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Contribution to the Themed Section: '*Marine Mammal Bycatch and Depredation*'

Original Article

Southeast Alaska Sperm Whale Avoidance Project (SEASWAP): a successful collaboration among scientists and industry to study depredation in Alaskan waters

Janice Straley[1]*, Victoria O'Connell[2], Joe Liddle[1], Aaron Thode[3], Lauren Wild[2], Linda Behnken[4], Dan Falvey[4], and Chris Lunsford[5]

[1]*University of Alaska Southeast, 1332 Seaward Avenue, Sitka, AK 99835, USA*
[2]*Sitka Sound Science Centre, 834 Lincoln Street, Sitka, AK 99835, USA*
[3]*Scripps Institution of Oceanography, University of California, 9500 Gilman Drive, La Jolla, CA 92093, USA*
[4]*Alaska Longline Fishermen's Association, 834 Lincoln Street, Sitka, AK 99835, USA*
[5]*NOAA Auke Bay Laboratories, Ted Stevens Marine Research Institute, 17109 Pt. Lena Loop Road, Juneau, AK 99801, USA*

**Corresponding author: tel: + 1 907 747 7779; e-mail: jmstraley@uas.alaska.edu*

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In Alaskan waters, depredation on sablefish longline gear by sperm whales increases harvesting cost, negatively biases stock assessments, and presents a risk of entanglement for whales. The Southeast Alaska Sperm Whale Avoidance Project (SEASWAP), a collaborative effort involving industry, scientists, and managers, since 2003 has undertaken research to evaluate depredation with a goal of recommending measures to reduce interactions. Prior to 2003, little was known about sperm whale distribution and behaviour in the Gulf of Alaska (GOA). Although fishers were reporting increasing interactions, the level of depredation varied with no apparent predictor of occurrence across vessels. Between 2003 and 2007, fishers were provided with fishery logbooks and recorded information on whale behaviour, whale presence and absence, during the set, soak, and haul for 319 sets in the GOA. Data were evaluated for a vessel, area, and seasonal (month) effect in the presence and absence of sperm whales. Using catch per unit effort (*cpue*) as a metric, in kg/100 hooks, results indicated that depredation depended on both the vessel and the area. More whales associated with vessels from April to August. Sperm whales were also likely to be present when *cpue* was high, revealing that whales and fishers both knew the most productive fishing areas, but confounding the use of *cpue* as a metric for depredation. Using a Bayesian mark-recapture analysis and the sightings histories of photo-identified whales, an estimated $\hat{N} = 135$ (95% *CI* 124, 153) sperm whales were associating with vessels in 2014. A spatial model was fitted to 319 longline sets and quantified a 3% loss in *cpue*, comparable to other global studies on sperm whale depredation. Through all phases of SEASWAP, our understanding of depredation has gained significantly. This successful collaboration should be considered as a model to create partnerships and build collaborations between researchers and fisherpeople encountering marine mammal interactions with fishing gear.

Keywords: behavioural ecology, collaboration, commercial fishing, depredation, Gulf of Alaska, longline, population estimate, sablefish, spatial analysis, sperm whales.

Introduction

Sperm whales (*Physeter macrocephalus*) associate with fishing operations, particularly demersal longline operations, in many locations around the globe (Rice, 1989; SCCAMLR, 1994; Ashford *et al.*, 1996; Capdeville, 1997; Nolan and Liddle, 2000; Hucke-Gaete *et al.*, 2004; Purves *et al.*, 2004; Guinet *et al.*, 2015). The earliest record of possible depredation is a reference to a sperm whale caught in 1904 off the Shetland Islands that had fishhooks in its stomach [Millais, 1906, as cited in Santos *et al.* (1999)]. In the Gulf of Alaska (GOA), depredation of sablefish (*Anoplopoma fimbria*) on longline gear by sperm whales has been occurring since at least the mid-1970s, when observers on Japanese and American longline fleets observed depredation in the GOA (V. O'Connell, pers. comm.; G. van Vilet, pers. comm.).

The Alaskan sablefish fishery operated year round until the early1980s, when fleet expansion resulted in a shortened season. In 1994, the entire quota was caught in 2 weeks. In 1995, individual fishing quotas were implemented, reducing overall effort while expanding the open season to 8 months, from March to November. Although the fishery became better managed, the extended season provided more opportunity for sperm whales to associate with fishing vessels. By 1997, reports of depredation had increased dramatically (Hill *et al.*, 1999). Fishers reported having differing problems with whales: some were hit hard by many whales, and others had less of a problem. The reasons why were not evident. It was not clear whether there were 5 or 500 whales associating with the vessels as they hauled their gear back to their vessel. Some fishers reported whales sleeping next to their vessels or waiting during the soak at the buoy and vertical line marking one end of a set. Furthermore, no information existed on the numbers of whales involved in depredation, their movements, the sexes, or age classes. In fact, national marine fisheries service (NMFS) has noted a lack of data of North Pacific sperm whales in their annual stock assessment reports for the North Pacific (Allen and Angliss, 2013).

Depredation is a serious issue for fishers and managers on several levels. The major concerns are that depredation increases harvesting costs (including increased bycatch) and may result in negatively biased stock assessments. Depredation also poses a risk of entanglement and injury to sperm whales and jeopardizes the health of the resource by creating unknown removals during the commercial fishery and annual federal sablefish assessment surveys.

Directly related to these concerns are questions asked by fishers and managers regarding the numbers of whales involved in depredation: (i) Are whale numbers increasing? (ii) How do current whale numbers compare with historical numbers? (iii) How fast is this depredation behaviour spreading? The answers to these questions will have a direct bearing on the current and future impacts; sperm whales pose to the fishery and management of the sablefish resource, as well as the risk to sperm whales.

We do have insights into some of these questions. Reports of entanglements have been low with only one whale entangled and released in the Alaskan longline fishery as reported by the observer programme, 2007–2011 (Allen and Angliss, 2013). Recent investigations by Ivashchenko *et al.* (2013) have revealed inaccuracies in the numbers and sexes of sperm whales removed in the North Pacific as recorded by the whaling industry. The altered reports documented more whales and certainly more females than were initially reported.

It is evident that sperm whales were very abundant historically and were the primary species caught by Soviet whaling in the later 20th century in the North Pacific (Ivashchenko *et al.*, 2013). In the GOA, removals were numerous and in 1964 alone, over 1800 sperm whales were removed north of 50°N latitude (Doroshenko *et al.*, 1965, unpublished; Y. Ivashchenko, pers. comm.). No sperm whales were removed in this area by the Soviet catcher fleet after 1967. In the North Pacific, intense whaling by multiple nations significantly decreased the numbers of sperm whales (Mizroch and Rice, 2012; Ivashchenko *et al.*, 2013) and, as a result of whaling, sperm whales were and still are listed as an endangered species in US waters under the Endangered Species Act of 1973.

Today, in Alaskan waters, it is unknown if sperm whale numbers have increased since the end of commercial whaling. There are no abundance estimates for most areas in the North Pacific. We do know from visually monitoring the number of whales present at stations used for the annual federal sablefish survey from 1998 to 2010 that in the GOA, depredation has spread west and south (Schakner *et al.*, 2014).

