TOOTHED WHALE INTERACTIONS WITH LONGLINE FISHERIES IN ALASKA

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A

THESIS

Presented to the Faculty

of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

By

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Fairbanks, Alaska

May 2014

Abstract

Killer whale (*Orcinus orca*) and sperm whale (*Physeter macrocephalus*) depredation occurs when whales damage or remove fish caught on longline gear. This project used a mixed methods approach incorporating Generalized Linear and Additive Modeling techniques and social research methods, such as semi-directed interviews and written questionnaires, to evaluate: 1) spatio-temporal depredation trends, 2) depredation effects on groundfish catch rates, and 3) socio-economic implications of depredation avoidance and changing fishing practices due to whale interactions. The occurrence of killer whale depredation varied by target species and area based on National Marine Fisheries Service longline survey data and observer commercial fishery data collected from 1998 to 2012 in the Bering Sea, Aleutian Islands, and Western Gulf of Alaska. The percentage of commercial fishery sets affected by killer whales was highest in Bering Sea fisheries for: sablefish (*Anoplopoma fimbria*; 21.4%), Greenland turbot (*Reinhardtius hippoglossoides*; 9.9%), and Pacific halibut (*Hippogolossus stenolepis*; 6.9%). Killer whale depredation was more common on the standardized longline survey (9.2-34.6% skates impacted) than the commercial sablefish fishery (1.0-21.4% sets impacted) in all three management areas. Catch reductions were consistent across data sets. Average commercial fleet catch reductions ranged from 35-69% for sablefish, Pacific halibut and Greenland turbot ($p<0.001$); survey catch reductions ranged from 51-73% ($p<0.001$). Sablefish catch per unit effort, gear haul time and location significantly impacted the proportion of sets depredated. Fishermen reported changing their fishing practices in response to depredating whales by soaking gear longer to "wait the whales out" or moving to different fishing sites. These avoidance measures resulted in increased operation costs and opportunity costs in lost time. In a follow-up analysis based on data collected by fishermen in 2011 and 2012, it was found that killer whale depredation avoidance measures resulted in an average additional cost of $494 per vessel-day for fuel and crew food. Opportunity costs of time lost by fishermen averaged $486 per additional vessel-day on the grounds. These results provide insight into the potential impacts of whale depredation on fish stock abundance indices and commercially important fisheries in Alaska and will inform future research on apex predator-fisheries interactions.

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Dedication and Acknowledgements

I am prone to the excessive use of superlatives in conversation. I have tried to steer clear of this habit when writing scientific papers; however, I now choose to take particular advantage of superlatives in this acknowledgements section. My gratitude and appreciation for my support networks throughout this four-plus year journey cannot be expressed otherwise.

I consider myself incredibly fortunate to have teamed up with my co-advisors, Dr. Courtney Carothers and Dr. Franz Mueter. They have both challenged and supported me throughout this process. Despite constantly getting myself in over my head, I never felt short of guidance or knowledge with their support on this project. Their kindness of character coupled with their unique knowledge in fisheries science enabled this project and me to achieve and even exceed my expectations. Words truly cannot express how grateful I am to Dr. Franz Mueter. Franz was the first instructor that was able to convince me that quantitative and statistical approaches are not just for aliens- and that I was in fact capable of succeeding with these methods myself. He was patient during meetings when I was completely confused and generally refrained from laughing at me when I informed him, "I don't do equation-speak, please tell me what this means in normal-person-speak." Franz supported and helped frame my thinking and analysis with every one of my chapters and my eventual employment. His contributions were invaluable. But just as important- Franz, his wonderful wife Susan and their family have become dear friends. Calli and I would have been lost without them these last few years.

Dr. Courtney Carothers has been a role model since I first met her in Seward at the Resurrect Art Coffee House Gallery. She is one of the most articulate and effective faculty I have worked with. Listening to her class lectures was both humbling and inspiring. Additionally, her poise and professionalism in the field and in research never ceased to amaze me. Courtney has faced an uphill battle and led the charge for her graduate students to incorporate social research and transdisciplinary research into more conventional fisheries science forums. With her guidance I have learned to value fisheries anthropology and social research and hope this is reflected in my current and future work. I also feel happy to point out that there are not many advisors willing to try surfing in Kodiak or take on skiing the West Ridge of Eaglecrest.

The guidance from co-advisors Franz and Courtney was strengthened by my exceptional committee members, Dr. Keith Criddle and Mr. Craig Matkin. Keith's innate understanding and unique experience in fisheries economics and policy contributed much to my understanding of whale interactions with longline fisheries and shaped the way I approached this project. Craig Matkin's long experience with killer whales in Alaska was also critical to this work. The world of marine mammal science can be a tricky place to navigate, and Craig was willing to work with me when other folks viewed a new player in the field as more threat than asset. Although not officially on my committee, Chris Lunsford, Dana Hanselman and Cara Rogdgveller at NOAA Auke Bay Laboratories were instrumental to this project from day one through supporting project design and eventual analysis, responding to multiple data requests, and getting me out on my first survey.

My support from family and friends has been boundless for the last four and a half years, and it is the reason I am close to completing this project as I write this. First off, I must thank my parents for seeing me through the highs and lows of this dissertation, for airline miles to fly me down to California when I needed a break or sunshine, and for the unconditional love and support that only parents can provide. My father continues to motivate my passion for science, and I appreciate each article he sends me on invasive fish or climate change. My mother has endured endless phone calls- representing various mental states- and dealing with all manner of topics including: Alaska weather, confidence intervals, politics and love lives. My brother and sister and siblings-in-laws have always provided meaningful advice and support throughout this project. A few friends and loved ones have been with me through this entire process. Suzie Teerlink, Amber Cavett, Amber Stephens and Heather Down have been there for me and have kept me laughing over these last few years.

I appreciate that I was dealt a wonderful hand in life; with loving family and friends, a funny dog, advisors and committee members I profoundly respect, and a very cool dissertation project. I look forward to taking these experiences and lessons learned with me throughout my career and hope that I can be as proud of my future projects as I am of this one.

On predators…

Over the thousands of millennia that our own lineage has spent in the company of killing beasts— competing with them for food and running from them as food— the great meat-eaters have quite naturally etched themselves in the human persona. Long before people had perfected the art of exterminating their fellow predators, they were worshipping them. Thirty thousand years ago, Paleolithic artists were decorating cave walls with reverently painted murals of lions.

-William Stolzenburg from "Where the Wild things Were"

General Introduction

The modernization and geographic expansion of longline fishing operations during the mid- to late-1900s expanded anthropogenic influences on marine environments and marine predators (Pauly et al., 2005; Read, 2008; Mansfield, 2011; Hamer et al., 2012). Interactions and competition with other cosmopolitan apex predators is a logical outcome of increased human presence in and reliance on marine environments (Hamer et al., 2012). This interaction is exemplified by the issue of *odontocete* or toothed whale interactions with sablefish (*Anoplopoma fimbria*), Pacific halibut (*Hippoglossus stenolepis*), and Greenland turbot (*Reinhardtius hippoglossoides*) longline fisheries in Alaska. Killer whale (*Orcinus orca*) interactions with fisheries occur in four main regions in Alaska: the Bering Sea, Aleutian Islands, Western Gulf of Alaska, and the coastal waters of Prince William Sound (Matkin, 1986; Dalheim, 1988). Sperm whale (*Physeter macrocephalus*) depredation predominates in the eastern Gulf of Alaska and throughout Southeast Alaska (Thode et al., 2005; Sigler et al., 2008). There are negative consequences associated with whale depredation for both the fishermen and the whales, and fishermen are changing fishing practices in response to and in anticipation of these interactions.

Marine mammal interactions with fisheries are defined as the presence of marine mammals in the immediate vicinity of fishing vessels (Purves et al., 2004). Interactions with fisheries include competition for prey, entanglement in fishing gear, vessel strikes, whales feeding on discarded offal, and depredation—the removal of catch or bait from fishing gear (Sigler et al., 2008). In Alaska, sperm whale and killer whale depredation occurs when whales take or damage fish that have been hooked on longlines. Although killer whales have been known to interact with trawl vessels (Perez, 2006a), toothed whales primarily depredate on demersal or pelagic longline operations such as fisheries for sablefish and Greenland turbot in Alaska (Dalheim, 1988; Sigler et al., 2008; Peterson et al., 2013), tuna (*Thunnus spp*) and swordfish (*Xiphaus gladius*) in tropical zones (Sivasubramaniam, 1964; Secchi and Vaske, 1998; Dalla Rosa and Secchi, 2007) and Patagonian toothfish (*Dissostichus eleginoides*) in the Southern Ocean (Hucke-Gaete et al., 2004; Clark and Agnew, 2010; Tixier et al., 2010).

Catch losses attributable to toothed whales are difficult to quantify because depredation does not always leave evidence, such as damaged fish left on the fishing gear (Clark and Agnew, 2010; Tixier et al., 2010; Peterson et al., 2013). For example, soft-mouthed fishes, such as sablefish and Patagonian toothfish, are often entirely removed or torn away from the hook when whales depredate. However, hooked fish can escape, be knocked off by mechanical forces, or eaten by a variety of predators; an empty hook cannot serve as sure evidence of whale depredation. Thus, there is a need for more advanced statistical approaches to estimate catch losses attributable to whale depredation. Modeling changes in catch per unit effort (CPUE) of a target fish species due to toothed whales, while accounting for other covariates such as depth, time of year, and region is one way to estimate catch losses due to these types of interactions (Clark and Agnew, 2010; Peterson et al., 2013). In other regions where depredation occurs on hard-billed fishes such as swordfish or tuna (fishes that often do not tear away fully from the gear), catch removals can be estimated as the proportion of damaged fish landed per set or per fishing trip. Evaluating the percentage of damaged fish tends to generate lower estimates of a depredation effect on catch (3-12%) (Secchi and Vaske, 1998; Hucke-Gaete et al., 2004). Model-estimates of overall catch rate reductions generally range between 25% and 35% (Dalheim, 1988; Yano and Dahlheim, 1995a; Matkin, 1988; Peterson et al., 2013), while individual set catch rates can be depressed by nearly 100% (Sivasubramaniam, 1964).

Whale depredation has negative consequences for fishermen, fisheries management, and whales. Depredation results in economic costs to fishery participants primarily though reduced catch rates and increased fuel, crew and operation costs (Yano and Dalheim, 1995b; Ashford et al., 1996; Purves et al., 2004; Goetz et al., 2011). The effects that depredation may have on the accuracy of fish stock abundance indices remain uncertain but is an important issue for management agencies and has serious implications for fishermen (Purves et al., 2004; Kock et al., 2006; Donoghue, 2007). Depredating whales may get a relatively easy meal of fish hooked on longline gear, but this activity can also have negative consequences for the whales (Northridge and Hofman, 1999; Hernandez-Milian and Goetz, 2008). Depredating whales may be at greater risk of mortality or injury from vessel strikes, entanglement in fishing gear, or injuries from deterrence by frustrated fishermen (Ashford et al., 1996; Northridge and Hofman, 1999; Roche et al., 2007; Hernandez-Milian et al., 2008). There are also risks associated with modifying marine mammal foraging behavior and creating a dependence on an unnaturally available and unreliable prey resource (Roche et al., 2007).

Organization of the Dissertation

This introduction provides a brief overview of killer whale and sperm whale life history and reviews current literature on sperm whale and killer whale depredation. The subsequent chapters present the results of a mixed methods approach towards developing a comprehensive understanding of the socio-ecological and economic impacts of toothed whale depredation on longline fisheries in Alaska. Chapter 1 uses quantitative methods to estimate catch reductions associated with killer whale depredation on the National Marine Fisheries Service (NMFS) sablefish longline survey in the Bering Sea, Aleutian Islands and Western Gulf of Alaska. Chapter 2 incorporates social research methods in conjunction with statistical analyses to assess fishermen's perceptions of and experience with whale interactions in Alaska and to identify ways in which fishing practices are changing as a result of these interactions. Chapter 3 synthesizes and builds upon results from the previous two chapters to estimate the additional operational and opportunity costs that longline fishermen incur due to killer whale depredation on commercial fisheries in western Alaska. In sum, this dissertation integrates fishermen's knowledge and experience with quantitative methods to elucidate trends in whale depredation in Alaska, to understand how these interactions are impacting the socio-economic viability of longline fisheries and to identify ways in which conflicts arising due to whale interactions can be minimized with long-term mitigation and management strategies.

Toothed whale life history

Killer whales and sperm whales are the two largest species of *odontocetes* or toothed whales. They are also cosmopolitan marine mammals with ranges that span the globe (Allen and Angliss, 2008; Angliss and Outlaw, 2010). Killer whales and sperm whales are K-selected species. K-selected species often function near the carrying capacity of the environment and tend to exhibit large body size, long life spans, low natality rates and high maternal investment (Anderson, 2001). Depredating killer whales in Alaska are presumed to be members of the resident ecotype as part of the Eastern North Pacific Alaskan Resident Stock (Angliss and Outlaw, 2010). In 2010, it was estimated that a minimum of 1300 resident killer whales occur in the Bering Sea, Aleutian Islands, and Western Gulf of Alaska (Angliss and Outlaw, 2010). More recent photographic mark-recapture assessments indicate that significantly more (perhaps twice this number) fish-eating killer whales use the coastal waters around the eastern and central Aleutians alone in some years (Fearnbach, 2012). Stock structure and abundance data are deficient for North Pacific sperm whales (Allen and Angliss, 2008) and, as of 2012, they were listed as "endangered" under the 1973 Endangered Species Act and "depleted" under the 1972 Marine Mammal Protection Act. Depredation by sperm whales in Alaska is presumed to be primarily by solitary mature males from the North Pacific stock (Mesnick et al., 2011). Whereas killer whale depredation has a longstanding history in Alaska (Dalheim, 1988), sperm whale depredation is a relatively recent phenomenon in the Gulf of Alaska. Documented interactions with sperm whales may have increased in frequency in the late 1990s following the implementation of individual fishing quotas (IFQs) and associated extended sablefish and Pacific halibut fishing seasons (Thode et al., 2005).

Killer whales

Killer whales are typically found in high-latitude productive coastal waters, although they also inhabit tropical and offshore waters (Dalheim and Heyning, 1999). Killer whales are most commonly found in the Southern Ocean around Antarctica, the North Pacific Ocean and the northeast Atlantic Ocean. Killer whale abundance may be linked to regions of higher ocean productivity, as indicated by remotely sensed chlorophyll levels and areas of higher prey availability (Forney and Wade, 2006). The minimum worldwide abundance estimate for killer whales is 50,000 individuals. This value is likely an underestimate because abundance estimates are not available for many high-latitude areas of the northern hemisphere and for significant areas of the South Pacific, South Atlantic, and Indian Oceans (Forney and Wade, 2006).

