked the ability to detect very distant fishing hauls. It is also possible that the whales heard another vessel in the area and swam to that sound instead, though reports from the skipper revealed that he detected very few other vessels during this time in the area he was fishing. Further acoustic analysis of sperm whale echolocation activity in the vicinity of the decoy throughout the duration of the fishing haul would be necessary to suggest likely scenarios for these data points.

All other data points suggest whales swam between the decoy and the fishing haul, though it must be noted that while detections could be made both at the decoy and at the fishing haul, the single hydrophone deployments restricted the ability to track animals between the two sites. Thus it was not possible to confirm that whales heard at the decoy were the same individuals that arrived at the fishing haul. It is entirely possible that whales arriving at the true haul were coming form a different direction and had not yet encountered the decoy. To tease out these nuances, the data should be examined more closely, and “loiter” times of acoustic detections at the decoy calculated. Depending upon the decoy-haul separation distance, it would be possible to estimate whether or not timing of arrivals at the true haul were plausible, given the average swim speed of a whale and the timing of departure from the decoy.

This experiment sought to collaborate with working commercial fishing operations, which requires SEASWAP to minimize the changes in fishing practices that were required for experimental design. Acknowledging the limitations of this collaboration, we allowed fishers to incorporate the acoustic decoy into their normal fishing operations, with limited modifications. As a result, our study had a small sample size, with a single vessel, region, and time period. It must be noted that time of year, fishing management area, and vessel variables may be important factors in the success of the decoy (or any depredation countermeasure), depending on whale presence and fishing pressure across management areas. Sperm whale presence does not show many seasonal trends within the fishing season (Straley et al., 2014), though fewer animals are thought to be present in the spring (Mar–Apr) and fall (Oct–Nov) months than the peak summer months (May–Sep) (Mellinger et al., 2004). Given our experiment was in June-July mid-summer, an interesting contrast would be to test the device early or late in the season when perhaps fewer whales were in the area. There is no evidence that specific vessels experience different levels of depredation, and the vessel of 58 ft. used in this study was consistent with the median length for the fishery of 56 ft. (NOAA Fisheries Service, 2013). Finally, depredation activity is spread across all management areas and regions in the Gulf of Alaska, though in every region hotspots do occur.

As a final note on the design and concept for this experiment, an additional manner in which to test the efficacy of an acoustic decoy would be to assess whale presence, numbers, timing, and/or catch rates as a function of whether or not the decoy was activated. We chose not to conduct the experiment in this fashion for a number of reasons. Depredation is a function of a multitude of factors, and to accurately assess how the presence of a decoy affected depredation rates, the sample size would need to be quite large. The experimental unit of a longline set is extremely high (labor, fuel, bait, etc.) and to test additional longline sets with and without an acoustic decoy activated would be cost prohibitive. Additionally, such an experiment would be time consuming, at a minimum doubling the sample size needed to include non-decoy sets in the analysis. Finally, whale presence cannot be controlled, and even further additional sets would be needed to achieve a large enough sample size where whales were present at either the decoy or fishing haul, for cases in which the decoy was and was not activated. As a result of these factors, we chose the decoy-haul separation distance as our response variable, and instead randomized the order of which distances were associated with which hauls.

While the concept of the acoustic decoy works, discussion with the fishermen involved with the project revealed concerns about the concept’s practicality using current designs. Fishermen stressed the need for several major changes in the gear design. The radio communication link was flawed; due to line-of-sight restrictions and weather complications, the maximum activation range of the buoy was limited at many times to 11 km, and the feedback from the buoy to the vessel was inconsistent. At present deploying and recovering the decoy buoy is time-consuming, and perhaps provides more time for sperm whales to detect a fishing vessel in the area. The current device is heavy and awkward, and could require fishermen to drive their vessel over 10 miles (16 km) to set the decoy away from their gear. A future device would either need to be made lighter and more manageable, or would require a longer-term installation with larger battery storage. These changes are feasible from an engineering perspective, but would require additional funding to improve and adjust the technology.