Details regarding the sperm whales themselves give insights into diet; fish in some regions are the predominant component of their diet (Berzin, 1971; Clarke and Macleod, 1976; Kawakami, 1980; Gosho *et al.*, 1984; Rice, 1989). Kawakami (1980) reviewed sperm whale diets worldwide and found that fish were an important part of their diet in the northern and northeastern North Pacific, New Zealand, and the northern part of the North Atlantic. Stomach samples from specimens examined at whaling stations from whales caught in Alaska revealed that cephalopods were important food in the western Aleutians and Bering Sea, but that fish, including sablefish, became progressively more important as prey towards the eastern Aleutians and into the GOA (Okutani and Nemoto, 1964). In 1937, at Port Hobron on Kodiak Island in the central GOA, squid, octopus, and unidentified fish were found in the stomachs of 14 sperm whales, but no proportions were reported to give an idea of the dominant prey (Thomspon, 1940). In our study area, based on the stomach content data from whaling stations, sperm whales feeding upon sablefish are targeting a natural prey.

Further insights were gained when Mesnick *et al.* (2011), using single-nucleotide polymorphisms along with microsatellite genotyping and mitochondrial DNA methods, determined whales sampled near fishing vessels in the GOA were all males ($n = 19$) with clear results that they originated from not one, but multiple, populations in the North Pacific.

Whitehead (2003) emphasized that one of the largest gaps in our understanding of sperm whales is movements of the males. These males have variable patterns of movement while at high latitudes, then move almost continually at low latitudes, with repeat visitation to groups of females. This variable high latitude movement was shown by Straley *et al.* (2014) with satellite tags deployed on 11 whales in the eastern GOA during summer of 2007 and 2009. While all the whale's movements were associated with the shelf edge, the tag transmissions for nine whales documented these whales stayed in the GOA. One moved north and west in the GOA, one went to Canada and returned back to the tagged location, and others stayed along the shelf edge not moving far from where they were tagged. Three whales travelled to lower latitudes and followed no pattern in timing of departure (one departed immediately after being tagged in June, and the others in August and October). Two clearly had different destinations. One whale's movements ended two-thirds into the Gulf of California and another's tag stopped transmitting at 14°S offshore of the border of Mexico and Guatemala. This whale's speed had not slowed, indicating that the whale was still on a southbound trajectory. The third whale's tag stopped transmitting off Baja California before a destination could be determined. These data have shown that the movements and timing of departure for these males from the high latitude feeding areas in the GOA follows no obvious pattern and is variable among individual whales.

SEASWAP has had three phases: the early SEASWAP years were dedicated to understanding the behaviour and ecology of the whales associating with vessels in the GOA. Therefore, the first phase was working with the coastal fishing fleet in the GOA to collect quantitative data on longline depredation to describe the population of whales involved associating with vessels. Second phase brought acoustics into the study design and evaluated an acoustic metric of depredation. Third phase focused on deterrents and testing methods to reduce interactions between whales and vessels. NOAA and Alaska Department of Fish and Game (ADFG) fishery managers have been collaborators and supporters of SEASWAP, providing in-kind support to data collection.

This study presents results from the first phase of SEASWAP in four sections. The overall goal of this study (phase 1) was to assess the impact of depredation on the fishery, essentially assessing the magnitude of the problem. Presented first are data collected by commercial fishers regarding fishing and whale behaviour during the set, soak, and haul. Here we focus primarily on the haul data. We used these data to evaluate whether there was a vessel, area, or seasonal (month) effect in the presence and absence of sperm whales using catch per unit effort (*cpue*) as a metric. Second, using these *cpue* data, we conducted a spatial analysis to determine whether there was a nearest-neighbour effect. Third, to gain an understanding of the number of whales associating with vessels, we applied a mark-recapture analysis using individual identification photographs of sperm whales associating with commercial and NOAA survey fishing vessels in the GOA study area. The fourth and last section put our results in perspective with other similar studies. We used a meta-analysis and compared the loss in catch to other published studies on depredation by sperm whales globally. In addition, this study includes a list of all the papers published to date by SEASWAP.

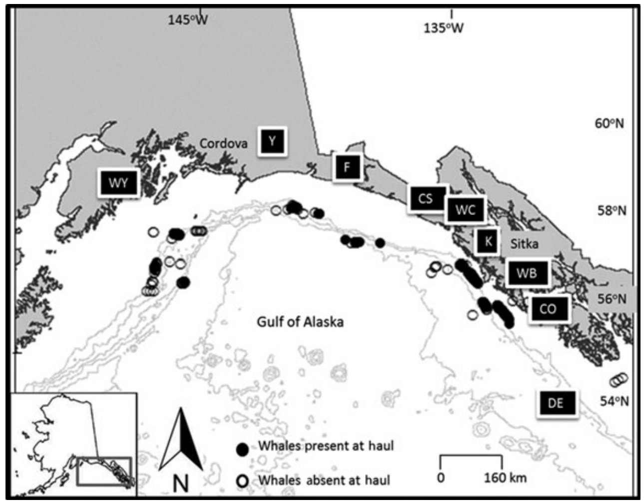

Figure 1. The SEASWAP study area is located along the shelf break in the GOA where longline fishing occurs. Eight fishers representing nine vessels monitored longline sets ($n = 319$) for the presence of whales and recorded other details of depredation from 2003 to 2007. The closed circles denote whale presence at the set during the haul and open circles signify the absence of whales. The black squares are the nine areas where fishers recorded fishing and whale behavioural data used for the comparison of *cpue* with and without whales present. The names were abbreviated on the map and represent the following areas: WY, West Yakutat; Y, Yakutat; F, Fairweather; CS, Cross Sound; WC, West Chichagof; K, Kruzof; WB, Whale Bay; CO, Cape Ommaney. The three sets made in Dixon Entrance (DE) and two in Whale Bay were excluded from comparisons of *cpue* by area, because the areas differed substantially from the characteristics of other areas along the edge of the continental slope edge.

Methods

All four sections of the first phase of SEASWAP presented in this study used data collected by the commercial fishing fleet with one exception. The estimate of the number of whales associating with vessels used data collected from the NOAA federal sablefish assessment survey as well as SEASWAP data. Methods generic to all four sections are provided followed by specific methods for each section.

General methods

Study area

The SEASWAP study area encompasses the continental slope 12–20 nm offshore Alaska, from about 56° to 59°N, latitude and 135° to 148°W, longitude, in the eastern GOA (Figure 1). Sitka is an ideal location to base SEASWAP, because the fishing grounds are easily accessible and much of the commercial fleet (primarily vessels <20 m) is based out of Sitka. The SEAWAP areas designated within the study area (Figure 1) were: WY, West Yakutat; Y, Yakutat; F, Fairweather; CS, Cross Sound; WC, West Chichagof; K, Kruzof; WB, Whale Bay; CO, Cape Ommaney, and DE, Dixon Entrance. NOAA data were collected following a systematic design by placing stations that are 30–60 km apart at depths of 150–1000 m that are sampled every year (www.afsc.noaa.gov/abl/mesa/mesa_sfs_lsd.htm) at the shelf edge. This area is the same general geographic area as fished by the commercial fleet, but with no overlap in data collection at the same specific locations because the fleet is restricted from fishing at the NOAA stations.