Killer whales are the largest species of the Delphinidae family. Killer whales exhibit sexual dimorphism; females can reach body lengths of 7.7 m and weights in excess of 3,800 kg; males can reach 9.0 m and 5,600 kg (Heyning and Brownell, 1990; Ridgway and Harrison, 1999). Based on research investigating the British Columbia northern resident population, mean life expectancy for female killer whales is 50 years, and maximum longevity is estimated to be 80 to 90 years. Mean male killer whale life expectancy is estimated at 29 years with maximum longevity extending 50 to 60 years. Females reach maturity at 4.6-4.9 m in length, around 15 years in age. Males reach physical maturity at around 21 years (Olesiuk et al., 1990). Killer whales are specialized predators (Forney and Wade, 2006). Based on current genetic, morphologic, diet and behavioral data, scientists have identified at least three distinct populations or ecotypes of killer whales in the North Pacific: "residents," "transients," and "offshores" (Ford et al., 1998; Dalheim and Heyning, 1999; Herman et al., 2005). Killer whale diet, communication and morphology vary with ecotypes; residents in the North Pacific are generally piscivorous while transients predate on marine mammals. North Pacific offshores are thought to rely primarily on sharks and other fish, although less is known about their diets (Herman et al., 2005). In waters surrounding Antarctica, there are at least three recognized ecotypes: minke whale (*Balaenoptera bonaerensis*) specialists (Type A), seal specialists (Type B), and fish specialists (Type C)(Pitman and Durban, 2012). Recent evidence also supports the existence of a fourth ecotype (Type D) of killer whales in sub-Antarctic waters (Pitman et al., 2010). Distinct killer whales ecotypes that have distributions that overalap rarely interact and generally do not interbreed (Forney and Wade, 2006).

Fish-specialist killer whales are generally found at higher latitudes in the Pacific, Atlantic and Southern Oceans (Forney and Wade, 2006). In the North Pacific and Southern oceans, fish-eating killer whales occur in parapatry or sympatry with marine-mammal specialists (Pitman and Durban, 2012). It is possible that killer whales residing in highly productive areas with abundant prey may have undergone a form of niche separation (Forney and Wade, 2006). Depredating killer whales in Alaska are thought to be a part of the resident ecotype. The diet of resident killer whales includes Pacific salmon (*Oncorhynchus spp.),* Pacific halibut, and Pacific herring (*Clupea pallasi*) (Ford et al., 1998; Saulitis et al., 2000; Perez, 2006b). Resident killer whales occur in highly stable social units known as matrilines. Pods are larger social groups composed of several matrilines and range from 5 to 50 whales on average (Forney and Wade, 2006).

Sperm whales

Sperm whales are found in all deep (>1000 m) oceans of the world from the equator to the edge of the north and south ice packs (Rice, 1989). Sperm whales have the largest brains of any animal on Earth and are the most sexually dimorphic cetacean species, with mature males reaching 18 m and females 12 m in length (Whitehead, 2003). Sperm whale social structure varies by age and sex. Calves are born into and raised within breeding schools or groups composed primarily of females. Calves are raised communally within sperm whale breeding schools, and calves will suckle from both kin and non-kin group members (Gero et al., 2009).

Immature males eventually leave their breeding schools and form "bachelor schools." As males mature, they become more solitary and their distribution shifts farther north or south. These males return to more tropical waters for breeding seasons (Kasuya and Miyashita, 1988; Allen and Angliss, 2008). Pelagic populations of sperm whales consume a larger percentage of cephalopods, whereas coastal populations rely more on fish such as sablefish and Pacific cod, and skates (*Rajidae*) (Gaskin, 1982; Rice, 1989; Sigler et al., 2008). Diet data from historic whaling stations indicated sperm whales caught in the Bering Sea and Aleutian Islands relied more heavily on cephalopods and fish became a more significant component of sperm whale diet towards the eastern Aleutians and Gulf of Alaska (Okutani and Nemotot, 1964; Sigler et al., 2008).

For management purposes under the Marine Mammal Protection Act, there are three recognized stocks of sperm whales in the North Pacific: Hawaii, California/Oregon/Washington, and Alaska. Recent genetic research using single-nucleotide polymorphisms indicate a somewhat different delineation of sperm whale stocks. Mesnick et al. (2011) identified three distinct strata of female/juvenile sperm whales: California Current, Hawaii, and the eastern tropical Pacific. Alaskan male sperm whales sampled have been linked to each stratum. Thus, Alaskan male sperm whales may represent an intermixing population of all three genetic stocks. This new genetic information suggests that sperm whale stock management may require revision to account for the split sex distribution and migratory behavior of male sperm whales (Mesnick et al., 2011).

Global Depredation Review

Atlantic Ocean

Killer whales depredate on a wide number of species in the Atlantic Ocean including swordfish, tuna, white marlin (*Tetrapturas albidus*), Greenland halibut, Patagonian toothfish, and Atlantic halibut (*Hippoglossus hippoglossus*) (Bloch and Lockyer, 1988; Secchi and Vaske, 1998; Dalla Rosa and Secchi, 2007). Additionally, killer whales interact with purse seine fisheries for Atlantic mackerel (*Scomber scombrus*) and Atlantic herring (*Clupea harengus*) (Bloch and Lockyer, 1988). Sperm whales in the Atlantic Ocean depredate on Patagonian toothfish, Greenland halibut, Atlantic cod (*Gadus morhua*), and Greenland cod (*Gadus ogac*) (Dyb, 2006; Mesnick et al., 2006).

Fishermen off the coast of Iceland reported killer whales taking Greenland halibut from longline gear as early as 1976. At times, killer whale depredation was so extensive that fishermen chose to leave the fishing grounds- even after having used dynamite in unsuccessful efforts to frighten-off the whales (Christensen, 1982). Killer whale depredation has also been reported in Faroese waters and in waters off Greenland. Although most of the accounts relate to herring and mackerel purse seine interactions, killer whales also learned to follow vessels and take Atlantic halibut off hooked lines around Iceland (Bloch and Lockyer, 1988). Sperm whales depredate on the Atlantic halibut and Greenland halibut fisheries. Fishermen from Greenland report that the number of depredating sperm whales is increasing to the extent that some fishermen have given up longline fishing due to diminished CPUEs (Dyb, 2006).

Secchi and Vaske (1998) reported killer whale depredation observations during nine cruises on tuna fishing vessels in Southern Brazil from 1987 to 1991. Depredation resulted in up to 50% decreases in daily swordfish catch, and fishermen stated they often lost 100% of their catch. Dalla Rosa and Secchi (2007) later described killer whale and shark interactions with approximately 17 longline fishing vessels off southern and southeastern Brazil from early 1993 to July 1995. Catch losses were calculated as the percentage of total catch of the target fish (swordfish and tuna) damaged per set or per fishing trip when interactions occurred. Killer whale–associated catch removals on sets varied from 0.5% to 47.5%. The average percentage of damaged catch on a killer whale depredated longline set was 12.4% (Dalla Rosa and Secchi, 2007). Killer whale entanglement in longline gear is fairly uncommon; however, one female killer whale was incidentally captured in July 2004 off Brazil; it escaped when the hook bent open (Dalla Rosa and Secchi, 2007).

Indian Ocean

As early as 1955, the tropical longline fishing industry in the Indian Ocean reported toothed whale interactions with fisheries off the coast of Java in Indonesia, in the Timor and Bandu Seas, and off western Australia (Sivasubramaniam, 1964; Iwashita et al., 1976). Depredation by killer whales has also been documented around Kenya, Tanzania and Madagascar. In addition to losing much of their tuna catch, skippers reported losing up to 75% of their bait to killer whales (Ndegwa and Makogola, 2007). Off South Africa, killer whales and sperm whales were documented depredating concurrently. Observers reported killer whales becoming aggressive towards the sperm whales, with estimated catch losses up to 50% (Tilney and Purves, 1999; Peterson and Williams, 2007).

Depredation in the southern Indian Ocean primarily occurs in the Patagonian toothfish longline fisheries. Killer whales and sperm whales depredate separately or in co-occurrence with one another in this region. In 2007, researchers found that killer whales and sperm whales were present, alone or in co-occurrence with each other, on 71% of 1,308 sets in the Crozet EEZ. CPUE was reduced by 22.5% in the presence of killer whales, 12.1% with sperm whales and 42.5% when both species were present (Roche et al., 2007). In a separate study in the Crozet EEZ, killer whales alone were estimated to be responsible for depressing CPUE by 27% ± 25%, sperm whales alone by 9% ± 13% and killer whales and sperm whales in tandem by 37% ± 31% (Tixier et al., 2010).

Pacific Ocean

Reports of killer whale depredation on Japanese longline fishing vessels in the Bering Sea were documented as early as the 1960s (Matkin, 1986). Based on a comparison of annual catch rates on the NMFS longline survey from 1980 to 1989, killer whale depredation resulted in catch losses ranging from 14 - 60% for sablefish, 39 - 69% for Greenland turbot, and 6 - 24% for arrowtooth flounder (*Atheresthes stomias*)(Yano and Dahlheim, 1995a). Depredation was first recorded in Prince William Sound in 1985, and in 1985 and 1986 it was estimated that 25 - 35% of overall sablefish catches were lost to killer whales, while catches of individual sablefish sets were depressed by as much as 80 - 90%.

Sperm whales primarily depredate on sablefish in the Gulf of Alaska, (Sigler et al., 2008) but also occasionally take Pacific halibut, grenadier (*Ventrifossa* spp.) and skates (Hill et al., 1999). Sperm whale depredation in Alaska was recorded as early as 1978 but has increased in frequency since the mid-1990s (Thode et al., 2007). Sigler et al. (2008) estimated that sperm whales removed up to 5% of catches at Gulf of Alaska stations where depredation occurred between 1998 and 2004, although the effect was not statistically significant.

Some of the earliest accounts of toothed whale depredation occurred in tropical Indian and Pacific Oceans where Japanese longliners targeted tuna and swordfish; however, these earlier reports did not identify the specific marine mammal species. "With the development of tuna fisheries [*during the 1950s and 1960s*] and the extension of fishing grounds the *Orcinus* groups are becoming a dominant factor and are running rampant over marine regions in the seas near fishing grounds" (Iwashita et al., 1976). Depredation by toothed whales was recorded in the 1960s around Palau, Samoa, New Britain, New Guinea and the Caroline and Marshall Islands (Sivasubramaniam, 1964; Iwashita et al., 1976). Killer whale distribution data (Forney and Wade, 2006) suggests it is unlikely that killer whales were the primary species involved with these interactions in the tropical Pacific Ocean. Based on current interactions and species descriptions by Sivasubramaniam (1964), false killer whales (*Pseudorca crassidens*), short-finned pilot whales (*Globicephala macrorhynchus*) or long-finned pilot whales (*Globicephala melas*) were more likely some of the primary species interacting with the gear during these studies (Sivasubramaniam, 1964; TEC Inc., 2009).

A study in New Zealand found that killer whales also depredate on school sharks (*Gateorhinus galeus*) and bluenose warehou (*Hypoeroglyphe antarchia*) (Visser, 2000). In interviews conducted with six New Zealand longline fishermen, fishermen estimated that 5 - 10% of their catch was lost per set. Interviewees also anonymously reported having shot whales in an attempt to deter them from depredating (Visser, 2000). Longline hauls targeting Patagonian toothfish were monitored off southern Chile between April 2002 and March 2003. Sperm whales were present at 60% of all monitored sets, while killer whales were observed during only 10% of sets. The estimated mean proportion of catch damaged was 3% (+-2%, n=180 sets) and ranged from 0 to 100% (Hucke-Gaete et al., 2004). Patagonian toothfish lips, heads and trunks were considered evidence of depredation. No depredation occurred when killer whales and sperm whales were both present during hauls. Hucke-Gaete et al. (2004) theorized killer whales may choose to predate on or harass sperm whales instead of taking fish from the gear.

Chapter 1

Killer whale (*Orcinus orca*) depredation effects on catch rates of six groundfish species: Implications for commercial longline fisheries in Alaska[1]

[1] Megan J. Peterson, Franz Mueter, Dana Hanselman, Chris Lunsford, Craig Matkin, Holly Fearnbach. 2013. ICES Journal of Marine Science 10(6): 91-108.

Abstract

Killer whale (*Orcinus orca*) depredation occurs when whales damage or remove fish caught on longline gear. This study uses National Marine Fisheries Service longline survey data from 1998-2011 to explore spatial and temporal trends in killer whale depredation and to quantify the effect of killer whale depredation on catches of six groundfish species within three management areas in Alaska: the Bering Sea, Aleutian Islands, and Western Gulf of Alaska. When killer whales were present during survey gear retrieval, whales removed an estimated 54-72% of sablefish (*Anoplopoma fimbria*), 41-84% of arrowtooth flounder (*Atheresthes stomias*), and 73% (Bering Sea only) of Greenland turbot (*Reinhardtius hippoglossoides*). Effects on Pacific halibut (*Hippoglossus stenolepis*) and Pacific cod (*Gadus macrocephalus*) were significant in the Western Gulf only with 51% and 46% reductions, respectively. Overall catches (depredated and non-depredated sets) for all groundfish species significantly impacted by killer whale depredation were lower by 9% to 28% ($p<0.05$). Effects on shortspine thornyhead (*Sebastolobus alascanus*) catches were not significant in any management area ($p>0.05$). These results provide insight into the potential impacts of killer whale depredation on fish stock abundance indices and commercially important fisheries in Alaska and will inform future research on apex predator-fisheries interactions.

1.1 Introduction

Killer whale (*Orcinus orca*) depredation (whales removing or damaging fish caught on fishing gear) impacts longline fisheries in all ocean basins (Sivasubramaniam, 1964; Iwashita et al., 1976; Yano and Dahlheim, 1995a; Visser, 2000; Garrison, 2007; Clark and Agnew, 2010; Belonovich and Burkanov, 2012). Killer whale depredation can reduce overall catch rates by up to 30% and individual sets by 100% (Sivasubramaniam, 1964; Kock et al., 2006; Roche et al., 2007; Dalla Rosa and Secchi, 2007). Depredation has negative consequences for the fishermen through reduced catch rates and increased operating costs (Yano and Dalheim, 1995b; Ashford et al., 1996; Purves et al., 2004; Goetz et al., 2011). Depredation also has negative consequences for the whales through increased risk of vessel strike, gear entanglement, fishermen aggression and altered foraging strategies (Ashford et al., 1996; Northridge and Hofman, 1999; Roche et al., 2007; Hernandez-Milian et al., 2008). An additional management concern stems from the impact that whale depredation may have on the accuracy of fish stock abundance indices (Purves et al., 2004; Gillman et al., 2006; Kock et al., 2006; Clark and Agnew, 2010; Hanselman et al., 2010).

Killer whale depredation has been documented in four main regions in Alaska: the Bering Sea (BS), Aleutian Islands (AI), Western Gulf of Alaska (WGOA), and the coastal waters of Prince William Sound. The problem of killer whale depredation is particularly acute in western Alaska, where high-dollar longline fisheries are prosecuted in areas supporting some of the greatest densities of “fish-eating" or resident killer whales in the world (Yano and Dahlheim, 1995a; Forney and Wade, 2006; Fearnbach, 2012). It was estimated in 2010 that a minimum of 1300 resident killer whales inhabit the BS, AI, and WGOA (Angliss and Outlaw, 2010). However, more recent photographic mark-recapture assessments indicate that significantly more (perhaps twice this number) fish-eating residents use the coastal waters around the eastern and central Aleutians alone in some years (Fearnbach, 2012). Alaskan resident killer whales have been observed feeding on Pacific salmon (*Oncorhynchus spp*.), Atka mackerel (*Pleurogrammus monopterygius*) and Pacific halibut (*Hippoglossus stenolepis)* (Ford et al., 1998; Saulitis et al., 2000; Herman et al., 2005; Krahn et al., 2007; Fearnbach, 2012). Resident killer whales in the BS, AI, and WGOA show strong long-term associations consistent with a matrilineal pattern and have been shown to exhibit a high degree of site fidelity over time. Ranges are generally limited to around 200 km, although longer movements have been documented (Ford and Ellis, 2006; Forney and Wade, 2006; Matkin et al., 2007; Fearnbach, 2012).

