Fisheries Research 200 (2018) 75–83

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Sperm whale depredation on longline surveys and implications for the assessment of Alaska sablefish

Dana H. Hanselman[a,*], Brian J. Pyper[b], Megan J. Peterson[a,c]

[a] Auke Bay Laboratories, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, 17109 Point Lena Loop Rd., Juneau, AK, 99801, USA
[b] Fish Metrics, 184 Park Drive, Salt Spring Island, B.C., V8 K 2R7, Canada
[c] Science Department, Sierra Nevada College, 999 Tahoe Blvd, Incline Village, NV, USA

ARTICLE INFO

Handled by A.E. Punt

Keywords:
Sablefish
Stock assessment
Sperm whale
Economic value
Depredation
Generalized linear mixed models

ABSTRACT

Sperm whales (*Physeter macrocephalus*) in the Gulf of Alaska depredate (remove or damage fish caught on fishing gear) on the annual National Marine Fisheries Service's longline survey. Depredation can reduce sablefish (*Anoplopoma fimbria*) catch rates and increase uncertainty in survey-derived estimates of sablefish biomass. Using 27 years of longline survey data, this study: 1) evaluates fixed- and mixed-effects generalized linear models to estimate the effects of sperm whale depredation on the sablefish survey abundance; and 2) evaluates the impact of accounting for sperm whale depredation in the sablefish stock assessment. Model evaluation and simulations showed that mixed-effect models were far superior to fixed-effect models in terms of precision and confidence interval coverage. The estimated reduction in sablefish catch rate due to depredation was approximately 15%, which was considerably higher than previous estimates. Correcting for sperm whale depredation in the assessment resulted in a 2% increase in estimated female spawning biomass in the terminal year and a 3% higher quota recommendation, valued at approximately US $3 million. Accounting for sperm whale depredation in the sablefish assessment should be done in concert with estimating the increase in fishing mortality caused by depredation in the commercial fishery.

1. Introduction

Sperm whale (*Physeter macrocephalus*) depredation (whales removing or damaging fish caught on fishing gear) is a key management concern for the National Marine Fisheries Service's (NMFS) longline survey and the Alaska commercial sablefish (*Anoplopoma fimbria*) fishery (Hanselman et al., 2016; Peterson and Carothers, 2013). There have been many studies with observations of mammal depredation on longline fisheries (e.g., Ashford et al., 1996; Secchi and Vaske, 1998; Nolan et al., 2000; Rabearisoa et al., 2015, Dalla Rosa and Secchi, 2007). The majority of the published research has examined interactions with killer whales, and much of the literature is focused on mitigation and deterrence strategies (Werner et al., 2015). However, very few studies outside of Alaska have attempted to quantitatively estimate the effect of depredation on catch-per-unit-effort on longline fisheries or surveys. The several quantitative studies that exist are based on fishery data and use *t*-tests (Purves et al., 2004), GLMs (Clark and Agnew, 2010; Passadore et al., 2015), or GLMMs (Tixier et al., 2016).

Sperm whale depredation, specifically, is a global issue that has also been documented in the Southern Ocean, associated with Patagonian toothfish (*Dissostichus eleginoides*) fisheries (Ashford et al., 1996; Purves et al., 2004; Roche et al., 2007; Tixier et al., 2010), and in North Atlantic Ocean fisheries for Greenland halibut (*Reinhardtius hippoglossoides*; Dyb, 2006; Mesnick et al., 2006). This study evaluates several statistical models for estimating sperm whale depredation on the NMFS longline survey and examines the implications of including sperm whale depredation in the sablefish stock assessment.