Description of commercial longlining

Commercial fisheries are Alaska's largest private sector employer and are critical to the state's economy. Longline fishing has been integral to coastal communities in Alaska for over 100 years. Demersal longline fishing consists of a line of baited hooks dropped to the seabed to fish for sablefish or other groundfish. The lengths of these sets typically range from 3 to 6 miles. A set is made of multiple segments, called skates, and a vertical line to the surface, with flagpole and buoys marking each end. Gear is deployed in depths between 200 and 1000 m, with the greater depths being selected for sablefish and shallower for halibut (*Hippoglossus stenolepis*). Fishing trips of 1–4 d are feasible for smaller vessels without freezer capability. The hooks are typically attached to the main longline, 13 mm diameter, with 1 m long lengths of narrow line called gangions. In the eastern GOA, the longline season for sablefish begins each year in early to mid-March and ends in mid-November.

Effort and data collection

Effort was reported as the number of sets fished for both the SEASWAP fishers and the NOAA survey vessel crew. Logbook data were used to quantify the depredation loss in *cpue*, compare to differences in depredation among and between vessels, and to describe depredation spatially, temporally, and seasonally, from 2003 to 2007.

Sablefish are assessed annually by NOAA Fisheries using a standardized, fishery-independent survey protocol (Hanselman *et al.*, 2014). Sampling occurs for 3 months in summer.

Evaluation of SEASWAP effort as representative of the entire fleet

We evaluated how representative our SEASWAP fishing effort was compared with the entire fleet. Comparing effort in terms of the average number of sets fished by each group (SEASWAP vs. entire fleet) would have been ideal; however, the number of sets for the entire fleet was not available. As an alternative, we used weight of catch as a proxy for effort. When each skipper sells their catch from a fishing trip, the weight is recorded on a fish ticket and reported by the fish buyer to the managing agency. While an individual vessels' catch was not public due to proprietary reasons (however, these data were provided by the quota share owner and used for *cpue* analysis), the combined catch for groups of vessels was available publically. The fish ticket data provided total weight of the catch of sablefish caught by area when sold at a port for (i) all vessels fishing within our eastern GOA study area and (ii) the SEASWAP vessels as a group. SEASWAP catch was then calculated as a percentage total catch by weight of the fish caught by the entire fleet. Using this method, we compared the percentages of catch in relationship with SEASWAP effort and evaluated if the results were a reasonable representation of the fleet's effort.

Determination of a whale in association with a vessel and defining depredation

Whales were determined to be associated with a vessel visually when observed surfacing within 500 m of the vessel, often confirmed with a laser rangefinder. This was the distance SEASWAP studies have documented as the divide between natural foraging behaviour and depredation (Mathias *et al.*, 2012). Sometimes, the whales slept near the vessel or were waiting at the vertical line and buoy marking one end of the set when the vessel arrived to haul the set. This behaviour was considered to be a whale in association with a vessel.

Depredation was noted visually by the presence of sperm whales near the vessel, repeatedly diving, often 15 min in duration. Sometimes, echolocation clicks and creaks were audible inside the baitshed on deck, especially if enclosed in aluminium, where the fishers work to set and haul fishing gear. A creak is a rapid series of clicks associated with prey detection by a sperm whale (Miller *et al.*, 2004; Watwood *et al.*, 2006). Acoustically, this was corroborated by a significantly higher creak rate when whales were within 500 m (Mathias *et al.*, 2012).

Visual evidence of depredation occurred when damaged sablefish were retrieved during haulback. Characteristics of damaged sablefish include missing body parts, shredded tissue, or lips remaining on hooks. Visual evidence confirmed the distance measurements and acoustic behaviour definition of depredation. The presence of empty hooks was not considered evidence of depredation.

Specific methods

SEASWAP logbook data

SEASWAP logbooks were designed and developed with assistance from the fishers. Logbooks were distributed to longliners interested in participating in this project, and detailed instructions and training occurred before participation in the programme. Logbook data included a detailed description of vessel and gear (including vessel hull type, electronics used, and hydraulic system), along with records of fishing activities and interactions with sperm whales. Example data recorded for this last situation included the number of mutilated fish recovered, and whether or not the skipper thought depredation occurred. Confidential envelopes were distributed and logbook pages collected at the end of each fishing trip, when ADFG port samplers offloaded fish, or at the end of the year. The Alaska Longline Fishermen's Association (ALFA) office entered and summarized the logbook data from nine SEASWAP vessels from nine SEASWAP areas (Figure 1) in the GOA from 2003 to 2007. The nine vessels were represented by eight fishers because one vessel was sold and another purchased during our study.

The vessel skippers communicated with the researchers regarding dates and locations of interactions. Core team members were trained in photographic techniques and data collection methods used for marine mammal behavioural studies. Each skipper reported the area fished, total catch, number of sets, number of skates, hooks per skate, the number of damaged fish per longline, and the type of damage (e.g. straightened hooks, heads, shredded bodies, etc.) in their SEASWAP logbook. These data were used to (i) describe the seasonal presence of whales by month associating with vessels and (ii) evaluate $\Delta cpue$ for each vessel with sperm whales present and absent during the haul.

Comparisons of mean *cpue* were made using both parametric and non-parametric hypothesis tests (Zar, 1984; Jennrich, 1995; Agresti, 2002; SAS9.2, 2014). *Cpue* was defined as the weight in kg of fish caught per 100 hooks. Fish were recorded in numbers by the fishers in the logbook and those numbers were converted to total weight using an average sablefish weight per hook (average weight from the commercial fishery is taken by port sampling of landed catch).

Therefore, each longline set *cpue* was defined as kg of sablefish per 100 hooks:

$$cpue = 100\frac{w}{hs},$$

where w is the weight of sablefish caught in kg from the vessel logbook recorded when sold or if only numbers of fish were available, an average weight per fish was used; h is the number of hooks per skate, and s is the number of skates per set. An average sablefish weight of 3.6 kg was used to convert fish per hook to weight per 100 hooks. Wald 95% confidence intervals (Zar, 1984) were computed from the difference in sample mean *cpue* $(\bar{x}_1 - \bar{x}_2)$, denoted $\Delta cpue$, by area and by vessel:

$$(\bar{x}_1 - \bar{x}_2) \pm t_{1-(\alpha/2),n_1+n_2-2,}s\sqrt{\frac{1}{n_1}+\frac{1}{n_2}},$$

where $t_{1-(\alpha/2),n_1+n_2-2}$ is the t statistic for significance level $\alpha = 1-0.95$ with $n_1 + n_2 - 2$ degrees of freedom, and where s is the square root of the pooled variance given by:

$$s = \sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2}}.$$

Here, s_i and n_i are the standard deviations and sample sizes, respectively, subscript $i = 1$ designates when there are no whales present at the gear, and subscript $i = 2$ designates when sperm whales are present at the gear.