The goal of this study was to improve our understanding of the effect of killer whales on National Marine Fisheries Service (NMFS) longline survey catches, fish stock abundance indices, and commercial fisheries. Killer whales are known to depredate on sablefish (*Anoplopoma fimbria*), arrowtooth flounder (*Atheresthes stomias*), Pacific halibut and Greenland turbot (*Reinhardtius hippoglossoides*) (Matkin, 1988; Yano and Dahlheim, 1995a). There is also some evidence suggesting killer whales may interact with Pacific cod (*Gadus macrocephalus)* longline fisheries in the BS (Perez, 2006). Exact catch losses due to killer whales are difficult to quantify as there are a number of confounding variables that can also impact catch rates, such as habitat type, geographical region, set soak time, set depth, and year (Clark and Agnew, 2010; Hanselman et al., 2010). Therefore, we used a generalized modeling approach to address two specific objectives: 1) to quantify temporal and spatial trends in killer whale depredation, and 2) to quantify the effect of killer whale depredation on catch rates of six commercially important groundfish during longline surveys off Alaska.

1.2 Materials and Methods

1.2.1 Data Collection

Data on killer whale depredation were collected during the annual NMFS sablefish longline survey 1998 - 2011. Stations were surveyed in the BS during odd years, in the AI during even years, and in the WGOA every year from June to August 1998 - 2011. Stations in the BS (odd years) and AI (even years) were fished approximately 31 May -14 June, while WGOA stations were fished each year 16 June – 30 June. Survey stations generally overlapped with sablefish commercial longline fishing grounds along the continental slope and were systematically spaced approximately 30 - 50 km (Fig. 1.1) apart at depths ranging from 150 - 1000 m (Sigler et al., 2008). The survey followed a systematic design, with stations fished in the same location each year. A station was fished from shallow to deep and consisted of two sets hauled end to end. The basic unit of gear was a skate; there were 80 or 90 skates per set depending on management area. Each skate consisted of 45 hooks, baited with squid, spaced 2 m apart. Stations in the BS had 180 skates for a total of 8100 hooks fished per day, while AI and WGOA stations had 160 skates for a total of 7200 hooks per day. Species-specific catch data were tallied for each hook retrieved. A fish was labeled as "depredated" if only lips or torn, punctured fish remnants were brought aboard (Fig. 1.2). Length and sex information were recorded for major species such as sablefish, Pacific cod, Greenland turbot, arrowtooth flounder, giant grenadier (*Albatrossia pectoralis*), and others. Sea surface temperature (SST) was measured immediately prior to gear retrieval at each station.

Catch was calculated for each species by summing the total number of individuals caught per skate. Catch per unit effort (CPUE) was then calculated by dividing the catch by the number of effective hooks per skate. Hooks were deemed "ineffective" if they were straightened, snarled, bent, or in any way unable to fish properly. Mean latitude and longitude for each set was computed by averaging the latitude and longitude of the set start and set end. Depth was recorded every fifth skate and interpolated for all other skates. An alternative depth index (depth stratum) was also used to identify broad depth ranges (stratum 1: 0 - 100 m, stratum 2: 101 - 200 m, stratum 3: 201 - 300 m, stratum 4: 301 - 400 m, stratum 5: 401 - 600 m, stratum 6: 601 - 800 m, stratum 7: 801 - 1000 m, stratum 8: 1001 - 1200 m). Killer whale depredation data were recorded at the skate level. The vessel captain and chief scientist recorded the time and skate number that killer whales were first sighted within approximately 300 meters of the vessel. Skates were labeled as “depredated” if whales were sighted near the vessel and there was evidence of depredation (e.g. damaged fish observed on the skate).

1.2.2 Data Analysis

The first objective of this study, quantifying spatial and temporal trends in killer whale depredation, was addressed by examining the proportion of skates depredated by station and year and modeling depredation as a function of time, fishery, or environmental variables. The second objective, exploring the effect of killer whale depredation on catch rates, was addressed by comparing CPUE between sets with and without killer whale depredation and modeling the catch per set as a function of station, year, presence of killer whales and other relevant covariates using a generalized modeling approach. All analyses were done using R Statistical Computing Software (version 2.15.0).

1.2.2.1 Spatial and Temporal Trends in Killer Whale Depredation

The average proportion of skates depredated was calculated for each station and year by dividing the number of skates depredated by killer whales by the total number of skates fished. To assess temporal trends in killer whale depredation in each management area, a logistic regression was used to determine if there was a significant trend in the proportion of depredated skates (π) over time. The logistic regression was fit in a Generalized Linear Modeling (GLM) framework assuming a binomial distribution for the response variable (Hardin and Hilbe, 2007). The response variable was the presence (1) or absence (0) of depredation on a given set, where '0' meant that no skates were depredated on the set and '1' meant that at least one skate was impacted by killer whale depredation. The binomial response variable was linked to the linear predictor, which included year and station as explanatory variables, through the logit function ($\log(\pi/(1-\pi))$). Two models were compared to examine trends in the proportion of depredated skates over time: one that estimated annual means across all years i and station means across all stations j and a second model that estimated station means and a simple linear trend (slope β_1) in the proportion of depredated skates over time:

$$\log\left(\frac{\pi_{ij}}{1-\pi_{ij}}\right) = \beta_0 + year_i + station_j$$

$$\log\left(\frac{\pi_{ij}}{1-\pi_{ij}}\right) = \beta_0 + station_j + \beta_1(year)$$

where π_{ij} is the estimated proportion of skates depredated at station j in year i. Each management area was modeled separately. Stations that experienced no depredation in any year were removed. Confidence intervals are reported as ± 1.96 * standard error.

To examine the effects of environmental and fishery-related variables on the frequency of killer whale depredation, the above models were extended to include smooth, non-parametric functions of potentially important covariates in a Generalized Additive Model (GAM; as implemented in the R package 'mgcv')(Wood, 2006; Zuur et al., 2009). Explanatory variables considered included SST, killer whale social cluster, gear soak time, depth, set haul time, latitude, longitude, distance fished, and ineffective hooks. Year was treated as a categorical variable. As a measure of local abundance, sablefish CPUE, Pacific halibut CPUE, and arrowtooth flounder CPUEs were averaged by station for all skates not affected by depredation. For this analysis, each station was assigned to one of three killer whale social clusters, based on social connectivity and geographic range, as defined by Fearnbach (2012). Social cluster was included to account for possible differences in depredation rates between different social groups of killer whales.

SST, soak time, haul time, distance fished, depth, and CPUE for sablefish, Pacific halibut, and arrowtooth were averaged by station and year for this analysis. Pairwise correlations were computed between all variables to check for collinearity. When significant collinearity occurred (Pearson's correlation test; $r > 0.5$, $p < 0.05$) one of the two variables was dropped from the final model based on lowest AIC score.

$$
\begin{aligned}
(proportion\ skates\ depredated) \\
= year_i + whale\ cluster_k + \ f_1(Lat, Long) + f_2(SST) + f_3(depth) \\
+ \ f_4(soak\ time) + \ f_5(haul\ time) + f_6(distance\ fished) \\
+ f_7(ineffective\ hooks) + f_8\ (Sable\ CPUE) + \ f_9\ (Hal\ CPUE) \\
+ \ f_{10}\ (Arrow\ CPUE) + \ \varepsilon
\end{aligned}
$$

The maximum degree of freedom for the smooth terms was restricted to 3 to accommodate biologically reasonable relationships with linear, dome-shaped or sigmoidal shapes (Goetz et al., 2011). Geographic differences were modeled by including location (latitude/longitude) as a covariate, hence data from all three management areas were combined in the analysis. Outliers were identified and removed if Cook's distance exceeded 0.5 (Cook, 2000). The best model was selected based on stepwise regression and lowest Akaike information criterion (AIC) values (Hardin and Hilbe, 2007; Zuur et al., 2009).

1.2.2.2 Catch Reductions of Groundfish Species

To quantify the effect of killer whales on catches of groundfish species we used a statistical modeling approach to analyze NMFS longline survey data for 1998 - 2011 and to compare CPUE between sets with and without killer whales present. The response variable consisted of counts of sablefish, Pacific halibut, Pacific cod, arrowtooth flounder, shortspine thornyhead (*Sebastolobus alascanus*, and Greenland turbot (BS only) per skate or stratum and was modeled using a GLM approach to estimate changes in catch associated with killer whale depredation (Zuur et al., 2009; Clark and Agnew, 2010; Hanselman et al., 2010). Years with no depredation (2004 in the AI; 1998, 1999 and 2001 in the WGOA) and stations where no killer whale depredation was observed in any year were excluded from the analysis. Due to limited catches, strata 1 and 8 were removed for sablefish, Greenland turbot, shortspine thornyhead, and arrowtooth flounder. Strata 6 - 8 were removed for Pacific cod and Pacific halibut.

A number of distributions were initially considered to model the count data in a GLM framework including: Poisson, Negative Binomial (NB; as implemented in the R package ‘MASS’) (Venables and Ripley, 2002), Zero-Inflated Negative Binomial (ZINB; as implemented in R package 'pscl'), and hurdle or zero-adjusted negative binomial models (ZANB; 'pscl')(Zeileis et al., 2008). The Poisson distribution is commonly used to model count data, but initial model explorations indicated that the observed counts were overdispersed in all three areas for all fish species, which occurs when the variance of the counts is greater than their mean. The NB distribution accounts for overdispersion by adding an additional parameter to model the higher variance (Zeileis et al., 2008; Zuur et al., 2009; Hilbe, 2011). Fitting a NB GLM to the catch data resulted in a much-improved fit compared to the Poisson model based on AIC and model diagnostics. Due to the large number of zero catches in the data, ZINB and ZANB models were also considered. However, ZINB and ZANB models failed to converge in most management areas (Hanselman et al., 2010), hence we only present results based on the NB GLM.

Explanatory variables considered included station, year, depth stratum and killer whale depredation as categorical variables and SST, haul time, distance fished, soak time and depth as continuous explanatory variables. Killer whale depredation was treated as a dummy variable consisting of ‘0’ for skates with no depredation and ‘1’ for skates with depredation. Selected interaction terms such as year and station and the interaction between killer whale depredation and depth were examined (Ai and Norton, 2003). To adjust catches for differences in effort resulting from ineffective hooks, all models included an “offset” term as log(effective hooks) and used a log-link to model log(catch) as a function of the linear predictor. The global model without interaction terms, therefore, had the following form:

$$\log(catch) = \beta_0 + year_i + station_j + killer\ whale\ depredation_k + stratum_l + \beta_1(soak\ time) + \beta_2(SST) + \beta_3(distance\ fished) + log(effective\ hooks) + \varepsilon$$

Outliers were excluded if Cook's distance exceeded 0.5 (Cook, 2000). The best reduced model for each management area and fish species was selected based on lowest AIC values (Hardin and Hilbe, 2007; Zuur et al., 2009). Residual diagnostics from the initial NB GLM modeling approach showed strong spatial autocorrelation between successive skates (Durbin-Watson test, $p < 0.05$), resulting in pseudo-replication and standard errors that were much too small. We addressed this issue by aggregating the data by depth stratum and modeled the aggregated number of fish caught per stratum at a given station and year using the same modeling approach as described above for catch per skate. Aggregating the catch data by stratum greatly reduced residual autocorrelation, and standard errors were more reasonable. Therefore, the aggregated NB GLM was selected for the final analyses.

Catch losses associated with killer whale depredation were quantified at two levels. First, for each fish species we estimated the overall average catch per stratum that would have been caught and the associated uncertainty had killer whales not been present at a given skate or station. The number of fish that would have been caught in the absence of depredation was estimated by setting the killer whale depredation variable to '0' and computing predicted catches per stratum for each station and year under this 'no-depredation scenario'. Differences between the observed and predicted catches by year and station were computed and graphically summarized by year and management area to illustrate killer whale effects on overall catch rates across both depredated and non-depredated sets. Second, the estimated reduction in catches for strata with confirmed killer whale depredation was calculated using the model-estimated killer whale depredation coefficients. The killer whale depredation coefficient represents the average difference in catch (on the log scale) of a given fish species with and without killer whales present. Models were also fit separately for each year/stratum combination to compare variations in the killer whale depredation coefficient across individual years and strata for sablefish, arrowtooth flounder, and Pacific halibut (primary depredated species).

1.3 Results

1.3.1 Spatial and Temporal Trends

A comparison of average catch rates for sablefish, Greenland turbot, Pacific halibut, Pacific cod, arrowtooth flounder, and shortspine thornyhead rockfish suggested that there were significant reductions in catch rates for all groundfish species (Kruskal-Wallis test, $p < 0.001$) except shortspine thornyhead (Kruskal-Wallis test, $p = 0.708$) when depredating killer whales were present (Fig. 1.3). From 1998 - 2011, a total of 57 043 skates (2 566 935 hooks) were fished in the BS, AI, and WGOA. The total number of skates depredated for all three areas was 12 021 skates, and the percentage of skates depredated by killer whales across all years and areas was 20.9 % ± 6.7%. Although effort differed between areas, both the number and percentage of affected sets was greatest in the BS, followed by the WGOA and the AI. Survey stations in the BS were located along the continental slope, and stations were generally fished trending northwest-southeast. Killer whale depredation was documented at 14 of 16 stations between 1998 and 2011 in the BS. The highest proportion of depredated skates in the BS was concentrated around stations 10, 12 and 13, approximately 180 km west of the Pribilof Islands (Fig. 1.1). The average proportion of skates depredated for these three BS stations exceeded 55%. In the AI and WGOA, stations were generally fished from east to west around 50° - 55° N. In the AI, killer whale depredation was documented at only 5 of 14 stations. Killer whale depredation in the WGOA region was most common at stations 62 – 64 (45% skates depredated) approximately 70 km south of Unalaska Island in the Umnak and Unalaska basins (Fig.1.1).

The percentage of skates depredated ranged from 12.3 - 55.0% per year ($\bar{x}$ = 34.5% ± 2.3%) in the BS, from 0 - 19% per year ($\bar{x}$ = 6.6% ± 1.5%) in the AI and from 0 - 41% ($\bar{x}$ = 18.9% ± 2.0%) in the WGOA. Based on AIC results and model diagnostics the models estimating station means and a simple linear trend in the proportion of depredated skates over time best summarized variability in depredation rates in the AI (ΔAIC = 3.16) and BS (ΔAIC = -1.32; Fig. 1.4). The model estimating separate means by year resulted in a much lower AIC score in the WGOA (ΔAIC = 7.4), and was thus selected for the final analysis in the WGOA only (Fig. 4). There was a significant increase in the proportion of skates depredated in the AI (p

= 0.049, %dev = 40.26) and significant differences among years in the WGOA (Likelihood ratio test; $\mathcal{X}^2$ < 0.001, %dev = 52.06). The increasing trend in the BS was not significant (p = 0.285, %dev = 9.50; Fig. 1.4).

1.3.2 Factors Affecting Depredation Occurrence

Stepwise regression and AIC results suggest that the proportion of skates depredated was related to sablefish CPUE, haul time and year (GAM; %dev = 32.50) and showed additional spatial variability not captured by these variables that could be described by a smooth spatial surface (f_1 term):

$$Proportion\ skates\ depredated = year_i + f_1(Lat, Long) + f_2(haul\ time) + f_3(sable\ cpue) + \varepsilon$$

The proportion of skates depredated decreased non-linearly with haul time and increased to an asymptote as sablefish CPUE increased (Fig. 1.5). The effect of year was not significant overall with all three management areas included (p = 0.16), however, there were significant differences between certain years. The proportion of skates depredated varied significantly between station locations with two primary "hotspots" evident: 1) along the Bering Sea slope southwest of the Pribilof Islands, and 2) along the continental shelf north and south of Unalaska and Umnak Islands. The proportion of depredated skates decreased to the east and west of these zones.