Sperm whale depredation on the commercial fishery and NMFS longline survey generally occurs in the central and eastern Gulf of Alaska (GOA), impacting sablefish and Pacific halibut (*Hippoglossus stenolepis*) catches during haulback of demersal longline fisheries. Observations of depredation are relatively recent, starting in the mid-1980s for the commercial longline fishery in Alaska and enumerated since 1998 for the NMFS longline survey (Straley et al., 2014). In contrast to killer whale (*Orcinus orca*) depredation in western Alaska, which has a strong negative effect (54–72%) on catch per unit effort (CPUE) (Peterson et al., 2013, 2014), the most recent study of sperm whale depredation on the NMFS longline survey estimated small ($\sim -2\%$) effects on sablefish CPUE (Sigler et al., 2008). Our analysis improves upon that of Sigler et al. (2008) by incorporating observations

* Corresponding author.
E-mail addresses: dana.hanselman@noaa.gov (D.H. Hanselman), brianpyper@gmail.com (B.J. Pyper), mpeterson@sierranevada.edu (M.J. Peterson).

https://doi.org/10.1016/j.fishres.2017.12.017
Received 17 July 2017; Received in revised form 27 December 2017; Accepted 29 December 2017
Available online 04 January 2018
0165-7836/ Published by Elsevier B.V.

from additional years and utilizing a mixed-effects statistical model to better estimate depredation effects.

Sablefish are a deep-dwelling, commercially valuable species in the northeastern Pacific that have been targeted by domestic and foreign fisheries since the early 1900s (Hanselman et al., 2016; McDevitt, 1986; Sasaki 1985). The 2014 catch of 11,580 t had an ex-vessel value of U.S. $98 million (Fissel, 2014), making sablefish one of the most valuable ($/kg) species in the region. The commercial sablefish fishery in Alaska federal waters has been managed under an Individual Fishing Quota (IFQ) system since 1995. The fishery is open each year from roughly mid-March to mid-November, and NMFS conducts a sablefish stock assessment annually between September and November. The current stock assessment model fits three active abundance indices (the longline survey evaluated in this study, a bottom trawl survey, and the US commercial longline fishery), and two historical abundance indices (the Japanese longline fishery and Japan-US cooperative longline survey; Hanselman et al., 2016). A recommended catch limit for the following year, called the Allowable Biological Catch (ABC), is calculated by applying a target fishing mortality rate to the estimate of present abundance projected for the next year. The ABC is then used to determine IFQ limits for the commercial fishery.

Currently, stations impacted by sperm whale depredation are included in the stock assessment, whereas skates (100 m section of longline with 45 hooks) impacted by killer whales are excluded from abundance calculations because the killer whale effect is easier to detect and typically severe (Peterson et al., 2013). However, there is concern that failing to account for removals of survey sablefish due to sperm whale depredation could result in biased assessment results (Hanselman et al., 2016). Biases in assessment results would only occur if there was a temporal trend in depredation on the survey, because the survey is used as an index of abundance in the assessment model and catchability is estimated. We show in this study that incidences of sperm whale depredation have increased over time, and hence, it is important to evaluate potential assessment biases due to depredation. However, estimating catch losses attributable to sperm whale depredation can be difficult because depredation does not always leave evidence, such as damaged fish or hooks on the fishing gear (Clark and Agnew, 2010; Peterson, 2014; Tixier et al., 2010). Additional challenges include variable catch rates, the sporadic nature of sperm whale depredation, which creates a highly unbalanced design, and correlation within and among longline survey station data. Several prior studies of whale depredation from this region utilized fixed-effects models (Hanselman et al., 2010; Hill et al., 1999; Straley et al., 2005; Peterson et al., 2013). However, analysis of unbalanced designs using fixed-effects models can result in poor estimation and inference compared to mixed-effects models (Garson, 2012).

Thus, in this study, we first compared the performance of Generalized Linear Mixed Models (GLMMs) with fixed-effects Generalized Linear Models (GLMs) traditionally used for estimating changes in CPUE due to sperm whale depredation, while accounting for covariates such as depth and location. Second, we evaluated the management implications of incorporating the sperm whale depredation effect into the annual Alaska sablefish stock assessment.