Spatial analysis

Cpue data exhibited positive spatial correlation (Cressie, 1991), meaning that longline sets that were geographically close together had similar *cpue*. Spatial models were fitted including vessel effects, a sperm whale depredation effect, and a spatial lag effect (Haining, 2003). The spatial lag variable *cpue1* was the mean *cpue* of the neighbouring longline sets. Neighbouring pairs of longline sets are defined as those for which the Euclidean distance metric was <56 km:

$$d = \sqrt{(y_1 - y_2)^2 + (x_1 - x_2)^2} < 56 \text{ km},$$

where y is the latitude and x is the longitude of the longline set. Scatterplots of *cpue* vs. average *cpue* at locations less than d km reveal that spatial correlation becomes insignificant ($p > 0.05$) for distances >56 km. Hence, *cpue* at longline sets hauled closer than d km was considered dependent observations.

Maximum-likelihood estimation was used to fit all models (Haining, 2003). Likelihood ratio tests were used for model selection:

$$2(L_1 - L_0) \sim \chi^2_{\mathrm{df}=p},$$

where p is the difference in the number of parameters for the two models, and L is the log likelihood given by:

$$L = -\frac{1}{2}\left(\frac{k_i(y_i - \mu_i)^2}{\sigma^2} + \log\left(\frac{\sigma^2}{k_i}\right) + \log(2\pi)\right),$$

where y_i is the observed *cpue* for the ith observation, and μ_i is the linear predictor of the mean *cpue* dependent on a vector of explanatory variables such as area, whales present or absent, vessel, gear, and *cpue1* (defined as the mean *cpue* at sets within d km of the i_{th} location, but not including the *cpue* at ith location), and k is a weight used during model fitting. We assume that errors are distributed with a normal distribution. Akaike's information criterion (*AIC*) was used to select from various competing models:

$$AIC = 2p2 - L.$$

The depredation effect of sperm whales on *cpue* was estimated within the context of these spatial models with a contrast hypothesis test. Likelihood ratio tests were used to compare models with and without a given predictor variable (e.g. whale presence, area, and vessel).

Estimated number of sperm whales associated with vessels

Photographs of individual whales

Photographs of individually naturally-marked sperm whales observed near vessels were collected by SEASWAP (commercial fishers and researchers) from 2003 to 2014 and by NOAA biologists during the federal sablefish assessment surveys from 2006 to 2012. Effort was reported in days for dedicated research surveys or in days of fishing for fishers.

Photographs were taken with digital cameras of the ventral or dorsal surface of the flukes of each sperm whale encountered and used to identify individual whales, determine a minimum count, and to establish the sighting, or capture, history of each whale. A whale was assigned a unique number and each subsequent photograph of an individual was considered a recapture. These capture–recapture sighting histories were used to estimate the number of whales associating with vessels in the GOA study area each year from 2003 to 2014. The resulting estimate of abundance represented the population of sperm whales associating with vessels or actively interacting with the fishing fleet during our study. This was not an estimate derived for the entire GOA.

Bayesian mark-recapture analysis

In a Petersen experiment, the number of animals marked at the first period is n_1. At the second period, the number examined for marks is n_2.The number of marked recaptures m_2 at the second period was assumed to have a binomial likelihood:

$$f(m_2|\pi) = \frac{n_2!}{(n_2 - m_2)!m_2!}\pi^{m_2}(1-\pi)^{n_2 - m_2}$$

for which the proportion marked $\pi = n_1/N$. The prior distribution for this proportion was chosen to be a beta distribution, the conjugate prior of the binomial:

$$g(\pi|a, b) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}\pi^{a-1}(1-\pi)^{b-1}.$$

The prior parameters $a = 1$ and $b = 8$ were chosen for plausibility to conform to the beliefs of whale biologists about uncertainty in whale abundance. This choice results in the posterior distribution of the marked proportion also being a beta distribution, with the usual updating rule for the beta parameters (Gelman *et al.*, 2004):

$$a' = a + m_2$$
$$b' = b + n_2 - m_2.$$

Thus, the posterior distribution is $g(\pi|a', b')$. The expected value of the proportion marked is the mean of the beta distribution:

$$E(\pi) = \frac{a'}{a' + b'}.$$

The probability density function for population abundance was derived from this posterior distribution (Liddle and Quinn, 2007):

$$f_N(N) = \left[\frac{\Gamma(a'+b')}{\Gamma(a')\Gamma(b')}\frac{n_1^{a'}}{N^{a'+1}}\left(1 - \frac{n_1}{N}\right)^{b'-1}\right], N \geq n_1.$$

A more extensive description of the approach is available in Liddle and Quinn (2007).

Comparison of SEASWAP cpue *lost to depredation to other published studies*

A meta-analysis (Gurevitch and Hedges, 1999) was conducted which summarized five sperm whale depredation studies: Hill *et al.*, 1999; Purves *et al.*, 2004; Sigler *et al.*, 2008; and Hucke-Gaete *et al.* (2004) and the SEASWAP results. Depredation effects with 95% confidence intervals reported in the five studies were all converted to a common scale of fish lost per 100 hooks. We tested for homogeneity of the five depredation estimates with the Cochran's Q statistic (Cochran, 1954; Hedges and Olkin, 1985):

$$Q = \sum_{i=1}^{5} w_i(T_i - T)^2,$$

where T is the depredation effect over the five studies and T_i is the depredation estimate reported by the ith study, and w_i is the inverse of the variance of the ith depredation estimate. This test addressed the question whether the five results were homogeneous in size and direction. A grand mean of the five depredation estimates using sample sizes N_h as weights yielded an overall depredation effect:

$$\Delta cpue = \sum_{h=1}^{5} \frac{N_h \Delta cpue_h}{N}.$$

A bootstrap programme (Hedges and Olkin, 1985; Adams *et al.*, 1997; Gurevitch and Hedges, 1999) was written in the R programming language (R Core Team, 2014) to obtain a confidence interval for the grand mean. It was assumed that the five depredation estimates each had a Student's *t*-distribution such that:

$$t \sim T\left(\mu_i, \frac{s_i}{\sqrt{n_i}}\right),$$

where the *i*th *t*-distribution was centred at the depredation point estimate μ_i and with standard error given by $s_i/\sqrt{n_i}$. From each of the five *t*-distributions, 2000 realizations were resampled and the grand mean computed for each realization. A histogram of these 2000 bootstrap realizations of the grand mean yielded the 2.5th and 97.5th percentiles which were used to summarize the results of the meta-analysis (Adams *et al.*, 1997; Manly, 1997). The area under the histogram to the right of zero is the *p*-value for the overall sperm whale depredation effect in the meta-analysis (Adams *et al.*, 1997; Manly, 1997).

Results

Overall SEASWAP effort (number of sets)

The eight SEASWAP skippers, representing nine vessels, recorded fishing and whale behaviour data from 319 sets across nine areas in the eastern GOA (Figure 1) from 2003 to 2007. The nine SEASWAP vessels represented 2.8% of the total fleet of 322 permitted vessels fishing each year, on average, in the eastern GOA from 2003 to 2007. The 319 sets were distributed unequally across the nine areas (DE = 5; CO = 43; WB = 61; K = 81; WC = 18; CS = 15; F = 14; Y = 35; and WY = 47). The majority of the fishing effort occurred offshore of the vessels homeport of Sitka, where 58% (185/319) of the sets occurred in the combined areas of Kruzof, Whale Bay, and Cape Ommaney (K, WB, and CO on Figure 1). Yakutat and West Yakutat effort represented 11 and 14%, respectively, of the fishing sets by the SEASWAP participants. Dixon Entrance had the least amount of effort.