1.3.3 Catch Reductions

The presence of killer whales was generally associated with lower catches of sablefish, arrowtooth flounder, and Pacific halibut in all three management areas. Greenland turbot in the BS ($p < 0.001$) and Pacific cod in the WGOA ($p = 0.015$) were also affected by killer whale depredation (NB GLM; Table 1.1). Killer whales did not appear to affect Pacific cod catches in the BS or AI or shortspine thornyhead catches in any management area ($p > 0.05$; Table 1.1). The best-performing model to evaluate the killer whale effect on groundfish catch rates included year and station and their interaction, killer whale depredation and depth stratum. Therefore, results from this model will be presented for each groundfish species in each management area:

$$\log(catch) = \beta_0 + year_i + station_j + (year * station)_{ij} + killer\ whale\ depredation_k + stratum_l + log(effective\ hooks) + \varepsilon$$

Predicted mean annual catch reductions from 1998 - 2011 on all sets (depredated and non-depredated) ranged from 13.5% to 28.9% for groundfish species affected in the BS. Killer whale depredation also resulted in predicted overall catch reductions in the AI and WGOA for sablefish (23.6% AI, 10.5% WGOA) and arrowtooth flounder (21.8% AI, 10.2% WGOA; Table 1.1). Overall predicted catch reductions varied by both year and groundfish species in each management area (Fig. 1.6). Sablefish catch losses calculated based on the killer whale coefficient (depredated sets only) were 72.0% in the BS and AI (Table 1.1). Depredated set catch losses were greatest in the BS for Greenland turbot (73.0%) and the AI for arrowtooth flounder (84.2%). Although depredated set catch losses were less severe in the WGOA for sablefish and arrowtooth flounder, Pacific halibut (51.8%) and Pacific cod (46.3%) incurred the highest catch losses in the WGOA (Table 1.1).

1.4 Discussion

1.4.1 Main Findings

Killer whale depredation had a significant effect on NMFS longline survey catch rates for five of the six groundfish species evaluated in this study. Moreover, there were indications that the frequency of depredation increased since the late 1990s in the AI and during the mid-2000s in the WGOA (GLM; Fig. 1.4), consistent with fishermen observations from these regions (M. Peterson, Unpublished). Based on the results from the NB GLM, the highest overall catch reductions in each region generally occurred for sablefish (10.5 - 28.9%), followed by arrowtooth flounder (10.2- 21.8%; Table 1.1). Although the percentage of skates depredated in the AI ($\bar{x}$ = 6.6% ± 1.5%) was lower than the BS ($\bar{x}$ = 34.5% ± 2.3%), killer whales in the AI were still highly effective at removing target groundfish from longline gear when they were present.

Sablefish CPUE, gear haul time and location significantly impacted the proportion of skates depredated (GAM; Fig. 5). Killer whales were more likely to depredate stations with higher average sablefish CPUE, which may be consistent with optimal foraging efficiency and maximizing net rate of energy gain (Estes et al., 2003). Killer whales also targeted stations southwest of the Pribilof Islands and north and south of Unalaska and Umnak Islands. Abundance data for killer whales are limited in these regions, however the increased prevalence of killer whale-fisheries interactions may be related to higher abundances of killer whales in these areas (Fearnbach, 2012). Killer whale depredation decreased with longer gear haul times. This may have occurred due to poor sea state conditions (vessels will often haul slower in poor weather conditions), combined with observations that killer whales may be less likely to depredate in stormy weather (Belonovich and Burkanov, 2012).

Pacific halibut catch reductions were statistically significant in the WGOA only (9.3%, $p < 0.001$). However, fishermen report that the BS and AI Pacific halibut commercial fisheries are heavily impacted by killer whale depredation. The failure of the Pacific halibut models in this study to show a significant effect on halibut catch rates in these areas, in spite of estimated effects that are of similar magnitude to the other regions, may be a result of low sample size (unaffected years and stations eliminated) and lower Pacific halibut catches overall (Table 1.1). Similar to Pacific halibut, Pacific cod catch reductions were statistically significant in the WGOA only (10.5%, $p = 0.015$). Unlike Pacific halibut, overall catch reductions estimated in BS and AI Pacific cod models do not suggest that killer whales are removing Pacific cod from longline gear in either area (Table 1.1). Killer whale depredation on Pacific Cod in the WGOA has not previously been documented on the survey. Using observer data, Perez (2006) did find that a small percentage of longline caught Pacific cod in the BS was affected by killer whale depredation; however, the study concluded killer whales were likely selectively taking other groundfish species off the line. Although it seems unlikely that killer whales were targeting Pacific cod in the WGOA, it is possible that whales opportunistically removed Pacific cod from the longline gear during the survey.

Killer whale depredation in the WGOA was relatively common ($\bar{x}$ = 18.9% ± 2.0%) and increased from very low levels in 1998-2001 to very high levels in the last decade; however, the estimated percentage of overall catch taken by killer whales was lower than in the BS and AI for primary species affected (sablefish, arrowtooth flounder; Table 1.1). The increased frequency of the whale depredation behavior is more recent in the WGOA, and it is possible killer whales in this area may be less effective ‘depredators’ or that the behavior is not as widespread among groups. However, catch rates of sablefish and Pacific halibut are much higher in the WGOA than the BS or AI (Kruskal-Wallis test; $p < 0.05$), therefore, lower percentages of killer whale removals could be related to killer whales reaching a degree of satiation based on natural daily energy requirements (Perez et al., 1993; Sigurjónsson and Víkingsson, 1997; Clark and Agnew, 2010). This is consistent with an asymptotic relationship between depredation and local sablefish abundance (1.. 1.5). Moreover, a significant gap in killer whale distribution between Kodiak Island and Unimak Pass may be contributing to lower overall depredation rates in the WGOA (Zerbini et al., 2007).

The method used to quantify depredation during surveys may lead to biased estimates of the proportion of skates affected by killer whale depredation. Skates were labeled as depredated if killer whales were sighted within 300 meters of the vessel and there was evidence of depredation or damaged fish on the set. Killer whale presence can be difficult to confirm visually if sea surface conditions are rough or the whales are depredating far off the vessel, resulting in an underestimate of the number of affected skates. In contrast, it is possible that some damaged fish brought on board were damaged by sharks, other fish, or sand fleas (Crustacea: Amphipoda) (High, 1980; Trumble et al., 2000; Dalla Rosa and Secchi, 2007; Stahl and Holum, 2008), possibly resulting in an overestimate of affected skates. Despite the challenges inherent in confirming killing whale depredation, we are confident these results represent a reasonable, if not slightly conservative, estimate of the proportion of skates affected by killer whales on the longline survey and associated catch reductions of depredated groundfish species.

The NMFS longline survey spends a relatively short amount of time sampling in western Alaska each year, making it difficult to identify seasonal trends in killer whale depredation or to draw larger fleet-wide conclusions. There are also important differences between NMFS longline survey methods and the operations of the commercial sablefish or Pacific halibut fisheries. The longline survey fishes pre-determined stations at set times each day irrespective of the presence of depredating whales. The longline survey also fishes with a factory processing vessel, which processes fish at sea and releases a stream of offal that may distract whales from the longlines. Conversely, many fishermen do not process at sea (delivering shoreside in the round) and employ a number of tactics to avoid depredating whales including dropping their gear to "wait the whales out," moving to a different fishing location, or using deterrents such as seal bombs. These whale avoidance measures employed by longline fisheries likely reduce the overall number of skates affected by killer whales. Despite these differences, this analysis of killer whale depredation using NMFS sablefish longline survey data serves as an important first proxy for what the commercial fisheries could experience when depredating killer whales arrive during fishing operations.

1.4.2 Killer Whale Depredation in Alaska

Trends in predicted mean catch reductions associated with killer whale depredation concur with previous regional catch reduction assessments conducted in the 1980s. Killer whale depredation was studied in the BS and AI during the Japan-U.S. cooperative longline survey from 1980 - 1989. Based on a comparison of annual average catch rates among years, killer whale depredation resulted in losses ranging from 14 - 60% for sablefish, 39 - 69% for Greenland turbot, and 6 - 42% for arrowtooth flounder (Yano and Dahlheim, 1995a). The impact of killer whale depredation on a commercial fishery was studied in Prince William Sound in 1985 and 1986, where it was estimated that 25% to 35% of overall sablefish catch was lost to killer whales. Individual sets were affected by as much as 80% to 90% for sablefish and Pacific halibut (Matkin, 1986; Matkin, 1988), consistent with our results that average reductions in the three management areas ranged from 54% to 72% for sablefish. The authors are aware of no previous studies investigating killer whale depredation and catch reductions specific to the WGOA, likely because killer whale depredation in this region has primarily been observed in more recent years (Yano and Dahlheim, 1995a).

Killer whale social structure and distribution likely plays a critical role in shaping their interactions with longline fisheries in western Alaska. A recent study by Fearnbach (2012) evaluating movement and association patterns based on photo-identification data from 2001 - 2010 in western Alaska indicated four distinct clusters or groups of “resident” killer whales in western Alaska, likely composed of stable matrilineal groups with unique ranging patterns. Cluster 2 whales (central AI with north/south movements in the BS) formed the largest cluster identified in this study (Fearnbach, 2012). The extensive ranges and relative abundance of cluster 2 whales in the BS overlapped with the highest proportion of skates depredated and percentage catch reductions experienced on the NMFS longline survey. It is possible that individual whales within this cluster have learned to specialize in the depredation behavior as a cooperative foraging strategy in this area (Tixier et al., 2010). There is significant spatial overlap and, therefore, social connectivity between the four clusters of killer whales in northwest Alaska. In particular, cluster 2 (central AI and BS) and 3 (eastern AI) whales showed relatively extensive ranges (maximum distance between repeated encounter locations), averaging 236 km and 430 km, respectively. The spatial overlap and social connectivity between these groups of whales provides insight into how the depredation behavior could spread throughout western Alaska through cultural transmission of the learned behavior (Fearnbach, 2012)

1.4.3 Implications for Commercial Longline Fisheries

Killer whale depredation was documented as early as the 1960s in the BS by Japanese longliners (Matkin, 1986; Dalheim, 1988), and whale depredation has played a major role in changing fishing practices of longline fleets; specifically gear type, season timing, and proportion of total allowable catch harvested of certain groundfish in the BS. The sablefish fishery in the BS has seen a large number of vessels transitioning to pots as a result of killer whale depredation. In 2000, the pot fishery accounted for less than 10% of the fixed gear sablefish catch in the BS and AI, whereas in 2009 pot fishing accounted for over 70% of sablefish catch in the BS (Hanselman et al., 2011). The Greenland turbot longline fishery was forced to delay the start of the fishing season to avoid depredating killer whales (Ianelli et al., 2011). And for the first time in 2008, the proportion of Greenland turbot caught by trawlers exceeded the proportion of Greenland turbot caught by longlines (Ianelli et al., 2011). Additionally, BS sablefish, Greenland turbot, and Pacific halibut fisheries have not been prosecuted to the full extent of the total allowable catch in recent years (Hanselman et al., 2011; Ianelli et al., 2011; NMFS RAM Division, 2012). Fishermen report that this is in part due to severe killer whale interactions in this area (M. Peterson, Unpublished). Changes in gear type, such as the increased prevalence of sablefish pot gear in the BS (which is not depredated), could result in the transfer of additional killer whale depredation effort to other longline fisheries, such as Pacific halibut or Greenland turbot (which cannot be fished with pots to date).

WGOA fishermen accounts and model results from this study indicate that killer whale depredation in the WGOA became more severe between the late 1990s through 2007. In addition to the growing problem of killer whale depredation in the WGOA, commercial longline fisheries face an extra challenge with sperm whale interactions occurring in the same region. The killer whale effect was significant for both sablefish and Pacific halibut catch in the WGOA, and overall survey catches were reduced by 10.5% and 9.3%, respectively. Despite relatively moderate catch rate reductions in the WGOA, especially compared to the BS, the magnitude of the economic losses to the commercial fisheries in the WGOA could exceed that of the BS or AI in the WGOA when higher quotas and increased fishing effort are taken into account. For instance, in 2011 sablefish commercial catch in the WGOA was twice as large as BS or AI sablefish catch, and the Pacific halibut catch in the WGOA (Area 3B) was two to three times larger than that in the AI (Area 4A/4B) or BS (Area 4C/4D; (NMFS RAM Division, 2012). Pot fishing for sablefish is currently not legal in the Gulf of Alaska; however, the North Pacific Fishery Management Council is conducting reviews to determine the feasibility of reintroducing pot fishing for target groundfish species in the Gulf of Alaska.

A number of studies have investigated mitigation measures to reduce whale interactions, such as shifted fishing seasons, deterrents, physical catch protection, gear modifications, and acoustic harassment devices (Mooney et al., 2009; Rabearisoa et al., 2009; McPherson and Nishida, 2010; Rabearisoa et al., 2012). In contrast to pelagic longline tuna and swordfish fisheries, killer whale depredation on demersal fisheries in Alaska typically occurs during haulback operations. Thus, physical catch protection for demersal fisheries could occur through gear modifications designed to protect the fish during gear retrieval. Catch protection devices such as the "umbrella-and stone" Chilean longline system were tested on Patagonian toothfish fisheries in the Southwest Atlantic. Although these devices did reduce depredation, there may be a negative effect on CPUE (Moreno et al., 2008; Goetz et al., 2011). Active or passive acoustic deterrents could be another method to deter killer whales away from fishing gear (Mooney et al., 2009). There is no single remedy against killer whale depredation to date, and it is possible that a combination of gear modifications, deterrents, and adaptive management (such as shifted fishing seasons or altered season durations) will be necessary to reduce the frequency of the interaction.

1.5 Conclusions

This study provides new information on the potential effects of killer whale depredation on the NMFS longline survey and commercial groundfish fisheries in western Alaska. Killer whale depredation primarily impacts catch rates of sablefish, Greenland turbot, arrowtooth flounder and Pacific halibut, and there are indications that killer whale depredation may be getting more severe in the AI and WGOA. Results from this work are also relevant for the development of a correction factor for the annual fish stock abundance indices to account for depredation. The NMFS longline survey is currently forced to drop data from skates affected by killer whale depredation. This is particularly problematic for the BS and AI management areas where stations are only sampled every other year. The modeling methodologies from this research using NMFS longline survey data provides a framework for future studies of whale depredation on commercial fisheries operating in the region, and we are currently examining NMFS Fishery Observer data and surveying fishermen to gain further insights into the effect of depredation on fishing operations. Effective management of whale depredation in Alaska requires the establishment of baseline data on depredation rates, depredation trends, and the impacts of depredation on catch rates on the NMFS longline survey and the commercial longline fisheries.

1.6 Acknowledgements

This research was also supported by the Rasmuson Fisheries Research Center, the National Science Foundation (NSF) Marine Ecosystem Sustainability in the Arctic and Subarctic (MESAS) IGERT (Award DGE-0801720) and the NSF Arctic Social Sciences Program (Award 1107401). Photographs were collected under Permit Number 14122, issued by NMFS.