The idea of “residency” time of fishing vessels on a particular fishing ground could potentially influence how many whales are in the area and how long they stay in a region before moving on, if at all. To lower fuel costs and maximize efficiency, vessels often spend concentrated time in a specific region to catch as many fish toward their quota in that region as possible. When whales are present, skippers tend travel into shallow waters during the soak of the gear, which is not typical habitat of sperm whales and where acoustic detections and propagation of sound makes vessels harder to track (Møhl et al., 2000; Thode et al., 2015; Watwood et al., 2006; Whitehead, 2003).

During this experiment the skipper noted that there were rarely other vessels in the area fishing. The presence of other vessels could cause a confounding effect with the acoustic decoy, as the decoy, in essence, is a pseudo-vessel. In fact, it has been shown that increased vessel activity and catches by fishers is positively correlated with the likelihood of experiencing depredation (Peterson and Hanselman, 2017). Other vessels in the area will have an effect on whale behavior and thus likely alter the outcome of success rates for the decoy device. For example, a vessel that deploys the decoy 5 km north of his fishing gear, while another vessel is fishing 5 km south of him, will have a higher chance of encountering whales simply by having two vessels plus the acoustic decoy making hauling noises rather than two. Further, if whales are initially depredating the vessel to the south of him, they will encounter his vessel as they hear vessels hauling gear and move north, before reaching the decoy, thus rendering the decoy counter-productive. Other vessels, if present, are essentially decoys themselves, removing the need to deploy an artificial one. An old fishermen trick, when fishing among multiple vessels when multiple sperm whales are present, is to wait to haul gear until another vessel begins hauling, or to drive by other vessels hauling gear and “drop whales off” at other vessels. It must also be noted that having a high number of vessels in an area with just a few whales may dilute the effect of depredation on specific vessels, but does not change the effect of depredation fleet-wide.

Similarly, the concept of “residency” in whale behavior could influence the likelihood of depredation and the investment of whales to stay in a particular area. Very little is known about social structure and residency in male sperm whales in high latitude foraging grounds such as this one. Whale movement is also likely tied to food availability, both natural and in the form of anthropogenic subsidies. Hotspots in depredation reporting usually align with areas where sablefish are abundant, with both whales and fishermen knowing where the good fishing areas are (Peterson and Hanselman, 2017; Straley et al., 2015). This begs the question of whether or not depredation is purely opportunistic, or if whales actively seek fishing vessels, and only focus on finding food naturally when vessels cannot be found. Of the 115 individual sperm whales in the SEASWAP catalog sighted some 420 times total, 10 individuals make up 1/3 of all sightings, indicating some animals may be more adept, reliant, or active in seeking out depredation opportunity than others (SEASWAP unpublished data). If the fish being depredated (i.e. sablefish) are indeed an important prey item for the whale, depredation behavior could be very different than for fish species not naturally part of their diet. In a review of data from Japanese whaling ships in the 1960s, sablefish and other deep sea fishes made up 68% of sperm whale stomach contents in the Gulf of Alaska versus up to 20% in the Bering Sea (Kawakami, 1980). However, current diet for sperm whales in this region remains poorly understood. We must acknowledge that our knowledge remains limited when it comes to the complexity and nuances of the drivers behind depredation.

A more fundamental concern expressed by fishermen is whether activating a decoy may serve to *attract* animals into the region, even if the animals are not attracted directly to the fishing vessel itself. Opposite from concerns about other vessels in the area saturating the area with sounds and rendering the device ineffective, this concern revolves around situations when there are not other vessels in the area. It was this concern about potentially attracting animals that led fishermen to use the decoy only when whales were actually sighted in the area during the vessel's initial arrival. This scenario would perhaps be more likely during spring and fall seasons, and if fishermen were fishing in areas that were not hotspots as mentioned above. While whale movements in this area can be unpredictable and depredation can be unpredictable, recent studies have shown that sperm whale depredation rates are correlated to areas were high catches occur in the fishery, and that sperm whales may target areas naturally where more fishing occurs (Peterson and Hanselman, 2017).