2. Materials and methods

2.1. Longline survey data collection

NMFS sablefish longline survey stations in the GOA have been sampled every year from June to August, 1990–2016. Survey stations generally align with sablefish commercial longline fishing grounds along the continental slope and are systematically spaced approximately 30–50 km apart (Fig. 1) (Peterson et al., 2013; Sigler et al., 2008). In a given year, each station was fished for one day from shallow to deep (depths ranging from roughly 150–1000 m) using two sets hauled end to end (Peterson et al., 2013). Each set consisted of 80 skates (string of 45 hooks), providing a total of 160 skates (7200 hooks) fished per station. Depth was recorded every fifth skate and interpolated for all other skates. Hooks were spaced 2 m apart and baited with squid. Upon retrieval, hooks were deemed "ineffective" if they were straightened, snarled, bent, or in any way unable to fish correctly (Hanselman et al., 2016; Peterson et al., 2013). While it is conceivable that some "ineffective" hooks could be caused by whale depredation, the proportion of ineffective hooks in the data was small (1.8%) and because these hooks are excluded in the abundance calculations, we excluded them in our analysis as well. Gully stations, which are stations that sample shallower cross-shelf habitat, were excluded because most are not used in the abundance index, are rarely affected by whale depredation, and are only weakly correlated with overall trends in CPUE (Hanselman et al., 2016). At each station, sablefish catch, effort, age, length, weight, and maturity data were collected (Hanselman et al., 2016).

Indicators of potential sperm whale interactions with the longline survey were collected starting in 1998. Two indicators were tracked at the station level: 1) "presence" of sperm whales (e.g., sightings within 100 m of the vessel); and 2) "evidence" of depredation, when sperm whales were present and retrieved sablefish were damaged in characteristic ways (e.g., missing body parts, crushed tissue, blunt tooth marks, shredded bodies). Damaged fish caused by other animals (e.g., sea lions and sharks) are rare for both the survey and the fishery. Incidences of sperm whale depredation on the longline survey have been frequent in the Central Gulf of Alaska (CGOA), West Yakutat (WY), and East Yakutat/Southeast (EY/SE) management areas (Fig. 1), but rare in the Bering Sea, Aleutian Islands, and Western Gulf of Alaska (Hanselman et al., 2016; Sigler et al., 2008). These previous studies have examined both the "presence" and "evidence" indicators, but our modeling showed that the "evidence" flag provided stronger inferences, so we largely focus on that indicator in this study.

The longline survey data are used to derive annual estimates of relative population numbers (RPN, an abundance index) for use in the sablefish stock assessment model (Hanselman et al., 2016). The RPN indices are computed by management area across five depth strata considered to be in exploitable habitat (200–300 m, 300–400 m, 400–600 m, 600–800 m, and 800–1000 m). Specifically, sablefish CPUE data are computed for each station and depth stratum by dividing total catch by the number of effective hooks fished. To estimate RPNs by management area, the CPUE data are then averaged across stations, multiplied by strata-specific habitat area sizes, and summed across depth strata.

2.2. Spatial and temporal patterns

Data analysis and modeling were limited to stations in the three areas with prevalent evidence of sperm whale depredation: CGOA (16 stations); WY (8 stations); and EY/SE (11 stations). These three areas contained 98% of the sperm whale depredation events across survey stations (Hanselman et al., 2016). For each area, logistic regression was used to assess time trends in the annual proportion of stations with sperm whale presence or evidence of depredation. To facilitate model development and interpretation, we first assessed patterns of variation in sablefish CPUE. We computed annual means of CPUE by station and standardized each index to have a mean of zero and standard deviation of one across years. The 35 standardized CPUE indices were then used in a principal components analysis (PCA; Dunteman, 1989) to assess the dominant spatial and temporal patterns in CPUE across stations and years. Full results and discussion from the PCA analysis are shown in Supplementary material.

2.3. Modeling depredation

The effect of whale depredation on survey sablefish CPUE was estimated using several model forms. Building upon previous studies