Evaluation if SEASWAP effort (as catch) was representative of the entire fleet

SEASWAP participants collectively caught 4% of the entire fleet's catch in the eastern GOA each year, except 2005 when 3% of the catch by weight was caught. While 4% represents the overall catch, fluctuations occurred by areas and years. Not surprising, 7–10% (mean = 8.3%, SE = 0.005) of the total weight of fish caught from 2003 to 2007 to the commercial fishery occurred in the areas just offshore of Sitka, the homeport for SEASWAP. Dixon Entrance had the lowest catch coupled with the fewest sets, as well.

SEASWAP logbook data

Seasonal presence of whales by month

The mean number of whales at the haul each month was revealed to be time-dependent (Figure 2). More whales were observed from April to July, than in March, August, or September. Whales joining the haul occurred with all vessels except one. That vessel fished at the start of the season (March); and the fact that no whales were present near his vessel during the haul may be a seasonal effect. Whales may not have yet arrived on the fishing grounds.

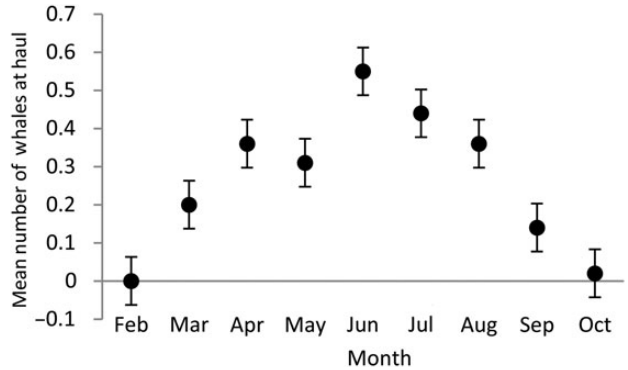

Figure 2. This bar graph shows the mean number of sperm whales associated with longline vessels at the haul during the 8-month sablefish fishery in the GOA, 2003–2007. Error bars represent 1 SE. Fewer whales were present near vessels at the start of the season and towards the end, with the peak in June. These data indicate that there may be a sperm whale peak seasonal presence from April to August.

Change in cpue by vessel and area in the presence or absence of sperm whales

Depredation by vessel

Sperm whales were present at 84 hauls of the 319 sets monitored by all fishing vessels regardless of area (Table 1). Three vessels suffered significant losses in *cpue* due to sperm whale depredation. Six vessels had non-significant effects when sperm whales were present at the haul.

Depredation by area

Sperm whales were present at the longline gear during the haul stage for 81 of the 314 sets along the shelf break. Five sets were excluded for this analysis because these areas were outside the geographic bounds of the study area and were dissimilar (near shore) compared with the other areas along the shelf break perimeter in the GOA. The presence of sperm whales at sets by area was variable, ranging from 19.4% at Cape Ommaney to a high of 35.0% at Kruzof (Table 2). Longline sets had significant reductions in *cpue* due to depredation by sperm whales at Cape Ommaney ($p = 0.0288$), Whale Bay ($p = 0.0256$), and Fairweather ($p = 0.0032$). Longline sets in the areas Yakutat ($p = 0.0221$) and Cross Sound ($p = 0.0178$) had significantly higher *cpue* when whales were present (Table 2). The West Chichagof area had a non-significant increase in *cpue* in the presence of whales. West Yakutat and Kruzof had non-significant reductions in *cpue*.

Spatial analysis

Geographic information system (GIS) analysis provided visual evidence that sperm whale depredation events were tightly clustered near the continental shelf break (Figure 1). *cpue* had significant spatial correlation ($r = 0.16$, $p = 0.0043$) with *cpue1*, the average *cpue* at neighbouring sets (Figure 3).

Using *AIC*, we found that the best fitting model accounts for spatial dependence (*cpue1*), the categorical vessel effect, and sperm whale depredation. This model can be described with a linear predictor of the form: $\mu_{cpue} \sim \alpha 0 + \alpha_1 cpue1 + \alpha_2 Vessel + \alpha_3 Whales$, where μ_{cpue} is the expected value of *cpue* for a longline

Table 1. Mean *cpue* in kg per 100 hooks for $n = 319$ longline sets fished by nine vessels, with and without sperm whales present, in the GOA, 2003–2014.

Vessel		V1	V2	V3	V4	V5	V6	V7	V8	V9
Interaction rate %		31.6	47.8	28.6	31.0	28.6	47.8	15.4	25.0	17.8
Mean latitude		56.3	56.5	56.5	56.9	57.0	57.2	57.7	58.4	58.7
	n	13	12	15	20	10	12	66	51	37
Whales	(SE)	(−4.7)	(−8.9)	(−7.6)	(−7.9)	(−3.7)	(−2.7)	(−1.5)	(−4.1)	(−4.4)
Absent	*cpue*	68.3	70.8	56.4	63.7	52.3	61.0	30.3	82.3	63.5
Difference	$\Delta cpue$	−1.6	−22.1	−28.0	8.2	−2.0	−18.5	0.9	−28.8	−1.5
	$(SE_{\Delta cpue})$	(−10.6)	(−12.6)	(−11.6)	(−17.7)	(−9.9)	(−5.4)	(−9.5)	(−7.4)	(−11.2)
	p-value	0.8696	0.098	0.0484	0.6094	0.8117	0.0022	0.8704	0.0022	0.8862
	cpue	66.7	48.8	28.4	71.9	50.3	42.5	31.1	53.5	62.0
Whales	(SE)	(−9.4)	(−8.9)	(−8.8)	(−15.9)	(−9.2)	(−4.7)	(−9.3)	(−6.1)	(−10.3)
Present	*n*	6	11	6	9	4	11	12	17	8

Interaction rate is calculated as the number of whales present over the total number of sets. Standard errors are given in parentheses.

Table 2. Mean *cpue* in kg per 100 hooks for $n = 314$ longline sets in eight areas, with and without sperm whales present in the GOA, 2003–2007.

Area		Cape Ommaney	Whale Bay	Kruzof	West Chichagof	Cross Sound	Fairw eather	Yakutat	West Yakutat
Interaction rate %		16.3	26.2	34.6	16.7	20.0	28.6	28.6	21.3
Mean latitude		56.4	56.5	57.1	57.4	58.2	58.4	59.2	58.7
	n	36	45	53	15	12	10	25	37
Whales	(SE)	(−5.8)	(−5.2)	(−4.1)	(−5.1)	(−3.7)	(−4.4)	(−4.1)	(−4.4)
Absent	*cpue*	71.2	68.6	53.4	46.0	32.8	52.2	43.5	63.5
Difference	$\Delta cpue$	−32.1	−22.5	−2.0	22.5	24.8	−31.5	19.4	−10.6
	$(SE_{\Delta cpue})$	(−12.5)	(−9.1)	(−7.9)	(−8.9)	(−12.2)	(−9.0)	(−8.8)	(−9.7)
	p-value	0.0288	0.0256	0.7909	0.0794	0.0178	0.0032	0.0221	0.2681
	cpue	39.1	46.1	51.4	68.5	57.6	20.7	62.8	52.9
Whales	(SE)	(−11.5)	(−7.5)	(−6.8)	(−7.3)	(−11.7)	(−7.8)	(−7.8)	(−8.7)
Present	*n*	7	16	28	3	3	4	10	10

Interaction rate was calculated as the number of whales present over the total number of sets. Standard errors are given in parentheses. Not included were five sets fished at near shore locations in coastal waters with no characteristics (e.g. not on the continental shelf break) of the other areas used in this analysis.

