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Acoustically monitoring the Hawai‘i longline fishery for interactions with false killer whales

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ABSTRACT

False killer whales (*Pseudorca crassidens*) feed primarily on several species of large pelagic fish, species that are also targeted by the Hawai‘i-permitted commercial deep-set longline fishery. False killer whales have been known to approach fishing lines in an attempt to procure bait or catch from the lines, a behavior known as depredation. This behavior can lead to the hooking or entanglement of an animal, which currently exceeds sustainable levels for pelagic false killer whales in Hawai‘i. Passive acoustic monitoring (PAM) was used to record false killer whales near longline fishing gear to investigate the timing, rate, and spatial extent of false killer whale occurrence. Acoustic data were collected using small autonomous recorders modified for deployment on the mainline of longline fishing gear. A total of 90 fishing sets were acoustically monitored in 2013 and 2014 on a chartered longline vessel using up to five acoustic recorders deployed throughout the fishing gear. Of the 102 odontocete click and/or whistle bouts detected on 55 sets, 26 bouts detected on 19 different fishing sets were classified as false killer whales with high or medium confidence based on either whistle classification, click classification, or both. The timing of false killer whale acoustic presence near the gear was related to the timing of fishing activities, with 57% of the false killer whale bouts occurring while gear was being hauled, with 50% of those bouts occurring during the first third of the haul. During three fishing sets, false killer whales were detected on more than one recorder, and in all cases the whales were recorded on instruments farther from the fishing vessel as the haul proceeded. Only three of the 19 sets with acoustically-confirmed false killer whale presence showed signs of bait or catch damage by marine mammals, which may relate to the difficulty of reporting depredation. PAM has proven to be a relatively inexpensive and efficient method for monitoring the Hawai‘i longline fishery for interactions with false killer whales.

1. Introduction

Direct interactions with commercial fisheries are one of the largest anthropogenic threats to marine mammals worldwide (Read, 2008). These are cases in which marine mammals come into physical contact with fishing gear and are “captured” but discarded, a process known as bycatch (Alverson et al., 1994). An increasingly prevalent cause of direct interaction between odontocetes and longline fisheries is dolphins and whales being attracted to longline gear to feed on bait or catch (Gilman et al., 2006; Thode et al., 2016). Attempting to depredate, or remove bait and catch from fishing hooks, occasionally leads to hooking or entanglement of the whale, potentially resulting in serious injury or death (Bradford and Forney 2014; Forney et al., 2011). This behavior also can lead to damage and loss of fishing gear and valuable catch, fishing restrictions, and fishery closures (Read 2008; Straley et al., 2015). In some fisheries, odontocetes may develop familiarity to sounds associated with longline vessels and a habit of depredating bait and catch from fisheries, such that these sounds serve as a cue to the animals and allow them to locate gear containing bait and catch (Gilman et al., 2006; Thode et al., 2007).

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There have been many attempts to reduce or discourage cetacean-longline interactions in several different fisheries around the world, although that work has resulted in only a few successes. For example, in the Coral Sea off Queensland, Australia, a vessel-based three dimensional acoustic tracking system was developed utilizing existing radio buoys to create a proximity detector that enables longline operators to potentially avoid false killer whales (*Pseudorca crassidens*) and sperm whales (*Physeter macrocephalus*) prior to setting fishing gear, effectively preventing interactions with cetaceans (McPherson et al., 2003). In contrast, deployment of acoustic pingers in the same fishery did not reduce depredation with these species (McPherson et al., 2003). Acoustic deterrents designed to prevent false killer whales from approaching longlines by interfering with the echolocation signals reflecting off of the fishing gear has been ineffective in captive environments (Mooney et al., 2009). Other attempts have included changes in fishing method (Straley et al., 2015; Thode et al., 2007) and even physical deterrents that protect a fish from depredation (Hamer et al., 2015; O'Connell et al., 2015). While scientists and fishermen continue to test potential mitigation options, this problem has proven difficult to solve.

Acoustic cues have been previously implicated in attracting cetaceans to longline fishing gear. For example, an ongoing study has identified specific gear-hauling sounds acting as a cue to sperm whales, which depredate from bottom-set longlines in the Gulf of Alaska (Thode et al., 2007). This study found that cavitation noise produced by changes in propeller rotation speed during hauling procedures was associated with increased acoustic pulse rate in sperm whales, suggesting a change in foraging behavior triggered by the fishing boat's acoustic cue production. It is possible that changes to the gear-hauling technique may reduce depredation by sperm whales.

In Hawai'i, interactions between false killer whales and the longline fishery have been reported as early as 1963 (Pryor 1975), though were only quantified and considered potentially unsustainable for the past two decades (Forney and Kobayashi 2007). There are three distinct populations of false killer whales in Hawai'i: the main Hawaiian Islands insular population, the Northwestern Hawaiian Islands population, and a broadly distributed pelagic population (Baird et al., 2008, 2012; Chivers et al., 2007; Martien et al., 2014). False killer whales feed primarily on large pelagic fish that are also targeted by commercial longline fishermen. The pelagic false killer whale population is known to depredate both bait and catch from the deep-set tuna-target longline fishery (Gilman et al., 2006; Nitta and Henderson, 1993; Thode et al., 2016); however, such depredation behavior sometimes leads to bycatch of false killer whales which exceeds sustainable levels (Carretta et al., 2015; Forney and Kobayashi 2007). Depredation of bait and catch by false killer whales often occurs at depth, and may occur anywhere within the approximately 70 km longline set, such that interactions are often not observed directly. In response to this ongoing problem, the National Marine Fisheries Service (NMFS) convened the False Killer Whale Take Reduction Team in 2010 to develop measures to reduce bycatch in the longline fishery. The resulting Take Reduction Plan (77 FR 71260, 29 November, 2012) also identified high-priority research needs crucial to understanding and mitigating false killer whale bycatch and depredation.

Although bycatch of false killer whales is currently above sustainable thresholds, observed interactions are rare, and depredation is reported in only about 5% of fishing sets, such that statistical power to detect patterns in bycatch and depredation is relatively low, making it difficult to identify viable solutions (Forney et al., 2011). False killer whales are highly vocal delphinids that can be readily identified to species level in passive acoustic recordings using the acoustic characteristics of their whistles and echolocation clicks (Bauman-Pickering et al., 2015; Rankin et al., 2008). While researchers have not identified any relationship between fishing gear or oceanographic variables and false killer whale bycatch (Forney et al., 2011), assessing patterns in false killer whale detections near gear using high-bandwidth passive acoustic monitoring (PAM) may provide more information than is available from fisheries observers alone. Since 2013, passive acoustic monitoring has been utilized in the Hawai'i longline fishery to better understand the rate of occurrence, timing, and movement of false killer whales around fishing gear. We compare acoustic detections of false killer whales with depredation rates, which may provide insight into potential mitigation strategies. There is likely a link between false killer whale depredation and direct interactions, and any long-term solution for bycatch reduction also likely will need to reduce depredation.