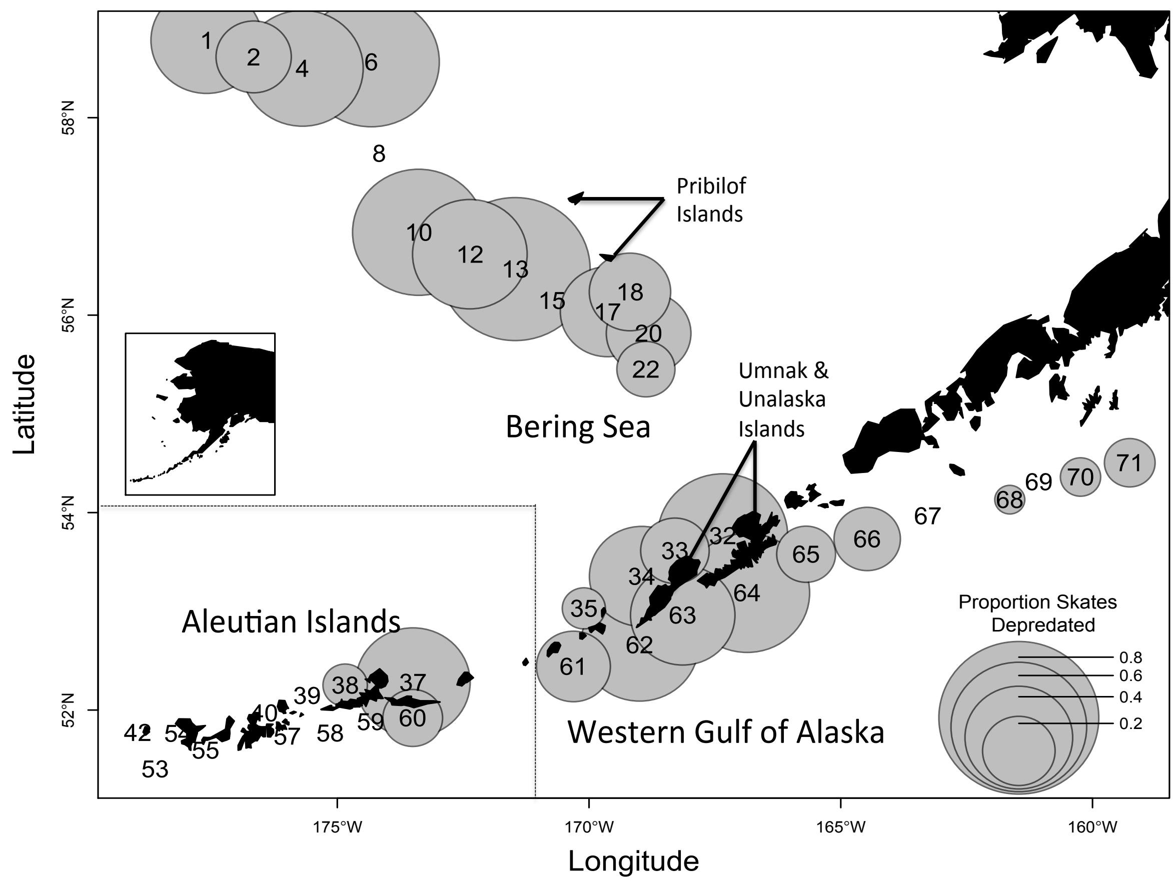

Figure 1.1 Stations surveyed on the NMFS sablefish longline survey (numbered 1-71) in the Bering Sea, Aleutian Islands and Western Gulf of Alaska, NMFS longline survey 1998-2011. Symbol sizes (grey circles) are equivalent to the average proportion of skates depredated by killer whales at each station.

Figure 1.2 Photographic evidence of killer whale depredation; (a) juvenile killer whale approaching to dive on the longline gear (b) Pacific halibut, arrowtooth flounder and sablefish damaged by killer whales (c) fisherman with killer whale photographed near longline vessel in background (d) evidence of bite marks, crushed tissue and lip remnants demonstrate varying degrees of damaged sablefish.

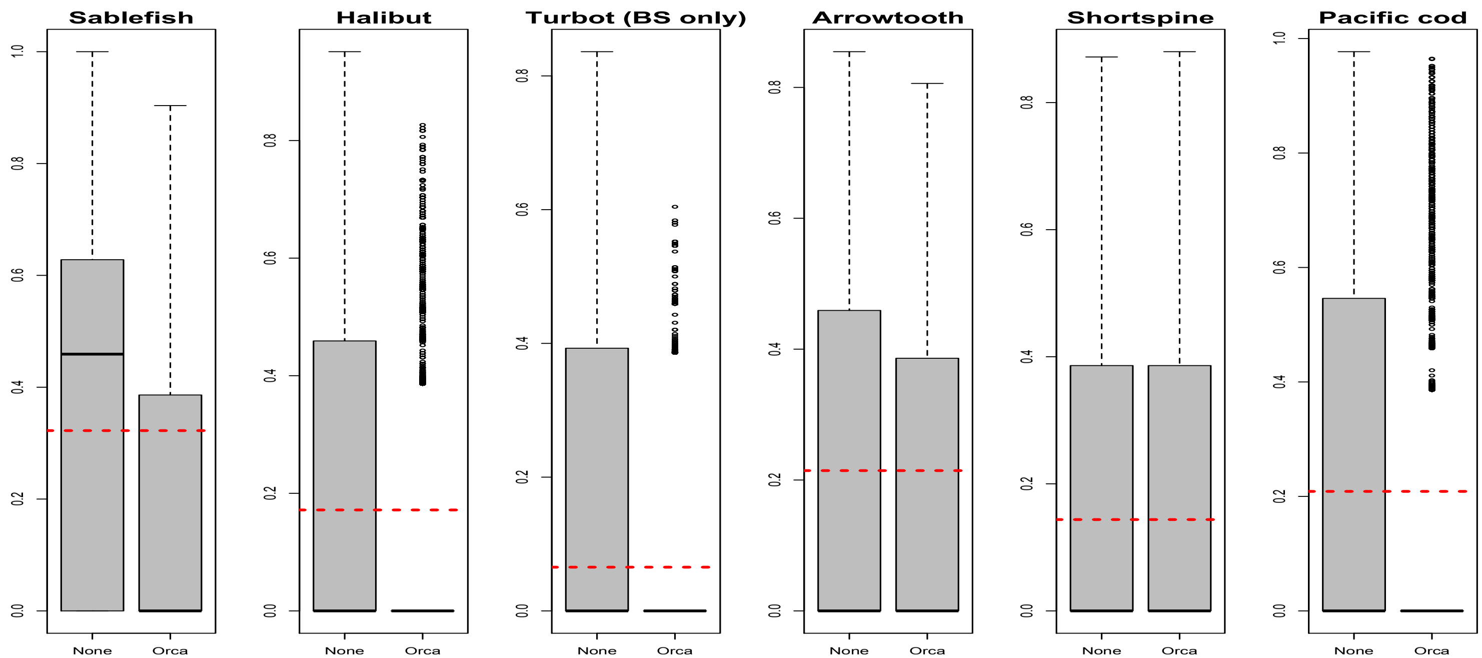

Figure 1.3 Groundfish CPUE and killer whale depredation. CPUE averaged over time and across all survey stations, with ('Orca') and without ('None') killer whales present, NMFS longline survey 1998-2011. Black bars denote median, dotted lines denote overall mean, grey boxes denote lower and upper quartiles and whiskers extend to the closest observation that is less than 1.5 times the interquartile range from the upper quartile.

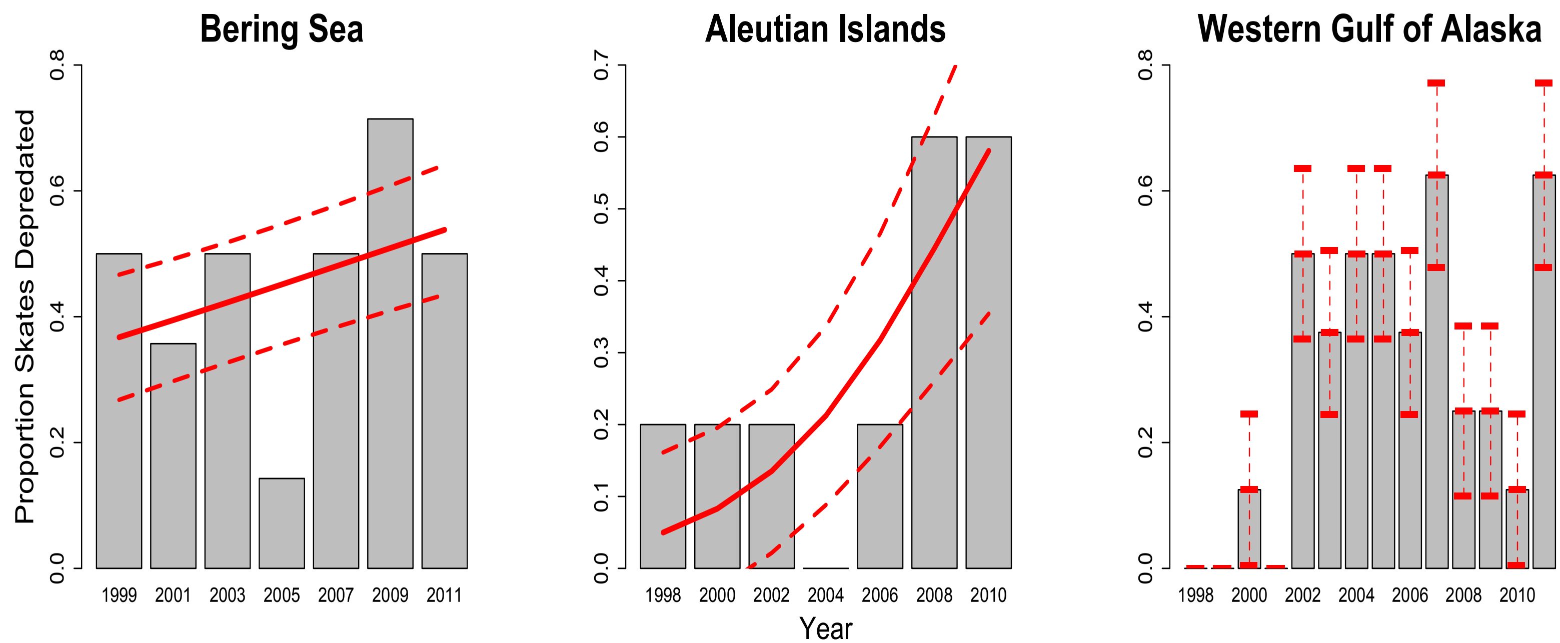

Figure 1.4 Observed and estimated proportion of skates depredated by killer whales +/-2SE for each management area, NMFS longline survey 1998-2011, based on AIC-best model (see text). Temporal trend was significant for Aleutian Islands ($p = 0.049$) and difference between years in the Western Gulf of Alaska were significant ($p < 0.001$).

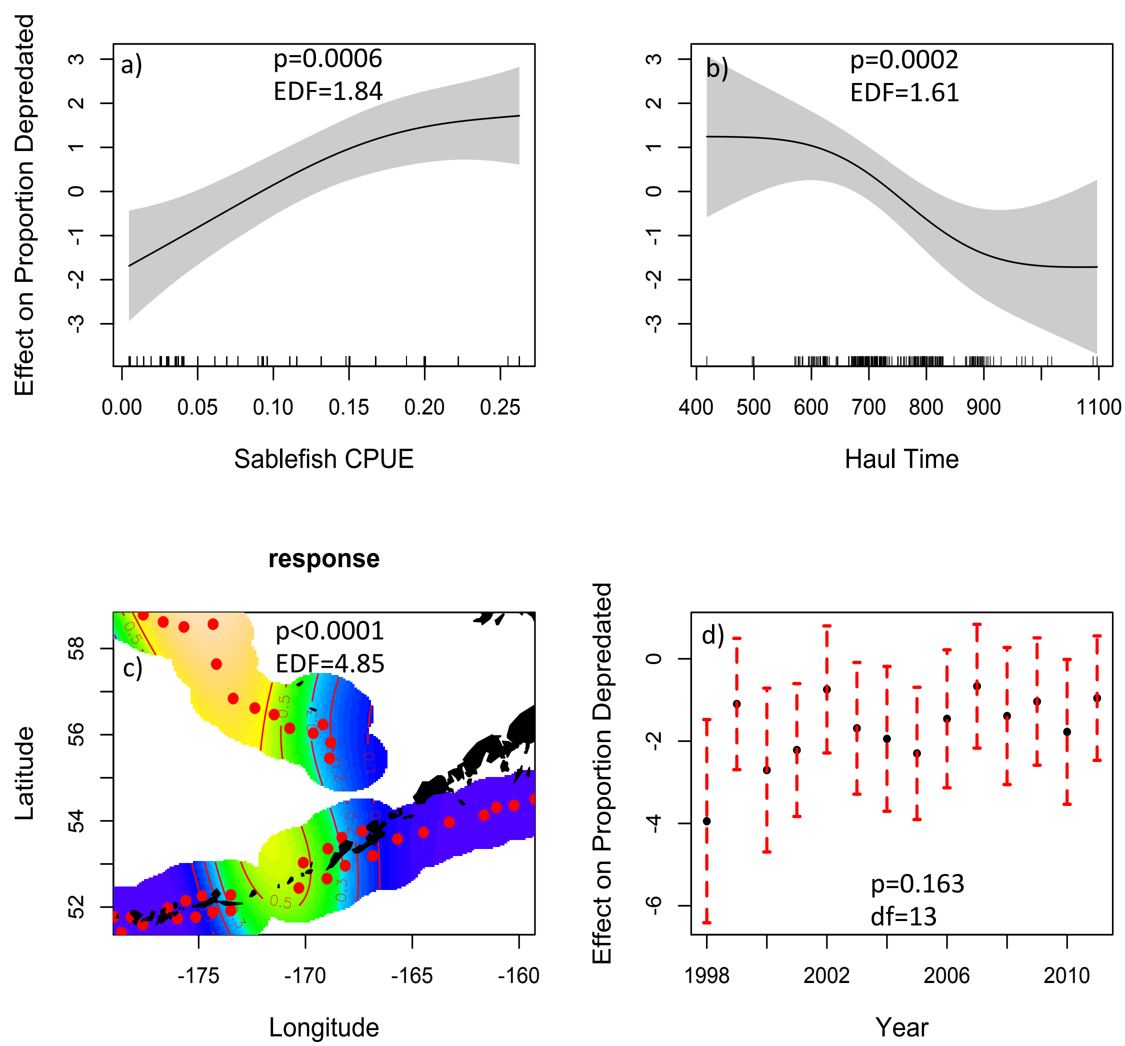

Figure 1.5 Factors affecting depredation occurrence. Additive effects of a) sablefish CPUE, b) haul time, c) spatial location (Latitude/Longitude), and d) year on the proportion of depredated skates estimated using generalized additive model with binomial response. Shaded areas represent approximate 95% confidence bands. Estimated degrees of freedom and p-values associated with each term are shown in associated panel. Significance based on z-test for year and Chi-square test for sablefish CPUE, haul time and latitude/longitude.