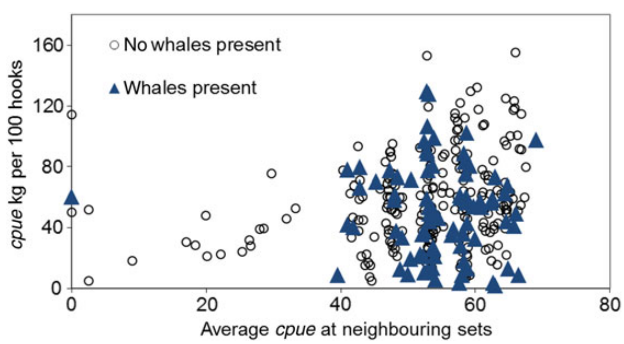

Figure 3. Comparison of *cpue* as kg per 100 hooks vs. average *cpue* at neighbouring longline sablefish sets in the GOA, 2003–2007. Fishers used logbooks to report details of their fishing efforts, catch, and the presence or absence of whales. The average *cpue* quantity equals the average of all geographically neighbouring sets regardless of year. Triangles indicate sets with whales present and open circles show sets where whales were absent. Results suggest that whale presence occurred at larger values of average *cpue*, suggesting that the whales, on average, know where the better fishing grounds are located as do some, but not all, fishers.

set with a given spatial lag effect *cpue1*, a given vessel, and *Whales* is the presence of sperm whales. Sperm whale depredation was estimated within a model that accounted for spatial dependence. The fishing vessel V4 was used to provide a baseline *cpue* for depredation, having the least negative impact in *cpue* (Table 1) from whale presence. This baseline, represented by the intercept α_0, was the expected value of *cpue* for which other vessels were compared (Table 3). Spatial dependence is represented by *cpue1*, the mean *cpue* at neighbouring sets, and had an effect size of 0.13 ($\pm$0.06) per kg per 100 hooks ($p = 0.0290$). Thus, the large values of *cpue1* are associated with large expected values of *cpue*. When sperm whales were present at the longline gear, there was a significant depredation effect ($p = 0.0007$) in *cpue* of −11.10 kg per 100 hooks (Table 3).

Estimated number of sperm whales associated with vessels

During 2003–2014, 115 individual whales were photographed by SEASWAP and NOAA. The Bayesian mark-recapture abundance model estimated $\hat{N} = 135$ (95% *CI* 124, 153) sperm whales in the GOA in 2014 (Table 4 and Figure 4). A discovery curve was used to plot the cumulative number of whales sighted each year plotted with effort in days (Figure 5). New whales have been seen each year with the curve levelling off towards the lower bounds of the estimated abundance of 124 sperm whales.

Comparison of SEASWAP depredation with other studies

The results of five sperm whale depredation studies from both hemispheres, Hill *et al.* (1999), Purves *et al.* (2004), Hucke-Gaete *et al.* (2004), Sigler *et al.* (2008), and the SEASWAP result, were converted into a common scale of fish lost per hook (Figure 6 and Supplementary Appendix 1). The plot of these confidence intervals

Table 3. Depredation was assessed from parameter estimates for spatial, vessel, and whale effects for $n = 319$ longline sets in the GOA.

Effect	$\hat{\alpha}$	SE	χ^2	*p*-value
Intercept	53.56	8.74	37.54	<0.0001
cpue1	0.13	0.06	4.77	0.0290
V8	9.87	5.53	3.19	0.0743
V7	−35.40	5.52	41.18	<0.0001
V2	−3.43	6.96	0.24	0.6223
V9	−2.00	6.04	0.11	0.7407
V1	2.69	7.35	0.13	0.7138
V6	−11.51	6.97	2.73	0.0985
V3	−19.24	7.14	7.27	0.0070
V5	−15.19	8.08	3.53	0.0603
V4	Baseline			
Sperm whales	−11.10	3.27	11.54	0.0007

The fishing vessel V4 having the lowest depredation impact (Table 1), provided a baseline cpue, represented by the intercept α_0, with which the expected value of cpue compared with other vessels. Spatial dependence was represented by cpue1, the mean cpue at neighbouring sets. The depredation effect due to sperm whale presence was estimated within the context of the model, thus controlling for all vessel effects and spatial dependence. Likelihood ratio tests were reported in the last two columns.

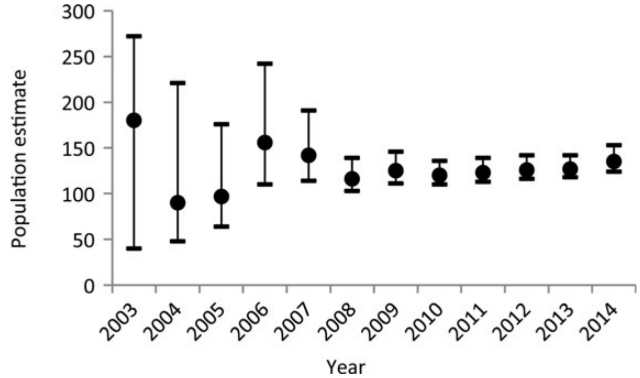

Figure 4. A Bayesian mark-recapture abundance model for small populations was used to estimate the annual number of sperm whales following longline vessels in the eastern GOA, 2003–2014. Each year the sample size for all sperm whales sighted and recaptured was used to derive an estimate ($\hat{N}$) with 95% upper and lower confidence levels (see Table 4 estimates for each year). The 2014 population size for sperm whales in our study was $\hat{N} = 135$ (95% *CI* 124, 153).

Table 4. A Bayesian mark-recapture abundance model for small populations was used to estimate the annual number of sperm whales following longline vessels in the eastern GOA, 2003–2014 (Liddle and Quinn, 2007).

Year	n_i	m_i	$\hat{N}$ (*LCL*, *UCL*)
2003	15	0	180 (40, 272)
2004	26	5	90 (48, 221)
2005	17	6	97 (64, 176)
2006	43	10	156 (110, 242)
2007	23	14	142 (114, 191)
2008	20	20	116 (103, 191)
2009	31	19	125 (111, 146)
2010	16	15	120 (110, 136)
2011	15	11	123 (113, 139)
2012	17	13	126 (116, 142)
2013	12	10	127 (118, 142)
2014	10	5	135 (124, 153)

Each year the sample size for all sperm whales sighted and recaptured was used to derive an estimate ($\hat{N}$) with 95% upper and lower confidence levels.