2. Methods

2.1. Longline set

A typical mid-water longline deep-set targeting bigeye tuna (*Thunnus obesus*) consists of up to 70 km of monofilament mainline set below the surface and supported by vertical float lines connected to surface floats at regular intervals approximately 0.4 km apart (Boggs and Ito 1993). A line shooter is needed to put sag in the line to fish deeply for bigeye tuna, with the deepest part of the line reaching up to 400 m depth while the shallowest sections fish near 40 m depth. The line between adjacent surface floats generally consists of 12–25 weighted branch lines, each with a single baited hook that hangs approximately 12 m below the mainline (Boggs and Ito 1993). A fishing set is characterized by three phases. Gear is set by deploying it from a vessel, generally starting around dawn. To set the entire mainline generally takes 4–5 h. The fishing gear soaks at depth during the daylight hours to target the daytime foraging of bigeye tuna on mesopelagic fish and cephalopods. Gear is hauled, generally starting in the afternoon and usually before sunset. Depending on the extent of fish catch, the haul can last 10–14 h (Bigelow et al., 2006). One complete set, from the beginning of the set to the end of the haul, results in about 19–24 fishing hours. The Hawai'i deep-set longline fishery operates year-round, but vessel activity is highest during the winter and spring months. Since 1994, mandatory fishery observers have been monitoring the fishery with coverage of at least 20 percent of trips since 2001 (NMFS, 2014).

For this study, the fishing vessel (F/V) *Katy Mary* was chartered for six fishing trips. A NMFS Pacific Islands Regional Office (PIRO) Observer Program fisheries observer was placed onboard to collect standard fisheries data, as well as the timing and location of acoustic recorder deployments within the gear. Initial experimentation with the fishing crew determined the optimal method and attachment locations for recorders within the longline gear to minimize disruption to the fishing process. Acoustic recorders were deployed during setting of the longline gear and retrieved during hauling in order to capture sounds that occur throughout the entire fishing process. The recorders were attached to the mainline using two locking branch clips (Fig. 1). Each deployment included placement of up to five acoustic recorders spread out evenly across the entire length of the longline during each set. On average, floats were 0.4 km apart, and recorders were placed from 11 to 55 km apart from each other on the mainline. The float number corresponding to a particular longline section and the hook location of each recorder were logged by the fisheries observer or fishing captain.

2.2. Fishery data collection

The fishery observer assigned to each trip collected all fisheries data typically collected as part of the PIRO Observer Program

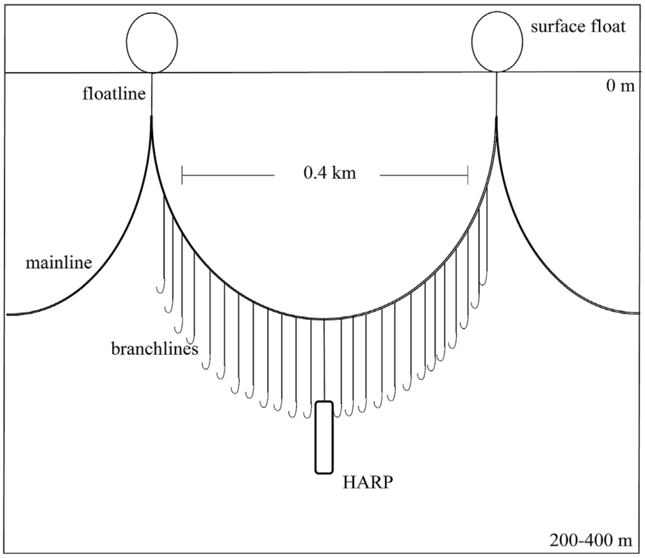

Fig. 1. Schematic of longline fishing set with HARP attached.

monitoring effort. Standard data collection includes the characteristics of fishing gear, such as diameter of branch line, hook size and shape, leader length, weight size, mainline diameter, total number of hooks fished, as well as the hook number and species of retained catch. Date, time, latitude, longitude, weather code, Beaufort scale, and sea surface temperature were recorded for the beginning and end of each set and haul. Set and haul events were also recorded, including haul back direction, line parting, number of sections retrieved, and interactions with protected species.[1] The onboard observer also recorded the extent of depredation of bait or catch by marine mammals. Catch depredation is judged based on the extent of fish body left on the hook, as well as the disposition of the remains, and considered from a marine mammal when nearly all of the fish's body is removed, leaving only the head attached to the hook. Marine mammal depredation is distinct from depredation by sharks, squid, or other predators, as the bite typically looks jagged, often leaving only strips of skin and tendons behind. This type of damage is distinguishable from shark damage that typically has sharp, defined edges of flesh removed as if cut from the body[1]. Photographs were taken of all marine mammal damage and viewed during debriefing sessions between the observer and Observer Program staff. Bait depredation was subjectively judged based on the number of segments of mainline between successive floats with a significant amount of missing bait and was considered possible marine mammal depredation if more than one segment had all bait missing. The existence of other marine mammal catch depredation within a given set was also used as an indication that the line was not poorly baited, but that a cetacean was depredating bait. It should be noted however that observer notes on depredation are, at best, an index of marine mammal depredation and not an unbiased and exact measure.

2.3. Acoustic recordings

To record false killer whale sounds, we used acoustic recorders known as High-frequency Acoustic Recording Packages (HARPs; Wiggins and Hildebrand, 2007) modified for use on the deep-set, tuna-target longlines. HARPs sample at 200 kHz, providing an effective bandwidth from 10 Hz to 100 kHz capable of recording sounds from low-frequency vessel noise to high frequency echolocation clicks. The original HARP data logger electronics, recording media, batteries, and pressure case design were miniaturized so that they could be easily attached to longline mainlines while maintaining near-neutral buoyancy. The miniaturization reduced the recording capacity from approximately one year to about one week. The pressure case (1000 m working depth) and a hydrophone were housed within a durable plastic tube that was easily attached to the mainline and protected the HARP as it was deployed and recovered from a fishing vessel. The hydrophone and a saltwater-sensing switch were cabled outside the pressure case via a high-pressure port, and the hydrophone was suspension-mounted using elastic cords within the plastic tube to reduce noise from movement in the water. The saltwater-sensing switch was incorporated into the HARP to activate the acoustic recordings only when the recorder was submerged to save battery power and data storage during non-use, and to make it easier to use by removing the need for a technician to manually turn the recorder on and off. Recordings captured the entire fishing process from the time the package entered the water until it was retrieved onboard.