Use of decoys to attract animals to another area is limited in the literature. Perhaps most similar to the present study is a trial experiment where female elephant estrus calls were played to attract male elephants away from areas where human conflict might arise (O'Connell-Rodwell et al., 2011). Here, results found success of playbacks in attracting males was dependent on age and hormonal status (O'Connell-Rodwell et al., 2011). Other studies of playback experiments, while not used in mitigation or to minimize conflict, do show reactions of animals to sounds of conspecifics or predators played to them. Playbacks of song and social sounds to humpback whales caused reactions in line to what would be expected if sounds were real rather than recordings (Tyack, 1983). Male warbler songs used to attract females were more likely to attract female warblers than other male warbler song, when recordings were played back (Catchpole and Leisler, 1996). This experiment is similar, in that the playback consisted of sounds known to be a strong attractant the target species.

One of the main concerns for playback experiments is the question of habituation. A number of playback devices that have been tested on odontocete depredation are designed to be deployed directly from the vessel, to deter the animals as they approach the fishing gear (Mooney et al., 2009; Tixier et al., 2014b). These experiments have found that while whales will exhibit reduced echolocation abilities, or avoid the area, over time animals appear to habituate and ignore the device (Gilman et al., 2006; Mooney et al., 2009; Tixier et al., 2014b). For the acoustic decoy experiment, habituation may not even arise as an issue, in that if sperm whales were to learn to disassociate vessel-hauling sounds from fishing hauls or depredation opportunities, the result would also be beneficial to fishermen. If whales habituated to this sound, or found that it did not always result in a free meal, they may no longer be attracted to engine hauling sounds themselves, reducing the conflict of whale-vessel interactions.

While the data for this study was collected over one month, the current data set cannot address the legitimate question of whether whales could recognize decoy playbacks as decoys over longer time intervals. While it is possible the pattern of engaging and disengaging of the engine on a particular playback might become recognizable, this could easily be overcome by developing multiple recordings of multiple vessels hauling gear. By using multiple clips of over 3 min, from multiple vessels, this design permits the randomized playback of non-repetitive sound sequences that last several minutes at a time, greatly expanding the amount of time required for an animal to recognize a particular sound sequence being associated with a decoy rather than a true fishing haul. A final conceptual advantage of an acoustic decoy, as opposed to playbacks designed to deter animals, is that fidelity of reproduction is not as big an issue of concern, as these signals are intended to be detected at large ranges and thus exhibit low signal-to-noise ratios (SNR) anyway.

We have shown that a decoy can attract whales, but it is up to fishermen to decide if it is worth it for them to bring on a particular trip and deploy it, given predictable conditions (region, season) and unpredictable conditions (other vessels on the grounds, whales sighted upon arrival to the grounds). While the results of this study reinforce initial studies of the efficacy of an acoustic decoy (Thode et al., 2015), its practical application would require more technological investment, and its utility is best suited for situations where vessels are fishing alone in areas where whales are already known to be present. It has become widely accepted that there will not be one solution to the problem of depredation and marine mammal interactions with fisheries, even within a specific fishery and a specific species (Arangio, 2012; Peterson and Carothers, 2013; Schakner and Blumstein, 2013). Changes in fishing practices have been explored worldwide, including changing the timing of fishing operations, avoiding fishing in areas known to have high numbers of depredating animals, and changing the vessel or fishing method to mask or minimize the effect of the attracting sound (usually the vessel engine) (Gilman et al., 2006; Rabearisoa et al., 2015; Thode et al., 2009; Tixier et al., 2014a). These techniques, combined with devices and gear modifications that have shown some success, may be used together to minimize effects of depredation. Adding a variety of tools to minimize these interactions to the toolbox of available techniques for fishers may be the best way to minimize detrimental effects of whale-fisheries interactions.

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