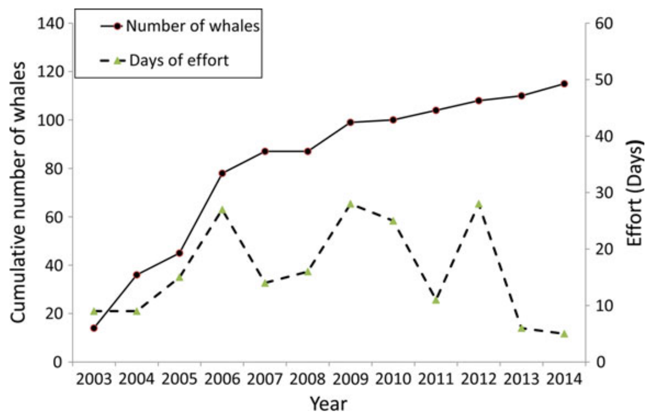

Figure 5. Whale discovery curve showing the cumulative total number of new whales sighted and corresponding days of effort for each field season in the GOA. The curve levels off towards the lower bounds of the estimated abundance [$\hat{N} = 135$ (95% *CI* 124, 153)] of sperm whales in the eastern GOA.

(Figure 6) is a type of funnel plot used to assess effect size and direction vs. sample size (Gurevitch and Hedges, 1999). An immediate observation was that all five point estimates are very close together, and that ~3% or less of the catch was lost in each study. However, Sigler *et al.* (2008), Purves *et al.* (2004), and Hill *et al.* (1999) all had standard errors that were sufficiently large so that a statistically non-significant loss in catch was reported.

The bootstrap distribution of the grand mean of the five depredation estimates (Figure 7) showed that there was a small yet significant overall depredation effect of 2.54% of the fish lost when sperm whales were present. The 95% percentile confidence interval for the grand mean of depredation estimates was (4.70, 0.41%). The *p*-value of this overall depredation estimate was the area of the histogram (Figure 7) exceeding zero or $p = 0.0105$.

Discussion

We believe that data gathered by the nine vessels and skippers used in our analysis were characteristic of the fleet. SEASWAP vessels were a mix of small, large, differing fishing schedules and gear types used (fixed vs. snap on hooks). The determination that these data were representative of longline fishing in the GOA was further supported by the fact SEASWAP that while vessels were represented in 2.8% of the overall fleet, but caught 3–4% of the total catch.

The data collected by fishers and reported in logbooks created a valuable comparison among and within vessel operational parameters. Essentially, every vessel had differing operational parameters and quantifying differences among vessels was difficult. We found that the loss in catch due to sperm whale depredation varies with the time of year, vessel, and/or the area where the fishing occurred. Some vessels seem to actually do better when compared with the vessel group as a whole, when sperm whales were present.

Fishers and their vessels have specific characteristics, including the skippers experience, gear used, the extent to which the fish are processed on board, hull design, differences in equipment, and engine type. The effects of these factors on depredation are all confounded in the vessel effect and cannot be separated out with the

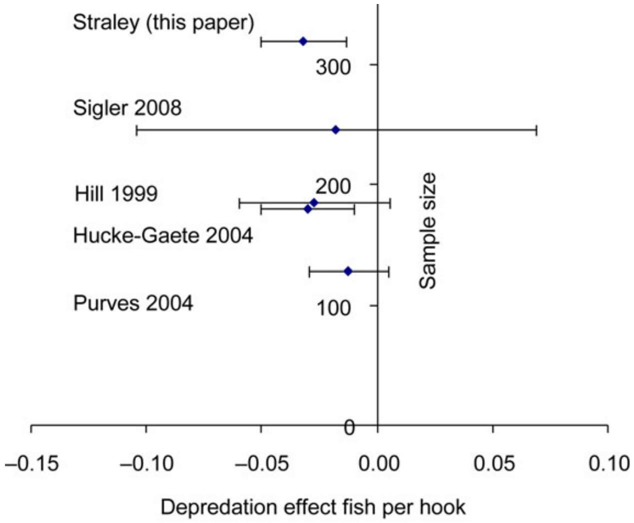

Figure 6. This funnel plot shows the comparative confidence intervals for reduction in *cpue* from five studies on sperm whale depredation vs. sample size. Depredation estimates from all five studies were expressed in fish lost per hook. See Supplementary Appendix 1 for details on how the metric for evaluating depredation was made comparable across the five studies.

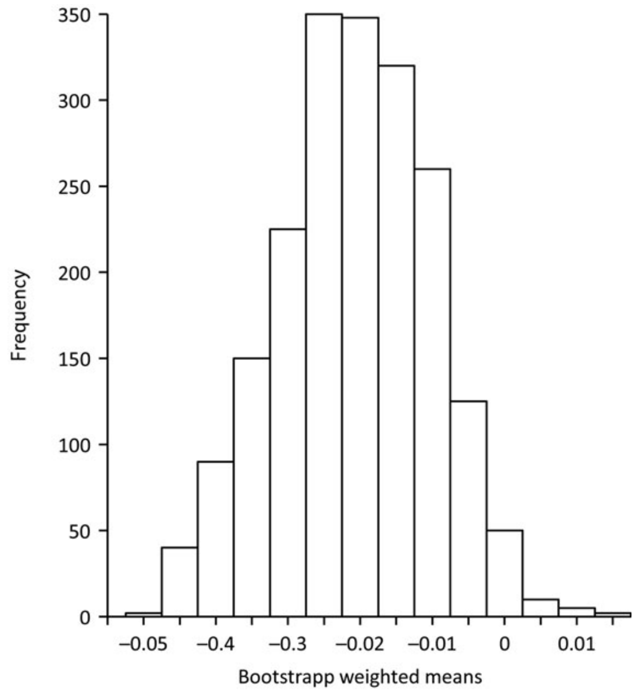

Figure 7. Bootstrap distribution of the grand mean of five sperm whale depredation estimates. The weighted mean of the depredation effect was 0.0254 fish per hook was lost to sperm whale depredation. The area of the histogram to the right of zero is 0.0105 and indicates the *p*-value of the depredation estimate.

current dataset. Parallel research in the Southern Ocean has found similar issues (Roche and Guinet, 2007; Guinet *et al.*, 2015).

The depredation effect due to sperm whale presence was estimated within the context of the model, thus controlling for all vessel effects and spatial dependence. A model that ignores spatial dependence would underestimate the standard error of the depredation effect. The spatial analysis approach was more conservative, with larger standard errors then if this effect had been ignored.

The estimated lower and upper bounds (4.67–16.16 kg per 100 hooks) of fish lost to depredation is a large economic loss to the fisher. With a mean of 2300 hooks per set, and a sablefish price of $2.34–3.09 per kg ($5.30–$7 per pound, 2014 dock price Southeast Alaska), the economic loss is on the upper order of $955–1180 US dollars per set. Even the lower bound of 4.67 kg per 100 hooks is significant at about $270–$330 US dollars per set. This accounting is only for fish lost during the presence of whales and does not account for added costs of increased effort for a fisher to catch their quota. Peterson *et al.* (2014) added these additional costs for fuel and crew at $500 per day on longlines from killer whale depredation, further west in the GOA and Bering Sea. The economic loss is not trivial. Interestingly, the Uruguayan longline fishing industry has a low level of depredation, measured by the percentage of total fish caught damaged by killer whales (*Orcinus orca*) and false killer whales (*Pseudorca crassidens*) with minor economic loss to the Uruguayan longline fishing industry study analyses depredation; Passadore *et al.*, 2015].