2.4. Acoustic data processing

Digitized hydrophone waveforms were recorded to solid-state drives, which were removed from HARP pressure cases for processing after each fishing trip. The acoustic recordings were processed from a raw format into audio wav files and long-term spectral averages (LTSAs; Wiggins and Hildebrand, 2007) for further analysis. The spectral averaging algorithm transforms the acoustic waveforms so that they can be analyzed as long-duration time-frequency spectrograms. Successive spectra were calculated with a frequency resolution of 100 Hz and temporal resolution of 5 s, and arranged in an extended time-series that could be quickly scanned for identifying bouts of echolocation clicks or whistles using one-hour-long windows. Periods of marine mammal calling, referred to as acoustic bouts, were identified and selected using LTSAs in the acoustic software program *Triton* (http://cetus.ucsd.edu/technologies_Software.html) running within high-level programming environment MATLAB (Mathworks). For the purpose of this analysis, an acoustic bout was defined as a period when vocalizations (clicks and/or whistles) were made continuously with less than 10 min gaps in between vocalizations. If gaps of more than 10 min were present, the acoustic detection would be considered a new bout. Once an acoustic bout was identified, based on recognizable acoustic signatures, the start and end times were recorded and successive 30-s files were saved for the duration of the bout to use in further click and whistle classification analysis. Bouts were numbered in order across all detected bouts starting with those detected in the first deployed recorder for each set, then proceeding through each detected bout on subsequent recorders within that set.

2.5. Acoustic species classification

2.5.1. Whistle classification

Classification of whistle bouts was made using the Real-time Odontocete Call Classification Algorithm (ROCCA; Oswald et al., 2007), which runs as a module within the acoustic software package, PAMGUARD (http://www.pamguard.org). ROCCA was used to automatically detect whistles, extract and measure whistle contours, and classify them to species level by comparing those contours to whistles of known origin. For this project, a random selection of ~50% of clear and good signal-to-noise ratio (SNR) whistles from each acoustic bout was made. This method of subsampling, based on the work of Oswald et al. (2007), was considered to have a sufficient sample size without over-sampling. Once whis-

[1] Hawaii Longline Observer Program Field Manual, Pacific Islands Regional Office Observer Program. Updated Aug. 17, 2015 http://www.fpir.noaa.gov/OBS/obs_observer_manual_forms.html.

tles were selected, they were traced by an analyst (ARB) in ROCCA. ROCCA was then used to provide an estimate of species identification for each whistle using a random forest analysis based on 54 automatically measured whistle contour features including various frequencies, durations, and slopes. A random forest is a collection of decision trees grown using binary partitioning of the data. Each of the trees in the forest produce a species classification and can be considered one 'vote' for a given species classification. Votes are tallied over all trees, and whistle classification is based on the species with the most 'votes'. The number of tree classifications for the predicted species was measured against a 'strong whistle threshold' (Oswald et al., 2011) specifically chosen to maximize correct classification scores. It was assumed that if 50% or more whistles from a bout were classified to the same species, then that classification had a high degree of certainty (Oswald et al., 2011; Oswald, 2013). If the percentage of the trees that classified the whistle was less than the strong whistle threshold of 50%, then the whistles were labeled as 'ambiguous' and species identification information was considered unreliable.

2.5.2. Click classification

Echolocation clicks were automatically detected using a computer algorithm with a two-step approach (Roch et al., 2011; Soldevilla et al., 2008). In the first step, a custom software program written in MATLAB was used to calculate and display the temporal and spectral characteristics of clicks from each acoustic bout. The spectrum of each click was calculated using 2.56 ms of Hann-windowed data centered on the signal and peak. Bandwidth and center frequency were subsequently processed using methods from Au (1993) and signals with peak frequencies below 15 kHz or durations greater than 1.5 ms contained spectral or temporal characteristics of noise and were omitted from the analysis (Bauman-Pickering et al., 2015). The software program output from each bout included plots of normalized mean spectra, histograms of inter-click interval (ms), peak frequency (kHz), click duration (μs), and a concatenated spectrogram of all detected clicks. The mean spectra provides the average frequency vs. magnitude relationship among all clicks within an acoustic bout, and provides comparison to spectral templates for clicks of known false killer whales and pilot whales taken from literature. In the second step of classification process, the presence or absence of false killer whales in acoustic bouts was determined by two experienced analysts (ARB and AES) using the ranges of click characteristics described by Bauman-Pickering et al. (2015).

2.5.3. Classification rankings

The classifications of whistles and echolocation clicks within each bout were used to derive a confidence score for each acoustic bout. Confidence scores were designed to address potential mismatches in the species classification of clicks and whistles from the same bout, or to assess confidence for bouts containing only one of the two signal types. An acoustic bout was rated with high confidence if the click classification score was judged by both analysts to be false killer whales and the ROCCA whistle classification score for the bout was greater than the strong whistle threshold. A bout was also judged to be high confidence if only clicks were present and both analysts classified the bout as false killer whale or if only whistles were present and the ROCCA classification score exceeded the strong whistle threshold. A bout was ranked medium confidence when the ROCCA whistle classification score exceeded the strong whistle threshold but only one of the analysts classified the clicks as being produced by false killer whales. A bout was ranked with low confidence if click classifications did not agree and/or the whistle percentages were below the 50% threshold. There were no cases where click classifications agreed but whistles were below the 50% threshold. Only bouts with high or medium confidence ratings were used in further analysis.

Our classification methods did not readily accommodate attempts to infer the occurrence of more than one species within an acoustic bout. Other odontocete species may have been encountered, and mismatches between click and whistle classification may be related to mixed species groupings. Such mismatches and subsequent low confidence scores would result in an underestimate of the total number of acoustic bouts correctly attributed to false killer whales. Any acoustic bouts with click and whistle classifications judged to be from a species other than false killer whales were assigned to another species if there was agreement in the classification, otherwise they were classified as an unidentified odontocete (UO). Bouts classified as being produced by another species or an unidentified odontocete were not analyzed further.