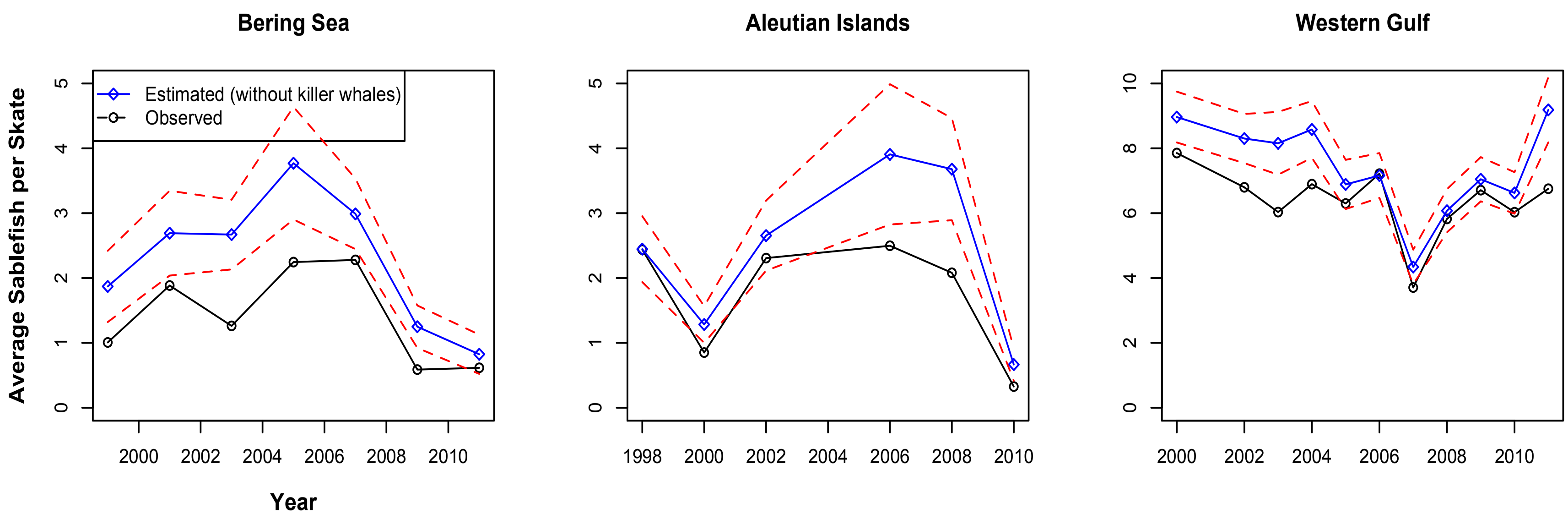

Figure 1.6 Observed and model-estimated catches of groundfish. Observed (open circles) and model-estimated (open squares) average annual catches of groundfish in the absence of killer whales with 95% confidence bands (dashed lines), NMFS longline survey 1998-2011

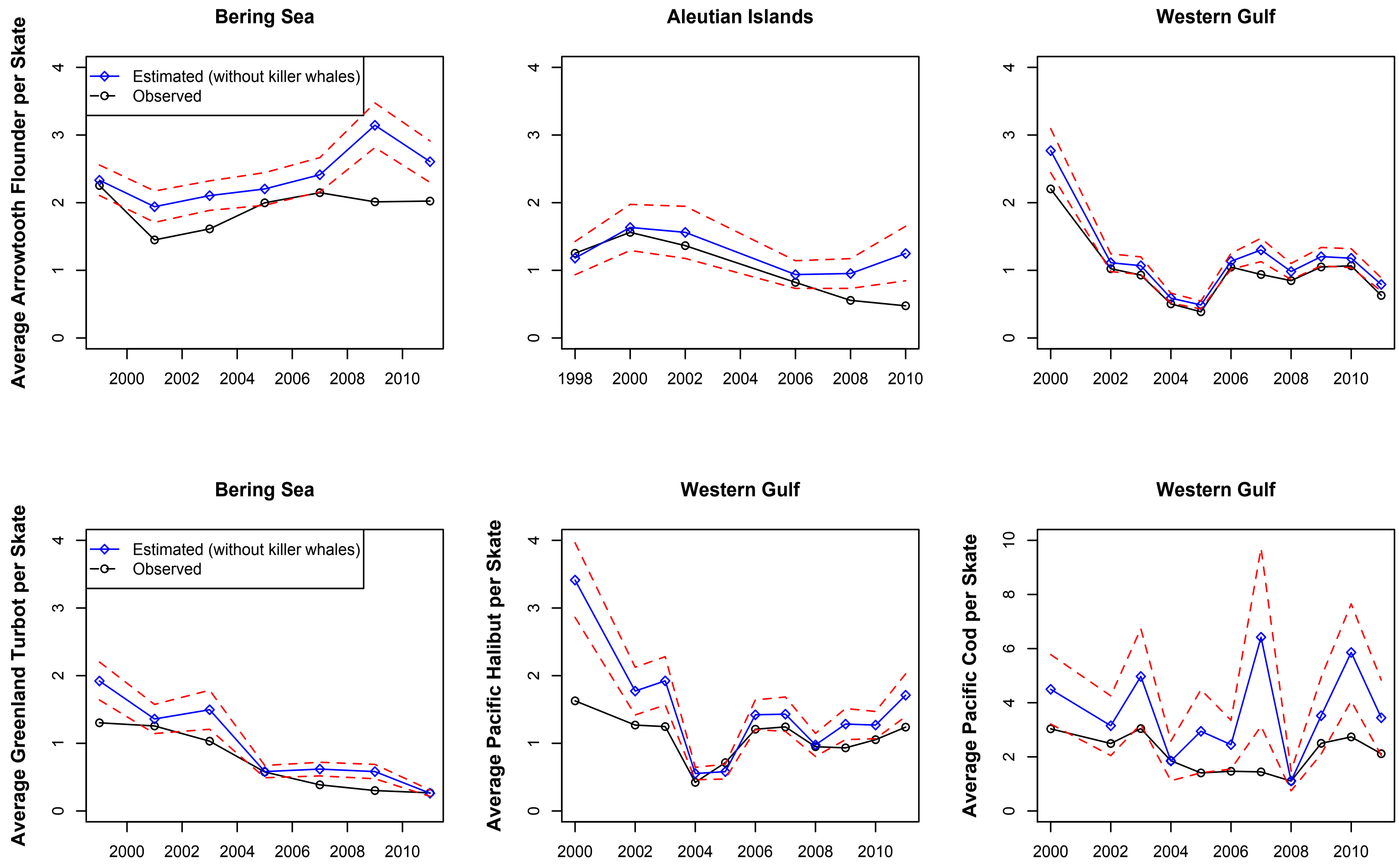

Figure 1.6 Continued.

Table 1.1 NB GLM results by management area and species. The response variable, number of fish caught per stratum, followed negative binomial distribution. The results displayed the mean and range of predicted annual catch losses associated with whale depredation, the model-estimated difference in catch between depredated and non-depredated skates, whether the killer whale depredation effect was significant (p<0.05), degrees of freedom (DF), percentage of deviance explained (%dev), the sample size (aggregated catch by stratum; n), Akaike Information Criterion (AIC) and the dispersion parameter (theta).

Area	Species	Mean Predicted Annual Catch Lost (%)	Minimum Predicted Annual Catch Lost (%)	Maximum Predicted Annual Catch Lost (%)	KW coefficient	KW Effect Signficant (p-value)	DF	%dev	n	AIC	Theta
Bering Sea	Sablefish	-28.9	-2.0	-50.6	-0.72	p<0.001	105	86.6	475	2839	2.11
	Greenland turbot	-22.0	-0.8	-39.1	-0.73	p<0.001	105	73.2	478	3018	1.53
	Arrowtooth flounder	-20.3	-1.8	-58.1	-0.51	p<0.001	105	65.0	478	4353	2.49
	Pacific halibut	-13.5	-0.8	-26.0	-0.39	p=0.088	97	63.3	455	3537	1.65
	Pacific cod	8.3	3.1	17.4	0.30	p=0.399	97	83.7	455	3719	2.01
	Shortspine thornyhead	NA	NA	NA	0.21	p=0.527	105	88.2	478	1987	3.15

Table 1.1 Continued.

Area	Species	Mean Predicted Annual Catch Lost (%)	Minimum Predicted Annual Catch Lost (%)	Maximum Predicted Annual Catch Lost (%)	KW coefficient	KW Effect Signficant (p-value)	DF	%dev	n	AIC	Theta
Aleutians	Sablefish	-23.6	-5.7	-62.0	-0.72	p<0.001	37	69.5	172	1275	1.35
	Arrowtooth flounder	-21.8	-3.3	-63.1	-0.84	p<0.001	37	56.1	178	1188	1.07
	Pacific halibut	-5.7	0.0	-26.0	-0.49	p=0.072	36	79.6	172	1096	2.37
	Pacific cod	1.8	0.0	9.0	0.32	p=0.507	37	93.4	178	1016	3.94
	Shortspine thornyhead	NA	NA	NA	-0.07	p=0.243	38	84.9	172	758	2.60
Western Gulf of	Sablefish	-10.5	-2.6	-22.3	-0.54	p<0.001	95	60.7	569	6028	2.17
	Arrowtooth flounder	-10.2	-1.8	-29.5	-0.44	p<0.001	95	65.5	569	3840	2.03
	Pacific halibut	-9.3	-0.7	-24.9	-0.51	p<0.001	93	75.1	484	3175	2.17
	Pacific cod	-10.5	-0.2	-25.9	-0.46	p=0.015	93	91.8	484	2322	1.74
	Shortspine thornyhead	-7.1	-1.8	-12.1	-0.18	p=0.32	95	44.5	569	4508	1.27

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Chapter 2

Whale interactions with Alaskan sablefish and Pacific halibut fisheries: Surveying fishermen's perception, changing fishing practices and mitigation[2]

[2] Megan J Peterson, Courtney Carothers. 2013. Marine Policy 42: 315-324.

Abstract

Whale depredation occurs when whales steal fish, damage fish or damage fishing gear. In Alaska, killer whales (*Orcinus orca*) and sperm whales (*Physeter macrocephalus*) primarily depredate on demersal sablefish (*Anoplopoma fimbria*) and Pacific halibut (*Hippogolossus stenolepis)* longline fisheries. Quantitative data on whale depredation in Alaska is limited due to low fishery observer coverage and minimal depredation evidence left on longline fishing gear. This study utilized semi-directed interviews (n=70) and written questionnaires (n=95) with longline fishermen to examine: 1) perceptions and experiences of whale-fishery interactions in Alaska, 2) effects of depredation on fishing practices, and 3) potential depredation mitigation measures. Eighty-seven percent of fishermen surveyed agreed that whale depredation became worse between 1990 and 2010. Respondents reported changing their fishing practices in response to depredating whales in several ways, including: traveling up to 50 nautical miles and ceasing hauling operations up to 24 hours until the whales left the fishing grounds. Respondents fishing in western Alaska, primarily encountering killer whales, were forced to wait longer and travel greater distances than fishermen operating in central and southeast Alaska, regions more affected by sperm whales. Deterrent research, gear modifications and real-time tracking of depredating whales were solutions favored by study participants. Survey respondent answers varied based on areas fished, quota owned, years involved in the fishery and vessel size. This study

presents the first statewide evaluation of fishermen's perception and knowledge of whale interactions with the Alaskan longline fleet and is a critical step towards developing baseline data and feasible depredation mitigation strategies.

2.1 Introduction

Increased fishing effort in Alaska throughout the 20th century has expanded anthropogenic influences on marine ecosystems and marine predators [1-3]. Interactions and competition with other cosmopolitan apex predators is a logical outcome of increased human presence in and reliance on marine environments. This interaction is exemplified by the issue of killer whale (*Orcinus orca*) and sperm whale (*Physeter macrocephalus*) depredation on longline fisheries in Alaska. Killer whale and sperm whale depredation occurs when whales remove fish from longline gear, damage fish or fishing gear. In Alaska, killer whales and sperm whales primarily depredate on high-dollar demersal longline fisheries such as sablefish (*Anoplopoma fimbria*) and Pacific halibut (*Hippogolossus stenolepis*). Killer whale interactions with longline fisheries occur in four main regions in Alaska: the Bering Sea, Aleutian Islands, Western Gulf of Alaska, and the coastal waters of Prince William Sound [4-6]. Sperm whale depredation predominates in the eastern Gulf of Alaska through Southeast Alaska [6, 7](Figure 2.1).

Whale depredation has negative consequences for fishermen, management agencies and the whales themselves. Depredation can lead to significant economic losses for fishermen in the form of reduced catch, increased operating costs, and damaged gear [8-11]. Overall catch rates can decline by as much as 30% and individual sets by 100% in the presence of depredating whales [6, 12, 13]. The potential effects that depredation may have on the accuracy of fish stock abundance indices is a critical issue for management agencies with important implications for fishermen [9, 14, 15]. Depredating whales may get a relatively easy meal of fish hooked on longline gear, but this activity can also have harmful consequences for the whales [16, 17]. Whales may be at greater risk of mortality or injury from vessel strikes, risk of entanglement in gear and fishermen's frustration [8, 17-19]. For instance, in Prince William Sound in the 1980s, killer whale groups known for their interactions with longline vessels were photographed with bullet holes in their dorsal fins [20]. There is also a risk associated with modifying marine mammal foraging behavior and energy balance towards an unnaturally available and unreliable prey resource [19].

Killer whales and sperm whales are the two largest species of *odontocetes* or toothed whales. They are also the most cosmopolitan marine mammals with ranges spanning the globe [21, 22]. Killer whales and sperm whales are K-selected species with large body size, long life spans, low natality rates and high maternal investment [23]. Killer whale depredation was documented as early as the 1960s by Japanese longliners in the Bering Sea [4]. It was estimated in 2010 that a minimum of 1300 resident killer whales inhabit the Bering Sea, Aleutian Islands and Western Gulf of Alaska [22]. However, more recent photographic mark-recapture assessments indicate that significantly more (perhaps twice this number) fish-eating killer whales use the coastal waters around the eastern and central Aleutians alone in some years [24]. Stock structure and abundance data are relatively deficient for north Pacific sperm whales [21], and as of 2012, they were listed as “endangered” under the 1973 Endangered Species Act and “depleted” under the 1972 Marine Mammal Protection Act. Depredation by sperm whales in Alaska is presumed to be primarily by solitary mature males from the North Pacific stock [25]. Whereas killer whale depredation has a longstanding history in Alaska [4], sperm whale depredation in the Gulf of Alaska is a relatively more recent phenomenon. Documented interactions with sperm whales may have increased in the late 1990s following the implementation of individual fishing quotas (IFQ) and associated extended sablefish and Pacific halibut fishing seasons [26].

The problem of toothed whale depredation is particularly acute in Alaska, where lucrative longline fisheries are prosecuted in areas supporting some of the world’s greatest densities of fish-eating killer whales in western Alaska and an anecdotally increasing population of sperm whales in the Gulf of Alaska [24, 26]. The Pacific halibut fishery is managed jointly by the US and Canada under the International Pacific Halibut Commission. The Alaska sablefish fishery is managed by the North Pacific Fisheries Management Council (NPFMC). During the mid-1970s both fisheries experienced a significant reduction in season length, resulting in “derby-style” fishing with openers as short as 24 hours [27, 28]. Due to shorter fishing seasons and increased harvesting capabilities of larger vessels, the NPFMC implemented an IFQ program in federal waters off Alaska for sablefish and Pacific halibut in 1995 [27, 29, 30]. These fisheries have experienced significant consolidation since the inception of the IFQ program, and the number of vessels participating in the fisheries declined dramatically from 1995-2011, by about 70% for both sablefish and halibut [31]. The sablefish and Pacific halibut commercial longline fisheries are typically open for nine months, from mid-March to mid-November. The majority of sablefish quota is harvested in April and May, whereas most halibut quota is harvested in June[31]. In 2011, standard ex-vessel prices averaged $5.25 per pound for sablefish and $6.60 per pound for Pacific halibut [32]

Pacific halibut fisheries are almost entirely prosecuted using fixed longline gear as Pacific halibut catch rates in pot fishing gear are relatively low [33]. Sablefish can effectively be fished with pot gear; however, pot fishing for sablefish or Pacific halibut is currently only allowed in the Bering Sea and Aleutian Islands management areas [34]. The sablefish fishery in the Bering Sea has seen a large number of vessels transitioning to pot fishing due in part to killer whale depredation [34]. In 2000, the pot fishery accounted for less than 10% of the fixed gear sablefish catch in the Bering Sea and Aleutian Islands, whereas in 2009 pot fishing accounted for over 70% of sablefish catch in the Bering Sea [34]. Sablefish and Pacific halibut fisheries in the Gulf of Alaska management areas are prosecuted with fixed longline gear only [35]. In 2012, the total allowable catch (TAC) for Pacific halibut was 23.3 million net pounds (headed and gutted) and 26.5 million round pounds for sablefish, with the highest catches occurring in the Central Gulf followed by the Western Gulf and Southeast Alaska [36]. The percentage of quota landed is generally close to 100% in most management areas, with the exception of Bering Sea sablefish and Pacific halibut fisheries, which typically have not been harvested to the full extent of the total allowable catch in recent years [31, 34, 37].