While comparing *cpue* in the presence and absence of whales provided insights to fishing and foraging choices, it is, however, not the best metric for depredation for our study. This was because the whales and fishers knew the best areas to fish and consequently fishers caught more fish with whales nearby than in the absence of whales. This has been observed, as well, in the Southern Ocean near the Crozets, where *cpue* was higher when sperm whales were present (Roche and Guinet, 2007). This was a confounding factor in using *cpue* as a metric for depredation.

Empty hooks presented a problem in determining if depredation occurred because of SEASWAP findings that a sperm whale can create line tension and pop a fish off a hook (Mathias *et al.*, 2009), documenting that an empty hook could be the result of depredation. This was a difficult assessment because empty hooks can also indicate lost bait, not lost target fish. Also, sablefish are a soft mouthed fish, as are Patagonian toothfish, and are easily pulled or can "spin" naturally off the hook. In our study, sperm whales benefited by being close to the line when spinoffs occur as reported in Mathias *et al.* (2012).

The GIS study showed that sperm whales stayed fairly close to the continental shelf break, which are the preferred longline fishing grounds. Also, sperm whales are much more likely to be at the gear when *cpue 1* is high (Figure 3). Thus, the areas that are considered best for fishing are also the best for encountering sperm whales.

After an initial surge of whales identified during the early years of SEASWAP, the discovery of new whales slowed considerably. Although the estimated numbers of whales in the SEASWAP study area is not large and will likely not come close to historical levels of hundreds of sperm whales roaming these waters, there are complexities to understanding the magnitude of the problem. The number of sperm whales involved in depredation is likely a subset of the estimated population size of sperm whales because not all whales are engaged in depredation when near a vessel. SEASWAP studies using satellite (Straley *et al.*, 2014; SEASWAP, unpublished data) and bioacoustics tags (Mathias *et al.*, 2012) documented some whales were near vessels but not necessarily removing fish off the line. Fishers and the NOAA biologists from the federal surveys have reported this as well. Some whales may target discard and others are naturally foraging and just happen to be near a vessel's gear. However, the most sperm whales in the GOA near a vessel are removing fish from longlines, but not all whales are depredating equally. Some individual whales are very skilled at depredation (SEASWAP fleet observations). As SEASWAP builds sighting histories and associations of individual whales and documents the behaviour and the level of interactions with vessels, patterns will emerge. These details will allow a better measure of the magnitude of depredation in the GOA. Deterrence or reducing interactions still will be challenging and a suite of tools will need to be considered dependent on the whales involved.

The SEASWAP study had several advantages over the other studies described in the meta-analysis (Figure 6 and Supplementary Appendix 1). Data collection was especially targeted towards estimating sperm whale depredation of sablefish longline gear. SEASWAP made use of commercial vessels as a platform for collecting data on sablefish and sperm whale behaviour. This partnership between commercial fishers and scientists was cost effective and allowed gathering a much larger sample size than would otherwise be possible. As a result, the SEASWAP sample size was considerably larger than all the other studies leading to greater power to detect the small depredation effect. The grand mean estimator favours the result with the largest sample size.

The meta-analysis developed naturally during the review of the results of comparative studies and is of great interest because getting a realistic metric for removal of fish off the gear is challenging. Two of the present authors (Straley and Liddle) were also involved with the Sigler *et al.* (2008) study conducted in the same geographic area but used the federal survey depredation data, whereas the results reported here were from commercial fisheries data. The meta-analysis incorporated the five sample sizes, the five sample variances, and the sizes of the five depredation estimates (Figure 6; Hedges and Olkin, 1985; Gurevitch and Hedges, 1999).

We suspect that differences in study design, type of fishery, the fish species, and the regions influenced the five results. For example, the two NOAA studies, Sigler *et al.* (2008) and Hill *et al.* (1999), were tangential to a sablefish stock assessment. The Purves *et al.* (2004) and Hucke-Gaete *et al.* (2004) studies were directed at depredation of Patagonian tooth fish in South American waters, by both sperm whales and killer whales. These situations are sufficiently different that it would be very surprising if the five depredation results were all the same with similar standard errors.

Our approach to the meta-analysis using the bootstrap was parallel with a mixed model approach (Adams *et al.*, 1997; Gurevitch and Hedges, 1999), where variability was assumed to be from differences between the studies as well as a sampling error. This was a more conservative approach resulting in the larger standard errors in the overall depredation estimate. It is a non-parametric randomization approach; hence, there was no need to specify a model describing exactly how the five studies were related to each other.

Future directions

Clearly, sperm whales eating fish off a longline as it is hauled back to the fishing vessel are not natural foraging behaviour (at least not historically, before humans fishing for deepwater species). The fishing vessel is an attractant for whales that, as individuals, may not typically associate with each other. In such instances (having multiple whales in the same vicinity feeding off a longline), much can be learned about their feeding behaviour such as prey preferences. [They leave rockfish, (*Sebastes* spp.), a spiny fish, and sometimes only bite halibut leaving teeth marks.) Bite marks on a fish could indicate the whale unintentionally or intentionally released the fish while hooked. Regardless, this demonstrates that quantifying and assessing removal of fish by whales off a longline has not been a straightforward task.

The association of whales with vessels may be artificial biologically, but this behaviour allows an opportunity to learn about sperm whale movement, prey acquisition, and social structure, among others. In the northern latitudes where sperm whales are not usually found in groups, multiple genetic tissue samples obtained from groups near fishing vessels will provide insights in defining who these whale are and how they fit into the bigger picture for sperm whales in the North Pacific. It is unknown how related or connected these whales are to each other.

Working with the fishing industry as full research partners and the managers of the sablefish fishery has increased our understanding of depredation significantly. Future directions for our studies include placing cameras on a longline to capture how a fish is removed from the line by a whale, developing an acoustic (or other) metric to better quantify removals and continuing to test potential deterrents or other methods to reduce interactions. SEASWAP will continue to work towards reducing interactions, improving management of sablefish fisheries, and gaining an understanding of the role of sperm whales within the ecosystem of the GOA. SEASWAP has ongoing partnerships with other fisheries groups (Central Bering Sea Fisheries Association and Hawaii Longline Fishermen's Association). Unlike many attempted solutions to problems where stakeholders are not engaged early in the process of finding a solution, SEASWAP included the fishers (stakeholders) from the beginning. SEASWAP should be considered as a model for building partnerships and working collaboratively towards finding solutions to marine mammal interactions with fisheries issues in other areas, with not only sperm whales but also with other species as well.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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conduct ethical research on vertebrates by the Institutional Animal Care and Use Committee (IACUC), University of Alaska Fairbanks, to JS under NOAA permit (14122) and IACUC protocol (08-07).

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