2.6. Timing analyses

The start and end times of gear setting and hauling were recorded by the fishery observer and these phases were compared against the occurrence of false killer whale calling bouts in a number of ways. These analyses considered each high and medium confidence acoustic bout individually, without regard for whether there were detections on more than one instrument per set. To examine the occurrence of calling bouts by fishing phase, the set, soak, and haul phases were divided further by determining the total time for each phase and then dividing the overall duration of each process into thirds. The timing of each high and medium confidence false killer whale bout was then compared to the timing of fishing activities to determine when false killer whales were near the fishing gear.

Real-time location information for fishing vessels were not available for this study, such that start and end of the set and haul, and the deployment and recovery locations for each instrument as recorded by the observer, are the only information available on vessel location during each set. To examine whether false killer whales may be responding to the movement of fishing vessels, we used the time and location stamp for the deployment and recovery of each instrument as a proxy for the location of the vessel at that time. We then calculated the time difference from the start and end of each calling bout and the time of the vessel at the location of that instrument. For each instrument, both instrument deployment and recovery are available, and for this analysis, we used the shorter time lapses. The time differences were then examined by fishing phase.

When bouts classified as false killer whales were recorded on more than one instrument within a set, the relative timing of each bout was analyzed to examine whether subsequent bouts could have been produced by the same group of false killer whales and if so, whether the whale may have been responding to vessel movements. For this analysis we used all confidence false killer whale bouts. When false killer whale bouts were heard on more than one recorder within a set, the relative timing of those detections was evaluated. The start and end of the calling bout relative to the start of the haul was calculated, with bouts occurring during the soak having negative times, and those after the haul began with positive times. The timing of each calling bout at the relative location of each instrument was then plotted to assess whether there was any pattern between subsequent detections within the set. Additionally, the feasibility of subsequent detections being from the same group of false killer whales was assessed by the speed that the whales would have had to travel between subsequent instrument locations. The geographic locations of the instrument deployments were used to estimate the distance between those recorders. An intermediate swim rate was calculated based on the time between the first detection on one instrument and the first detection on the subsequent instrument. A maximum possible swim rate was calculated when acoustic bouts did not overlap between instruments based on the time between the last detection on one instrument and the first detection on a subsequent instrument. If acoustic bouts occurred on more than one instrument in different fishing phases, an average was calculated for those detections that occurred during each phase. Both intermediate and maximum swim rates were compared to observed sustainable swim speeds for false killer whales (Baird et al., 2012), to determine whether it was plausible that a single group was being detected.

3. Results

3.1. Acoustic species classification

A total of 90 fishing sets were acoustically monitored on six fishing trips (identified as A-F) onboard the F/V *Katy Mary* from March 2013 to March 2014. No bycatch of false killer whales was observed during any of these sets. A total of 102 cetacean acoustic bouts containing whistles, clicks, or both were identified on 55 sets across all six trips. A total of 26 acoustic bouts on 19 of 90 (21%) fishing sets were classified as false killer whales with high or medium confidence (Table 1). Two additional bouts consisted of clicks only, and the analysts disagreed on the species classification. These bouts were considered low confidence and were not considered in further analysis. All six trips had at least one acoustic bout judged with high or medium confidence to be produced by false killer whales (Table 2). Sperm whales, short-finned pilot whales (*Globicephala macrorhynchus*), and common bottlenose dolphins (*Tursiops truncatus*) were also acoustically detected, but were not used in further analyses. Those bouts judged to be produced by false killer whales included a minimum of 14 whistles and a maximum of 387 whistles. Of the 26 high and medium confidence bouts, one was based solely on whistles, four were based solely on clicks, and 21 bouts were classified based on both clicks and whistles. Acoustic bouts ranged in duration from 5 min to over 4 h, with a median bout duration of 31 min.

Although there were typically 5 recorders available for deployment on each fishing set, in several cases a recorder either failed during deployment, the captain chose not to deploy all recorders on each set, or a recorder was not deployed so that the observer could install new batteries and hard drives. The number of operational acoustic recorders across all sets ranged from 1 to 5 (median = 4), one greater than for those sets with false killer whale detections (median = 3). It was not possible to assess whale-to-recorder distance from these recordings because the recorders were not calibrated. However, it is possible that whistles may propagate over 5 km in sub-tropical and tropical waters (Rankin et al., 2008; Thode et al., 2016), and hence detection of a group may occur from several longline segments away.

3.2. Depredation

Only three of the 19 sets (16%) with false killer whale detections had signs of marine mammal catch or bait depredation as recorded by the onboard observer (Table 2). All three of these cases are classified as false killer whales with high confidence. There were four other sets that showed signs of marine mammal depredation out of the total 90 sets monitored. Two of these sets had whistles or clicks judged to be produced by an unidentified odontocete, and the remaining two sets with marine mammal depredation had no marine mammal sounds present. Sixteen sets had acoustic detections of false killer whales but were without signs of catch or bait depredation.

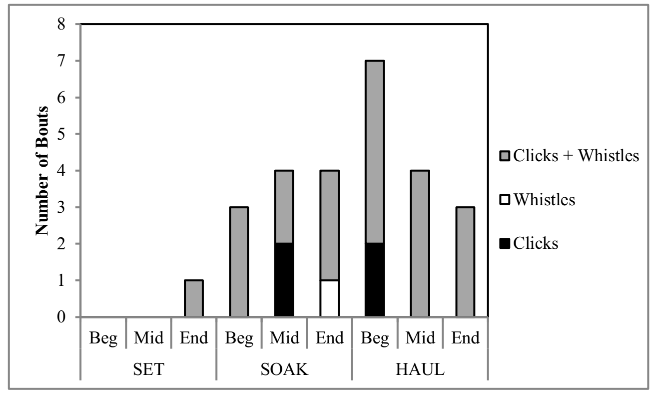

Fig. 2. Occurrence of acoustically detected false killer whales by fishing phase based on classification of clicks, whistles, or both.

3.3. False killer whale occurrence in relation to fishing activities

We examined the occurrence of false killer whale bouts relative to the fishing gear and fishing activity in a number of ways. For most sets, several recorders were deployed within the set, such that the location of the recorder with false killer whale calling bouts may provide insight into the occurrence of the whales near the gear. On only two of 19 monitored sets were false killer whales detected with high or medium confidence on more than one recorder. Those are described in greater detail below. For the remaining 17 sets, the false killer whale detections occurred on the recorder at one end or the other of the series of deployed instruments (or in one case, on the only deployed recorder- TripSet A14-5/6) in 13 cases (Table 1). In only 4 sets were false killer whales detected on a recorder between other recorders without any false killer whale detections.