This study of fishermen's knowledge uses a mixed methods approach of semi-directed interviews and written questionnaires to examine how fishermen perceive whale interactions, the way in which depredation shapes fishing behavior, and potential depredation mitigation solutions. Fishing knowledge is based upon experience and interactions with marine environments through long-term observation and direct interaction with marine resources [38-40]. Studies incorporating fishermen's local knowledge are gaining traction in conventional scientific and policy forums [39, 41, 42]. Fishermen's knowledge can elucidate long-term time trends and spatial components to systems not captured within traditional data sets [43-45]. Fishermen's knowledge can also be useful in studies examining topics, such as whale depredation, where data is deficient [42]. Previous studies of depredation in Alaska are limited and have focused on quantifying the magnitude of depredation, relying primarily on biological survey data [6, 7, 46]. To our knowledge, this study serves as the first detailed examination of whale depredation in Alaska using social science research methods, focusing on fishermen's perception and experience based on results from interviews and written surveys collected across Alaska from 2010 to 2012.

2. 2 Methods

2.2.1 Interviews

Semi-directed interviews (n=70) were conducted with longline fishermen from July 2010 through December 2011. Semi-directed interviews enable a researcher to guide an interview, but provide space for participants to dictate the direction and scope of the interview [47, 48]. Informants were selected using snowball sampling methods. Snowball sampling is a nonprobability method for selecting respondents, often based on their representativeness or fishing experience [49]. In this study, colleagues and fisheries managers recommended fishermen with long-term experience in the longline fishery. These fishermen in turn recommended other fishermen with long-term experience in the Alaskan longline fleet. Interviews ranged in length from 30 minutes to 150 minutes. Interviews were conducted in-person and recorded via livescribe with permission when logistically feasible. Remaining interviews were conducted over the phone and were recorded with permission via skype call recording. Recorded interviews (n=55) were then transcribed and uploaded into Atlas.ti, a qualitative data analysis software. Interview data were list-coded for thematic content based on inductive coding methods and a grounded theory approach [47, 50, 51]. These techniques were used to identify concepts and themes that appear in the interview text and link emergent concepts together to develop formal theories [50]. Interviews were analyzed for code frequency and code co-occurrence.

2.2.2 Written Survey Instruments

Results from a literature review and thematically coded interviews were used to construct a written survey instrument distributed to longline fishermen in 2011 and 2012. A purposive sample of respondents (n=95) was selected based on long term fishing experience and, therefore, was deliberately non-random [39, 49, 52]. This nonprobability method limits the theoretical basis for drawing fleet-wide inferences and for measuring variability and bias [49]. Despite limitations associated with nonprobability sampling, selectively targeting respondents with long-term fishing engagement enables researchers to work with fishing participants with the most experience in and "direct links" to the marine environment [39]. The written survey was distributed in-person to experienced Alaskan quota holders across a wide geographic range of fishing communities in Alaska and Washington at community meetings, longline fishing association, and regional fishery management meetings. Survey distribution generally followed an introductory presentation about the subject matter and the research project. The distribution of reported survey respondent effort by management area and quota harvested by vessel category closely mirrored the 2012 true fishery breakdown for quota units harvested by management area and vessel categories [53], indicating a sample that was representative of basic true fishery characteristics.

The written survey was divided into four sections: demographic and fishing information, perceptions of the depredation problem, strategies for depredation avoidance, and suggested solutions. In the survey, specific management areas were grouped into three main regions: 1) Western Alaska (Bering Sea, Aleutian Islands, Western Gulf) 2) Central Gulf, and 3) Southeast Alaska (Figure 2.1). Written survey question methods included Likert scales, true-false, multiple-choice and open-ended questions [54-57]. Survey questions were analyzed for basic trends and to explore hypotheses addressing response differences by management area, region, species most often encountered (sperm whales or killer whales) or vessel size.

A generalized linear proportional odds model for ordered categorical data was used to investigate factors shaping fishermen's depredation avoidance practices. Proportional odds models require fewer parameters and are commonly used to estimate the odds ratio of the cumulative probabilities of responses for ordered categorical data [49, 58, 59]. Four models were run to address each question individually: 1) average time fishermen waited to avoid depredating whales per season, 2) average number of times per season fishermen were forced to wait, 3) distance fishermen traveled to avoid depredating whales, and 4) average number of times per season fishermen were forced to travel due to whales. Based on interview results, whale species most often encountered and vessel size were hypothesized to influence changed fishing practices. Additional explanatory variables considered included primary fishing region, total quota owned, and years fishing. The final model for each question was selected based on lowest Akaike Information Criterion (AIC) score and model diagnostics [58-60].

Individual Likert-type items with the same directionality were grouped together by theme and summed to create composite Likert scales [54-56] with four focus areas: depredation trends (assessing how fishermen perceived temporal trends); personal impacts (measuring the severity of impacts that fishermen experienced due to whale interactions); solutions (evaluating how fishermen perceive depredation solution options); changing fishing practices (investigating whether fishermen significantly altered their fishing behavior in response to depredating whales). These four Likert scale composites were analyzed using linear regression methods [49, 60]. Final models were selected based on stepwise regression and model diagnostics [60].

2.3 Results

2.3.1 Interviews

Fifty-five interviews were transcribed and analyzed in Atlas.ti. In total, 921 interview excerpts were assigned a specific code. Four themes were identified during qualitative data analysis: changing fishing practices, management issues (e.g. stock assessment, quota allocation), depredation trends and whale behavior (Figure 2.2). Changing fishing practices was broken down into three sub-categories: shifted fishing seasons, depredation avoidance measures to evade whale interactions, and deterrent measures to confuse or disturb the whales. Example deterrents included seal bombs and acoustic harassment devices. Forty codes were designated under the four themes. “Depredation avoidance,” “deterrents,” “pot gear,” “management,” and “depredation trends” were the most commonly occurring codes across all interviews (Figure 2.3). The highest code co-occurrence rates were: “changing fishing practices" and "depredation avoidance (r=0.17)," and "personal quota" and "depredation impacts on quota (r=0.15)." "Pot gear" co-occurred most commonly with "management (r=0.10)" and "depredation solutions (r=0.11)."

2.3.2 Written Surveys

2.3.2.1 Respondent Demographics

A total of 95 longline fishermen completed written questionnaires. Combined, these fishermen fished approximately 6.4 million pounds of Pacific halibut quota (27% of overall halibut quota in 2012) and 5.8 million pounds of sablefish (20% of overall sablefish quota harvested in 2012). The average number of years respondents were involved in the longline fishery was 22.6 years for a sum total of 1,990 years for all respondents. The majority (92%) of respondents were male, and the average age of all respondents was approximately 47.5 years. Survey respondents reported primary fishing effort in the Central Gulf (36%), Southeast Alaska (31%), Western Gulf (17%), Bering Sea (10%), and Aleutian Islands (6%). The total amount of quota owned by respondents was not correlated with the number of years spent fishing or age (Pearson correlation test, $p > 0.50$) but was significantly different among management areas (ANOVA, $F=4.4$, $p = 0.003$), with the median quota higher for fishermen operating primarily in the Western Gulf and Bering Sea. Only six of the 95 respondents reported having fished pot gear for sablefish at some point during their career. Respondents reported the majority of quota (lbs) was caught on catcher vessels less than 60 ft (category C; 44%), followed by catcher vessels greater than 60 ft (B; 39%), freezer vessels (A; 12%), and catcher vessels less than 35 ft (D; 4%), which corresponded closely with the true fishery breakdown of quota harvested by vessel category [36].

2.3.3 Fishermen Experience and Perception

2.3.3.1 Depredation Trends

The majority of respondents strongly agreed (78.3%) or mostly agreed (8.7%) that whale depredation became worse between 1990 and 2010, and most respondents strongly agreed (57.6%) or mostly agreed (16.3%) that they were frustrated by whale depredation. Respondents (65.6%) cited "more whales" or "whales learning the behavior" as the primary reasons for depredation becoming more severe as an interaction. "Longer fishing seasons [associated with the IFQ program]" (11.8%) was also noted as a reason for the interaction becoming more problematic for longline fishermen in Alaska. Respondents were asked which species of whale generally depredated where they fished. Just over half of the respondents reported interactions primarily with sperm whales (56.7%). The remaining 41 respondents (43.1%) reported encountering mostly killer whales. The species fishermen described interacting with most frequently was significantly correlated with the area where they reported fishing most (Pearson's Chi-squared test, $X^2 = 47.5$, $p < 0.001$); with fishermen in the Bering Sea, Aleutian Islands and Western Gulf confronting killer whales and fishermen in Southeast interacting almost entirely with sperm whales.

Survey respondents were asked an open-ended question to list any marine environment characteristics they associated with whale depredation. The majority of respondents (55%) that responded to the question (n=42) listed “high catch rates,” suggesting whales target fishing grounds with higher catch per unit effort (CPUE). Additional factors reported to contribute to depredation included, “season” or “time of year” and “depth,” with depredation generally thought to be more severe in the spring in April or May and along the shelf edge at depths greater than 100 fathoms for sperm whales (Figure 2.4). Fishermen expressed “loss of catch” associated with whale depredation was their biggest concern (34.7%), followed by “inaccurate stock assessments (17.9%).” Eighty-three percent of respondents strongly agreed or mostly agreed that whale depredation is reducing the accuracy of sablefish and Pacific halibut stock assessments.

2.3.3.2 Depredation Rates: Sperm Whales Versus Killer Whales

Survey respondents mostly encountering sperm whales reported seeing on average one to five sperm whales around the vessel when depredation occurred (93.6%). Respondents interacting mostly with killer whales reported an average of six to ten killer whales around the vessel during depredation events (52.6%). The majority of respondents (31.2%) estimated the overall percentage of sets depredated was 10-25%. There was no significant difference in the reported proportion of sets depredated between whale species or among fishing regions (Fisher’s exact test, $p > 0.05$). There were, however, significant differences in the reported depredation rate (catch removal) on individual sets when whales were present, based on whale species and region (Fisher's exact test, $p < 0.001$). The majority of respondents (70.7%) that reported interactions with killer whales (primarily western Alaska) estimated that depredation rates exceeded 40% of catch. In contrast, the majority of respondents (42.6%) experiencing interactions with sperm whales (eastern Gulf of Alaska) reported that depredation rates on individual sets were less than 20% of catch. Sablefish and Pacific halibut were the species most targeted by whales according to survey respondents. Additional groundfish species whales targeted included arrowtooth flounder (*Atheresthes stomias*), Greenland turbot (*Reinhardtius hippoglossoides)*, giant grenadier (*Albatrossia pectoralis*), and Pacific cod (*Gadus macrocephalus*).

2.3.4 Changing Fishing Practices and Depredation Avoidance

Survey respondents confirmed that fishermen are forced to change the way they fish in response to the threat or presence of depredating killer whales and sperm whales. Most respondents (64.1%) strongly agreed or agreed that they often had to fish less efficiently to avoid depredating whales, and 88.0% agreed or strongly agreed that they were constantly on the lookout for whales when fishing. Respondents reported that "moving to different fishing grounds (36.3%)" and "dropping the gear to wait the whales out (37.4%)" were their preferred methods to avoid depredating killer whales and sperm whales. A small percentage of respondents did report they preferred to fish through the set when whales were present (12.1%). Respondent answers varied by fishing region, and fishermen operating in central and eastern Gulf were more likely to report "moving to a different site" (Fisher's exact test, $p < 0.001$). Other avoidance measures selected included "fishing in tandem with other boats" (34.2%) and "hauling the gear quickly" (30.1%)."

Respondents were asked to estimate the frequency and extent of depredation avoidance measures they employed throughout the season; including the amount of time and how often they were forced to extend their gear soak time if whales showed up on the gear during haul-back operations and how far and how often they traveled to avoid depredating whales (Table 2.1). The majority of respondents fishing in central and eastern Alaska reported wait times less than 12 hours (68.3%) and forced travel distances generally less than 25 nautical miles (63%) in the presence of depredating whales (Table 2.1). Respondents fishing in western Alaska (Bering Sea, Aleutian Islands and Western Gulf) generally reported wait times greater than 12 hours (50.0%) and travel distances greater than 25 nautical miles (69.0%; Table 2.1).

2.3.5 Deterrents

Above we defined depredation avoidance as evasion methods employed once whales have already begun to depredate on set fishing gear. Deterrents were defined as aversive stimuli introduced to the whales' environment to deter or confuse the whales so that depredation may be less likely to occur. One interview respondent noted that deterrents are often ineffective, as whales learn to adapt:

> [We've tried] all kinds of electronic sounds, music, whatever; anything that would confuse them. But whatever you do, it seems they adapt to it. They know the sound of everybody's propeller screw out there.

Interview respondents reported using acoustic devices such as echolocation blockers or killer whale sound playbacks, targeted sonar, seal bombs, and dummy sets as deterrents. Most survey respondents answered that "acoustic deterrents (50.0%)" had the best chance of being an effective deterrent, followed by gear modifications (29.0%).

2.3.6 Management and Solutions

The issue of whale interactions with sablefish and Pacific halibut fisheries has implications for fishermen and fishery managers. There is concern amongst both groups that whale depredation negatively impacts the ability of fishery managers to accurately assess fish stocks. The majority of respondents strongly agreed (58.7%) or agreed (25.0%) that whale depredation reduces the accuracy of fish stock assessments. Over half of all respondents (56.5%) and 74.1% of western Alaska respondents disagreed or strongly disagreed with the statement that "managers have been up front and proactive in dealing with whale depredation."

When respondents were asked about management solutions to reduce the effects of whale depredation, 83.0% answered that "real-time tracking of whales" was a preferred management option, and 76.1% of respondents agreed or strongly agreed that they would be "interested in real-time tracking of groups of depredating whales by fishermen." Respondents had the option to list additional management measures not included on the survey question. Of those participants that responded to this optional open question (n=21), 33.3% listed "pot fishing" as their preferred management solution followed by "acoustic deterrents" (19.0%). Respondents were also asked the open question, "what could managers do to assist fishermen dealing with whale depredation?" The majority of participants who listed management solutions (n=54) focused on additional deterrent research (29.6%), the flexibility to switch to pot gear (18.5%) and additional whale abundance and movement research (16.7%). Real time tracking of whales, limited whale harvests, and federal reimbursement programs for losses were also commonly listed by respondents as potential management solutions (Figure 2.5).

The option to transition to pot gear is relevant to discussions of depredation avoidance, depredation mitigation, and management. Interview and survey respondent opinions were divided on the issue of opening up sablefish to pot fishing in federal Gulf of Alaska waters. Respondents fishing in the Bering Sea, Aleutian Islands, and Western Gulf were more likely to consider the transition to pots a viable option. For instance, 32.3% of western Alaska respondents strongly agreed that the transition to pots was a possibility versus 11.1% of Southeast respondents. Although respondent answers to the feasibility of a pot transition for sablefish harvesting was not statistically different based on fishing region (Fisher's exact test, p = 0.666), there was a significant relationship between vessel category and pot transition perception (Pearson's Chi-squared test, X^2 = 21.1, p = 0.049). Fishermen operating B class (catcher > 60 feet) and C class (catcher 35 – 59 feet) vessels were more likely to agree that the transition to pot fishing was a possibility on their vessels.