The timing of false killer whale acoustic presence near longline gear was compared to the phases of a fishing set. Of the 26 bouts classified as false killer whales with high or medium confidence, 14 (54%) occurred during the haul (Fig. 2). A total of 11 of 14 (79%) bouts heard during the haul occurred during the beginning and middle of the haul, with 7 of those (64%) during the beginning one-third of the haul. Only one false killer whale bout (4%) occurred during the setting phase of longline deployment.

To evaluate whether false killer whales may have been responding to vessel sound or movement, the known location and time of recorder deployment and retrieval was used to provide the known vessel location and time stamp. The time difference between the known vessel presence at a recorder location and the beginning and ending of false killer whale calling bouts at that location was examined. During the soak phase, the time lapse between both the start and end of calling bouts relative to the time the vessel was known to be at that location was fairly evenly distributed, with 1–3 bouts for each hourly time step from <1 h to 6–7 h (Fig. 3). For bouts occurring during the hauling phase, the distribution of bout start time relative to the time the vessel was at that location was also evenly distributed with most bouts starting less than 4 h from the instrument retrieval. In contrast, 10 of 14 bouts that ended during the haul ended within 2 h of the instrument retrieval, with 7 of those ending 1–2 h from retrieval.

3.4. Detections across several recorders

Of the 19 sets with false killer whale detections, there were three sets during which they were acoustically detected on more than one recorder. Both the timing and spatial arrangement of these detections are shown in Fig. 4. For each of these three sets (TripSet A3, F5, and F7) at least one calling bout was judged to be false killer

Table 1
Classification information for false killer whale (FKW) acoustic bouts. FKW bout IDs identify the trip (ie. A for the first trip), set number and bout number within that set. The relative location of the HARP with a calling bout is noted out of the total number of HARPs deployed on that particular set, where HARP 1 was deployed first. The species classification from ROCCA, along with the percentage of whistles classified as FKW is provided for each bout with whistles. Click classification from each analyst are provided for each bout (FKW, UO- unidentified odonotocete). Fishing phase indicates the fishing activity underway when each bout was detected and the Beaufort indicates the wind state noted by the fisheries observer. Only those low confidence bouts with one classification component judged as FKW are shown. Bout IDs denoted with an * indicate those with multiple detections of FKWs across multiple instruments within that set.

Bout ID (TripSet-Bout)	HARP #/total	Date	Duration (h:min)	ROCCA ID	% FKW	Click Analyst 1/2	Confidence Score	Fishing Phase	Beaufort
A2-2	3/3	4/5/13	0:05	–	–	FKW/FKW	High	Haul	4
A3-1*	1/3	4/6/13	4:41	FKW	88%	UO/UO	Med	Haul	4
A3-2*	3/3	4/6/13	1:42	FKW	65%	FKW/FKW	High	Haul	4
A4-1	1/3	4/7/13	0:19	FKW	83%	UO/UO	Med	Haul	4
A11-1	1/2	4/14/13	0:22	FKW	100%	FKW/FKW	High	Soak	4
A14-1	1/1	4/17/13	1:01	FKW	82%	UO/UO	Med	Soak	4
A14-2	1/1	4/17/13	0:17	FKW	59%	UO/UO	Med	Haul	4
B1-1	3/3	5/1/13	0:52	FKW	87%	UO/UO	Med	Soak	2
C9-1	1/4	7/2/13	0:34	–	–	FKW/FKW	High	Soak	3
C10-1	1/4	7/3/13	0:17	FKW	90%	FKW/UO	Med	Haul	4
C14-1	1/4	7/07/13	0:17	–	–	FKW/UO	Low	Haul	2
D4-3	2/4	11/14/13	0:16	–	–	FKW/FKW	High	Soak	4
D7-1	1/4	11/16/13	0:58	–	–	FKW/FKW	High	Haul	2
D9-1	3/5	11/20/13	0:47	FKW	83%	FKW/FKW	High	Haul	3
D12-1	2/2	11/24/13	0:05	FKW	81%	UO/UO	High	Soak	3
D15-1	2/2	11/28/13	0:06	FKW	89%	UO/UO	High	Haul	3
E11-1	3/3	1/15/14	0:21	FKW	88%	–	High	Soak	2
F5-1*	1/4	3/11/14	0:23	FKW	51%	UO/FKW	Med	Soak	3
F5-3*	2/4	3/11/14	0:29	FKW	89%	FKW/FKW	High	Soak	3
F5-5*	3/4	3/11/14	0:38	FKW	89%	FKW/FKW	High	Soak	3
F5-7*	4/4	3/11/14	1:16	FKW	85%	UO/UO	Med	Soak	3
F5-6*	3/4	3/11/14	0:19	FKW	72%	UO/UO	Med	Haul	3
F5-4*	2/4	3/11/14	0:59	FKW	84%	FKW/FKW	High	Haul	3
F5-2*	1/4	3/11/14	0:36	FKW	88%	UO/UO	Med	Haul	3
F7-1*	3/5	3/13/14	0:45	FKW	54%	FKW/FKW	High	Haul	3
F7-3*	5/5	3/13/14	1:12	–	–	FKW/UO	Low	Haul	3
F11-3	2/4	3/18/14	0:24	FKW	73%	FKW/UO	High	Set	3
F14-1	1/4	3/22/14	0:47	FKW	69%	UO/UO	Med	Haul	2

Table 2
False killer whale (FKW) presence, based on high and medium confidence classifications, as compared to catch and bait depredation events recorded by the fisheries observer.

Trip	Total monitored sets	Sets w/FKW	Sets w/Catch Depredation	Sets w/Bait Depredation	Sets w/FKW and Depredation
A	14	6	1	1	1
B	14	1	0	1	1
C	15	2	0	0	0
D	15	5	2	0	0
E	15	1	0	0	0
F	17	4	1	1	1
Total	**90**	**19**	**4**	**3**	**3**

whales with high confidence. In all three cases, false killer whales were detected on a recorder that was closer to the vessel during the soak and farther away from the vessel during the haul. For one (TripSet F5), false killer whales were detected on each of the four deployed instruments over a 10 h period. False killer whales were first detected on the recorder farthest from the vessel, about 4.5 h before the haul began. Subsequent detections occurred during the soak on recorders sequentially closer to the vessel location. After the onset of the haul, false killer whale detections proceeded in the opposite direction with subsequent detections at recorders farther from the vessel as it hauled gear back toward float 1. The observer recorded a high degree of marine mammal depredation, including the remains of multiple target catch species and multiple longline segments empty of bait. In each case, evidence of depredation was found in longline segments less than 10 segments away from an instrument.

Based on the calculated distance between recorders and the timing of whistle detections, the intermediate and maximum swim rates were calculated for each of the three cases (Table 3). Based on the calculated swim rates and the known maximum sustainable swim speed of 20 km/hr for false killer whales (Baird et al., 2012), it is plausible that the calling bouts detected across multiple HARPs could have been produced by a single group of animals. For example, during TripSet F5, average swim speeds ranged from 8.9 and 15.9 km/hr, which falls within reasonable swim speeds for false killer whales.

4. Discussion

Passive acoustic recorders developed specifically for deployment on deep-set longline gear have provided an efficient and easy-to-use system for acoustic monitoring of the Hawai‘i longline fishery. This novel approach to understanding how false killer whales interact with longline gear has provided insight into the timing and location of detections in relation to fishing activities.

We acoustically monitored six fishing trips, consisting of 90 total fishing sets, resulting in the detection of 26 bouts classified as false killer whales with high or medium confidence. The majority of those false killer whales calling bouts were detected during the hauling phase of fishing, and only one occurred during the setting phase. False killer whale movements relative to the fishing vessel and throughout the fishing set were examined, though are findings

Table 3
Swim rate estimation in km/hr based on distance between recorders with false killer whale bouts and the start and/or end time of those bouts. When bouts occurred across multiple recorders during more than one fishing phase, an average of the swim speed estimates were provided for each phase separately.

TripSet ID	Distance (km)	Intermediate Rate (km/hr)	Max. Rate (km/hr)
TripSet F5, Soak Avg.	17.0	15.9	30.7
TripSet F5, Haul Avg.	17.0	8.9	16.6
TripSet A3	31.1	32.7	–
TripSet F7	37.6	16.5	34.8

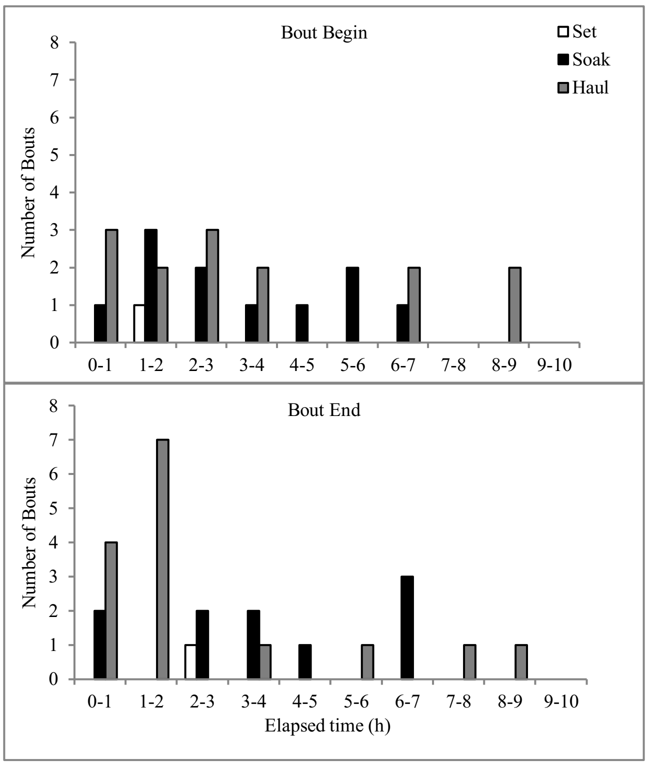

Fig. 3. Distribution of time elapsed from beginning (top panel) and end (bottom panel) of each false killer whale bout to the time of deployment or recovery of the HARP it was recorded on.

do not suggest that all false killer whale interactions with gear are easily explained by vessel behavior. Eleven call bouts occur during the soak phase of fishing and the timing of those bouts appears to be relatively evenly distributed throughout that phase (Figs. 2 and 3). In contrast, of the 14 bouts occurring during the haul there appears to be clear link between the occurrence false killer whale detections and the timing of vessel movements, such that the whales may be responding to the movement of the fishing vessel in several cases. When the vessel is relatively nearby, and during sets with detections on multiple recorders, the whales appear to be moving in the same direction as the vessel as gear is hauled. The onboard fisheries observer reported catch depredation at levels somewhat lower than the long-term average depredation rate, though our sample size is low for such a comparison.

We have also chosen not to focus here on encounters that are judged to be a species other than false killer whale. We have done so because no other species is seen interacting with deep-set fishing gear in Hawaii at such a high rate, nor has been identified for mitigation measures to reduce take of those species. Fishery observers indicate that between 2009 and 2013, 52% of all interactions with cetaceans involved false killer whales, a rate much higher than any other individual cetacean species (Bradford and Forney 2014). Subsequent evaluation of whether the injuries sustained by hooked or entangled cetaceans indicate 79.2% of false killer whales interactions during that period resulted in serious injury or death of the whale.

4.1. Acoustic species discrimination and automated classification

Successful and effective use of autonomous passive acoustic instrumentation for assessing species occurrence requires that the species' sound can be identified with reasonable certainty without verification by a visual observer. Sounds from many species of delphinid cannot be classified with high confidence; however, false killer whales are among a small group of delphinids whose whistles and echolocation clicks have been found to be species-specific and identifiable. Using whistles collected concurrently with observer-based visually-identified groups, ROCCA was found to correctly classify 80% of false killer whale encounters (Oswald et al., 2007), with more recent improvements in the algorithm producing even higher correct classification scores. Based on those results and the further use of 'strong whistle thresholds' for classifying encounters, we are confident in the assignment of high or medium confidence to encounters with greater than 50% whistles classified as false killer whale.

There have been few studies attempting to classify echolocation clicks from delphinids, but a recent study suggested that satellite tagged false killer whales and short-finned pilot whales could be correctly discriminated to species using echolocation clicks detected on a seafloor recorder during the period the tagged animals passed nearby (Bauman-Pickering et al., 2015). Acoustic features, such as average click spectra and inter-click interval, are reliable features for click classification in false killer whales (Bauman-Pickering et al., 2015). Classification of echolocation clicks relies on an analyst judgment of various acoustic features of the encounter against a set of reference signals derived from visually-verified groups. Reliance on analyst judgment introduces a degree of subjectivity to the classification decision. To overcome this subjectivity, we employed two analysts to independently classify clicks from each encounter, and then used the findings of both analysts to assess our confidence in the overall classification.

Occasionally, assignment of species using the measured click parameters was not straight-forward. For example, in some cases the average spectra for the encounter was similar to the false killer whale reference spectra, but the peak frequency did not fall within the expected range for the species, or the average click duration and peak frequency where most similar to false killer whale values, but the average spectra did not match. There are several reasons for such mismatch, and most suggest the classification results are still reliable even when some characters do not fit the false killer whale template. System and environmental noise are measured as part of the click classification process, and in some cases noise levels are quite high. The impacts of noise on classification success were not quantified and could be significant. Spectral measures of clicks may be affected by animal distance, with higher frequency components of the signal attenuated at greater ranges or when the animal is not facing the recorder. We are not able to measure distance between the recorder and the animals with our recorder configuration, such that such signal propagation affects cannot be examined or mitigated within our dataset. Furthermore, it is possible that more

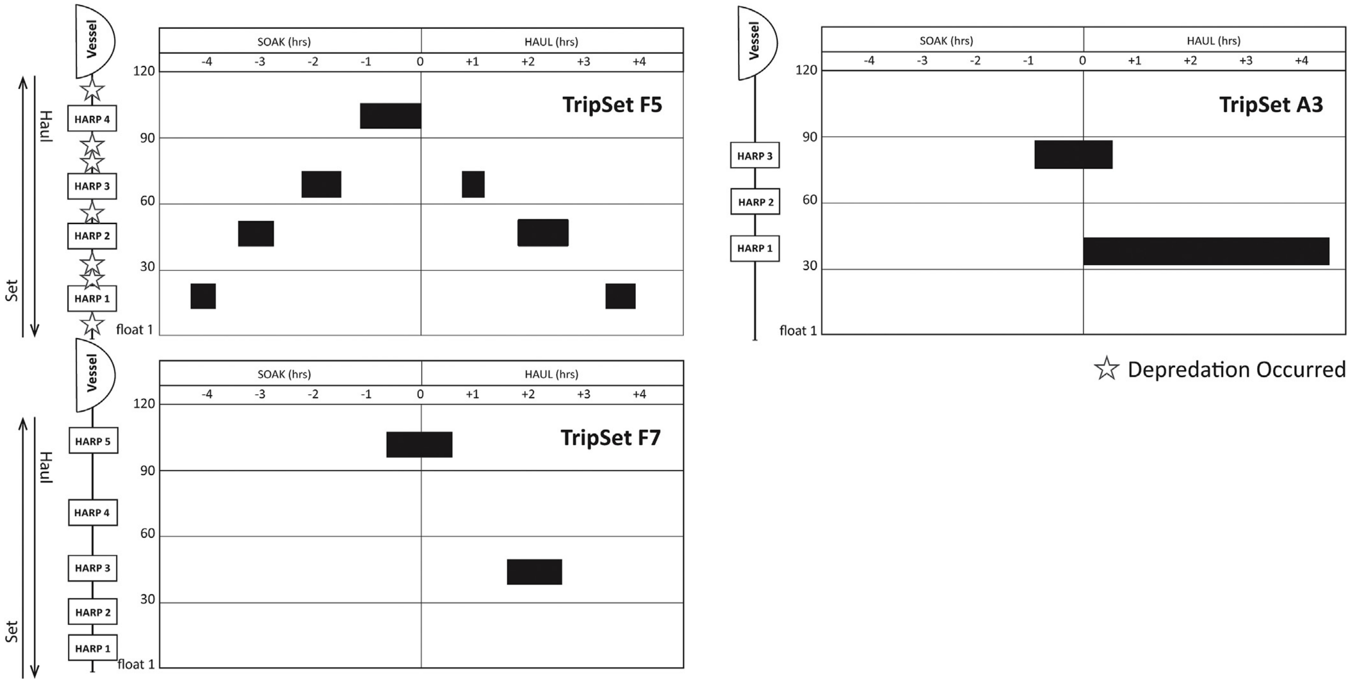

Fig. 4. Acoustic detections across multiple HARPs are shown for three different sets. 'TripSet'refers to the trip number, which has been labeled alphabetically with the first trip represented by the letter A, the last trip represented by the letter F, as well as the set number. Float numbers are shown along the y-axis and time is shown along the x-axis in 1 h time steps, with t = 0 representing the onset of the haul. The longline was deployed beginning at float 1 to float 120, with the vessel moving up along the y-axis. The HARPs were deployed beginning with HARP1, and in numerical order up to the number available for each set. The HARPs were subsequently recovered in the opposite direction, with HARP1 recovered last. In some cases, fewer than five HARPs were deployed or had usable data. The relative locations of marine mammal catch and bait depredation are denoted by the stars along the y-axis.

than one group of delphinids was vocalizing within the detection range of an individual recorder and that these encounters appear as a single encounter to the analyst, complicating assessment of the averaged click features. Using the classification decision from both analysts together with the quantitative assessment of classification certainty from ROCCA, we are confident that the potential for falsely classifying an encounter as false killer whale was small. However, it is possible we eliminated some encounters from later analysis that were false killer whales because we could not account for noise or mixed-species groups. Use of only high and medium confidence bouts provides a conservative assessment of false killer whale occurrence in our autonomous recordings, but does allow us to assess the association between acoustic encounters judged to be false killer whales and other aspects of the fishing activities.

4.2. Depredation

Assessment of Observer Program data suggests that depredation is often recorded primarily in a single or few adjacent longline segments, although occasionally large segments of the gear appear to have been depredated based on the characteristics of remaining fish heads.[2] Marine mammal damage is reported by observers but verified post-trip through photographs in most instances. There are relatively few reports of bait depredation as it is difficult for an observer to objectively judge or quantify. In general, lack of bait on a large number of hooks and in several segments throughout a set are judged as bait depredation, though the depredating species cannot be assessed based on an empty hook alone. Interestingly, during the six trips of our study, there were relatively low rates of catch and bait depredation while false killer whales were acoustically detected at a relatively high rate. Across the fleet, about 6% of sets have signs of catch depredation attributed to marine mammals[2]. During our study, four sets were verified to have catch depredation attributed to marine mammals (~4%) and another 3 were judged to have possible bait depredation (~3%).

Surprisingly, less than half of those sets with signs of marine mammal damage also had acoustic detections of false killer whales. Incidence of depredation without concurrent acoustic detection could be a matter of recorder distance to depredation events, such that acoustic recorders were not in the same section of gear as the whales. Also, catch depredation is generally not uniformly distributed throughout the fleet (Forney et al., 2011), so could be related to fishing location, time of year, or environmental factors. The catch records from the F/V *Katy Mary* during acoustically monitored trips did not vary in target catch rates relative to their long-term average fishing performance. More interesting is the relatively high rate of acoustic detection of false killer whales relative to the overall low rate of reported catch and bait depredation. It is possible that false killer whales are depredating bait more often than catch, and this bait depredation is not wide-spread enough within each set to trigger an observer to report bait depredation. While catch species are reported by hook, the status of hooks without catch (i.e. whether a hook comes up empty or with bait) is not reported in the Observer Program notes, so that it is not possible to retrospectively examine the extent of empty versus baited hooks at the end of each set. Underwater video recordings from this fishery indicate that false killer whales do take bait from the fishing hook (Thode et al., 2016). Our findings in combination with video evidence of bait depredation suggest that bait depredation may be much more common than previously recognized.

It is also plausible that our high acoustic detection rates may be attributed to detection of whales passing near the gear, but not actually interacting with it. False killer whale whistle detection range was modeled by Thode et al. (2016). The authors assert

[2] False Killer Whale Take-Reduction Plan (http://www.fisheries.noaa.gov/pr/pdfs/interactions/fkwtrp_draft.pdf).

that for a receiver above the thermocline (~130 m in the central Pacific), whistles may be detectable at ranges of 2–10 km during sea state 4 conditions, common conditions for this region and during our study (see Table 1). During our study, instruments were typically deployed to depths deeper than 130 m, such that detection range should be reduced. Using these modeled values, we assume false killer whale whistle detection range may be less than 5 km from the receiver for most deployments. Further, all but one false killer whale detection included echolocation clicks, a signal with a much shorter detection range due to its narrow beam and higher frequency content. Detection of echolocation clicks suggests the whales were likely much closer than 5 km from the fishing gear. Although animals may certainly pass within 5 km without interacting with gear, we feel this would represent a small proportion of the overall encounters reported here.

4.3. False killer whale occurrence in relation to fishing activities

Our analysis of the timing of false killer whale acoustic bouts relative to the phase of fishing activities indicates that false killer whales are most commonly detected during the haul and to a lesser extent, during the soak (Fig. 2). Fishermen generally do not set longline gear or may abort already initiated fishing activity when false killer whales have been observed in the immediate area (NMFS 2012), such that the peak in detections during the soak and haul could be related to the time it takes for roaming whales to randomly come in contact with the gear. However, in general we feel it is more likely that the whales are alerted to the presence of the gear through transmission of an acoustic cue produced by the gear or the vessel. This is further supported by the timing of the start and end of false killer whale calling bouts relative to the time that the vessel is at that recorder location. The start and end time of bouts occurring during the haul appear to be linked to vessel movements (Fig. 3), though our data could not provide insight into the distance at which the whales are likely reacting or choosing to remain from the vessel. However, several calling bouts do occur entirely within the soaking phase of the fishing set (Table 1, Fig. 2), such that without additional information on the sounds produced by the gear or vessel, or the behavior of the vessel during the soak, it is difficult to draw conclusions about how the whales may have located the gear in these cases.

Transmission of acoustic cues was suggested as the driver of increased depredation of sable fish in the demersal longline fishery in Alaska by sperm whales (Straley et al., 2015; Thode et al., 2007). Subsequent investigation of the behavior of individual tagged sperm whales during acoustic transmission of a variety of different gear and vessel-generated sounds revealed that the propeller generated bubble cavitation arising from changes in vessel speeds during gear hauling led to interruptions in sperm whale diving patterns and an increase in attendant sperm whales near the vessels replicating such sounds, whether hauling gear or not (Thode et al., 2007). Other studies have also suggested that depredation is most common during the haul (reviewed by Gilman et al., 2006), although there have been few studies relating specific gear or vessel sounds to depredating whale behavior. Analysis of the specific vessel and gear sounds detected within our dataset could provide a better understanding of what drove increased detection of false killer whales during the haul and soak phases.

4.4. Detections across several recorders

False killer whales were detected concurrently on more than one recorder during three fishing sets. On one set, false killer whales were recorded at all four deployed recorders, initially with successive detections at recorders closer to the fishing vessel throughout the soak, then at recorders farther from the vessel during the haul (Fig. 4). In the remaining case the whales were recorded at a recorder closer to the fishing vessel during the soak and beginning of the haul, and subsequently at a recorder farther away from the vessel after the onset of the haul (Fig. 4). Detections at adjacent recorders generally did not overlap temporally. Based on calculated swim rates, it is feasible that subsequent detections within the same set may have been produced by the same group of animals moving along the line. The swim speed calculations assume a single coordinated and tightly packed group of animals moving among the gear, which we know is not generally indicative of false killer whale behavior, such that the values are a conservative metric for addressing this question. Coordinated sub-groups of false killer whales are known to occur over at least 50 km (Baird et al., 2008; Bradford et al., 2014), but it is not possible for us to identify the spread of groups or how many sub-groups we may detect from our recordings. Previous assessments of Observer Program data have suggested that depredation is most common in adjacent or nearby longline segments, rather than being distributed more randomly or evenly throughout a set. Our results provide some support for the assertion that once false killer whales locate fishing gear, they move along the gear taking advantage of relatively immobile fish dangling from fishing hooks; however, we have at least 4 sets with false killer whale detections at one recorder, with no detections at the recorders to either side, suggesting these movements do not always span long distances within the gear.

The detection of false killer whale sounds at sequentially farther locations from the vessel throughout the haul (Fig. 4), together without assessment of the time difference between whale detections and vessel occurrence at that location (Fig. 3) suggests awareness of the vessel's location and movement and some motivation to stay ahead of the vessel. Such motivation could simply be to take maximum advantage of the remaining catch before the vessel arrives. For example, the first detections illustrated in Fig. 4 (TripSet F5), suggest that animals may be depredating as they move along the line. While it is unknown if this is one group of false killer whales, the sequence of acoustic detections and extensive depredation on this set suggests a coordinated group of false killer whales moving along the line toward the vessel during the soak, then switching directions and moving back down the line away from the vessel during the haul. The change of direction in this set and the subsequent detection of false killer whales at more distant recorders after the onset of the haul in other sets, suggests that the whales further supports the concept of an acoustic cue, produced either by the hauling vessel or the gear.

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