2.3.7 Predicting Perceptions and Changing Fishing Practices

Individual Likert questions were grouped together to create composite Likert scales for further analysis. The impacts scale dealt with the severity of impacts that fishermen experienced due to whale interactions. Higher impact scale values represented strong support or agreement that depredation significantly impacted continued fishing behavior and profitability of an individual. The AIC-best model for the impacts scale included fishing region as a categorical variable and years fishing as a continuous variable (ANCOVA, R^2 = 0.17, p = 0.002).

$$Perceived\ impacts\ scale = \beta_0 + area\ fished_i + \beta_1(years\ fishing) + \varepsilon$$

Respondent Likert scale responses decreased linearly with years fished (Figure 2.6b) and were highest in western Alaska, followed by the central and southeast Alaska (Figure 2.6a). The depredation impacts scale was significantly correlated with the changing fishing practices scale (Pearson's correlation test, r = 0.573, p < 0.001), and depredation solutions scale (Pearson's correlation test, r = 0.456, p < 0.001).

Area fished and years fishing also significantly impacted respondent answers to the Likert scale addressing changing fishing practices. Higher composite scores on the fishing practice scale indicated strong agreement that fishermen would alter the way they fish in response to depredating whales. The final linear model for the changing fishing practices scale included fishing region as a categorical variable and years fishing as a continuous variable (ANCOVA, $R^2 = 0.13$, $p = 0.012$).

$$Changing\ fishing\ practices\ scale = \beta_0 + area\ fished_i + \beta_1(years\ fishing) + \varepsilon$$

Respondents from western and central Alaska were more likely to change their fishing practices due to depredating whales (Figure 2.6c), and the amount of years fishing also impacted responses to the changing fishing practices scale (Figure 2.6d).

Respondent perception of depredation trends involved Likert questions assessing whether whale depredation is getting worse over time. The solutions scale evaluated how fishermen perceived various potential depredation mitigation solutions. The final linear model for the depredation trends scale (ANOVA, $R^2 = 0.09$, $p = 0.004$) and depredation solutions scale models (ANOVA, $R^2 = 0.13$, $p < 0.001$), selected using stepwise regression methods, included total quota owned (halibut and sablefish quota summed) as a continuous variable.

$$Perceived\ depredation\ trends = \beta_0 + \beta_1(total\ quota\ owned) + \varepsilon$$

$$Perceived\ depredation\ solutions = \beta_0 + \beta_1(total\ quota\ owned) + \varepsilon$$

The more quota an individual owned the more likely they were to strongly agree that depredation is spreading and getting worse (Figure 2.6e) and to express strong support of various management options including real-time tracking and deterrent use (Figure 2.6f).

A proportional odds model for ordered categorical data was used to examine the factors influencing how respondents changed their fishing practices to avoid depredating whales, specifically how far and how often they would travel to avoid the whales and how long and how many times they would "wait the whales out" [49, 58]. The best model for wait times, wait frequency and travel frequency questions included region fished (West, Central, East) and years fishing as explanatory variables.

$$Logit\ (Wait\ length, Number\ of\ waits, or\ Number\ of\ motors)$$
$$= \beta_0 + region_i + \beta_1(years\ fishing) + \varepsilon$$

The effect estimates from all three models suggested that the cumulative probability of respondents reporting a higher number of wait events or motor events increased with respondents fishing primarily in western Alaska, followed by central Alaska and Southeast respondents (Figures 2.7a and 2.7b, Figure 2.7d). A higher number of years fished was also associated with increases in the reported wait and motor events. The best model for the estimated average distance motored when whales were present included vessel category, species most encountered (sperm whales versus. killer whales) and years fishing as explanatory variables.

$$Logit(Average\ distance\ traveled)$$
$$= \beta_0 + whale\ species_i + vessel\ category_j + \beta_1(years\ fishing) + \varepsilon$$

For this model, the cumulative probability of a respondent traveling longer distances was significantly higher for respondents dealing primarily with killer whales and respondents fishing larger B class vessels (>60 feet). Respondents fishing smaller D class vessels (<35 feet) were more likely to report shorter distances traveled (Figure 2.7c).

2.4 Discussion

Depredation by killer whales and sperm whales on longline Pacific halibut and sablefish fisheries is a relatively common occurrence in Alaskan waters and is changing the way the fisheries are pursued. Survey respondents estimated that on average 10 – 25% of sets are impacted by whale interactions; however, the direct catch losses associated with whale depredation varied significantly by species and region fished. Reported depredation rates and catch removals associated with killer whales (>40%) tended to be higher than sperm whale catch removals (<20%). The majority of interview and written questionnaire respondents expressed that depredation by both killer whales and sperm whales became more severe in the last 20 years due to an increasing number of whales learning the depredation behavior. Many respondents also noted that with the implementation of the IFQ program and extension of the fishing season to 9 months there are more opportunities for whales to learn depredation behavior throughout the longer season. Questionnaire respondents reported that whales targeted fishing grounds with higher catch rates. This link between high catch rates and whale depredation has been shown in previous studies investigating sperm whale depredation on longline Patagonian toothfish (*Dissostichus eleginoides*) fisheries in the Southern Ocean [15, 61-63] and more recently in a study that linked killer whale depredation to areas of high sablefish catch rates in western Alaska [6].

Fishermen primarily operating in Southeast (generally encountering sperm whales) perceived whale depredation impacts to be less severe than fishermen operating in western and central Alaska (Figure 2.6a) and were the least likely to agree that they changed their fishing practices due to depredating whales (Figure 2.6c, Figure 2.7). Fishermen with more years fishing experience stated that depredation had relatively lower impacts on their desire to remain in the fishery (Figure 2.6b), and they were less likely to report changing their fishing practices (Figure 2.6d). This is consistent with interview findings that respondents with longstanding experience in the fishery perceived that changes to fishing practices were ineffective at avoiding whales. It is also not surprising that respondents with a demonstrated long-term history in the longline fishery would be less likely to consider leaving the fishery (due to whale interactions or other issues). Owners of higher quota amounts agreed more strongly with the statement that depredation is spreading and getting worse (Figure 2.6e) and that depredation mitigation solutions such as real-time tracking of depredating killer whales and deterrents could reduce the severity of whale interactions with the longline fleet (Figure 2.6f). Thus, the personal finanacial investment (quota owned) of study participants may be linked to perceptions of depredation severity and the importance of deterrent research.

This study confirms that fishermen are forced to change their fishing practices to avoid depredating whales, resulting in reduced overall economic efficiency for the Alaskan longline fleet. The financial impacts of whale depredation have been estimated in other fisheries where interactions occur. Between 2003 and 2008, killer whales and sperm whales were responsible for $6.1 million losses in the Crozet Islands Exclusive Economic Zone (EEZ) and an annual loss of $2.1 million in the Kerguelen Islands EEZ based on the current market price of Patagonian toothfish [19, 63]. Despite the economic challenges posed by whale depredation, respondent answers to questions about the impact of depredation on their desire to remain in the fishery were mixed. Approximately 40% of respondents agreed that depredation could affect their decision to continue fishing quota, 28% were neutral and 31% disagreed that depredation would influence their decision to continue fishing.

This study also investigated fishermen perception of depredation management and mitigation solutions. Over 80% of respondents expressed concern that whale depredation was reducing the accuracy of the sablefish and Pacific halibut stock assessments. As one interview respondent from the Bering Sea stated:

> This is our living. We don't want to knock the stocks down. We don't want the whales to knock the stocks down. We want healthy, sustainable stocks that we can take our part of but still have a sustainable biomass. It's critically important for us to know what's out there, both on the survey and knowing how much the whales are actually taking.

The majority of respondents also expressed that management agencies had not been proactive and up-front in dealing with depredation, indicating a degree of frustration amongst respondents with regards to the current depredation management strategies employed by the IPHC and NMFS. A Central Gulf longliner noted during an interview: "It's [whale depredation is] so touchy that it's almost like the elephant in the room."

Respondents listed deterrent research, allowing the switch to pot fishing in the Gulf of Alaska, whale abundance/distribution studies, and real-time tracking of depredating whales as management or research measures they would like to see agencies place more emphasis on going forward. In interviews and open-ended questions, respondents expressed an interest in cooperative research and improving the lines of communication with management agencies. There are inherent challenges that fishermen and government agencies would face in cooperatively addressing a topic involving charismatic megafauna (whales) and endangered marine mammals and lucrative longline fisheries with long-term investments by fishery participants. A Central Gulf longliner touched on this issue during an interview:

> If the fishermen and the scientists work together… and I've seen it happen, and it's such a great thing to be involved in. If we could work together, but this whole whale thing is such an emotional issue. And whales are more valuable than people.

Pot gear is currently allowed only in the Bering Sea and Aleutian Islands, and killer whale depredation has been a factor in a number of vessels changing from longline gear to pot gear in the Bering Sea [34]. The transition to pot fishing gear was a commonly noted depredation mitigation option by survey and interview respondents. Pot gear is currently not susceptible to killer whale or sperm whale depredation; however, interview and questionnaire results demonstrated that opening up the Gulf of Alaska to pot fishing for sablefish was a contentious topic for the longline fleet. For instance, pot gear can be used to harvest sablefish but is not suitable for effectively harvesting Pacific halibut at this time. There is a risk that the Pacific halibut fishery would, therefore, incur increased depredation pressure if pot gear were legalized for sablefish in the Gulf of Alaska. Gear conflict was an additional concern associated with allowing pot gear in the Gulf of Alaska. A longliner from the Western Gulf noted:

> The two fisheries don't mix. They wouldn't overlap. Because if you try to fish black cod pots where another boat is fishing longline gear, the longline gear always loses. And unless you go to halibut pots too, you are just going to be pushing the sperm whales on to another fishery.

Despite the complexities discussed above, many study participants supported some degree of pot fishing for sablefish in the Gulf of Alaska. The NPFMC is currently conducting reviews to determine the feasibility of reintroducing pot fishing for target groundfish species in federal Gulf of Alaska waters.

2.5 Conclusions

This study represents the first statewide survey of Pacific halibut and sablefish fishermen interactions with killer whales and sperm whales. The sample for this study was selected non-randomly, based on fishing experience, and therefore fleet-wide conclusions cannot be drawn based upon these results. Despite these limitations, respondents accounted for over 19% of sablefish and 26% of halibut quota and were representative of basic true fishery characteristics including reported effort by management area and quota harvested by vessel category [53]. Results suggest that the impacts of depredation are widespread in Alaska, but there are significant regional differences in killer whale and sperm whale depredation. The severity of killer whale depredation in western Alaska necessitates more extreme depredation avoidance measures and altered fishing practices. Additionally, the ability of individual vessels to avoid depredating whales and change fishing practices differed based on vessel size, gear type, and the amount of quota harvested. Fishery policies, such as the transition to sablefish and Pacific halibut IFQs in 1995, can have unforeseen long-term consequences and may be linked to the spread of the whale depredation behavior in Alaska. Future management actions should recognize regional and species-level differences in whale depredation and vessel adaptability and incorporate studies estimating costs to the fleet and depredation mitigation options.

2.6 Acknowledgements

This research was supported by the Rasmuson Fisheries Research Center, the National Science Foundation Marine Ecosystem Sustainability in the Arctic and Subarctic (MESAS) IGERT and the National Science Foundation Arctic Social

Sciences Program (Award Number 1107401). Jan Straley (SEASWAP), Pat McBride (NPFA), Natalie Sattler (ALFA), Julianne Curry (UFA), Julie Matweyou (MAP Alaska Sea Grant) and Courtney Cross (UAS) provided assistance with various aspects of this research. Jordan Watson (UAF) and Franz Mueter (UAF) also provided valuable assistance with data analysis. The authors would like to expressly thank the fishermen that participated in the interviews and written surveys.

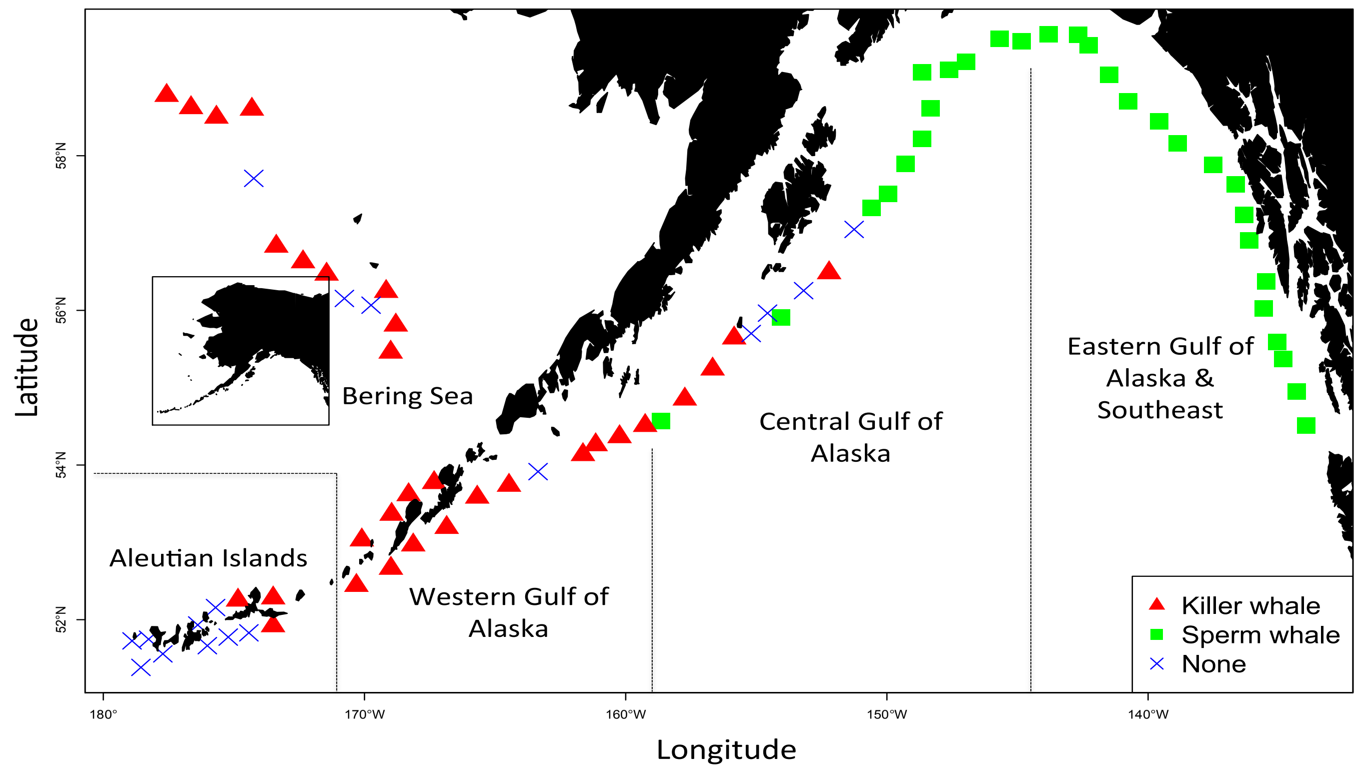

Figure 2.1 Whale depredation by species and management area based on the National Marine Fisheries Service (NMFS) longline survey, 1998-2011. NMFS longline survey locations mirror true longline fishery grounds along the continental slope.

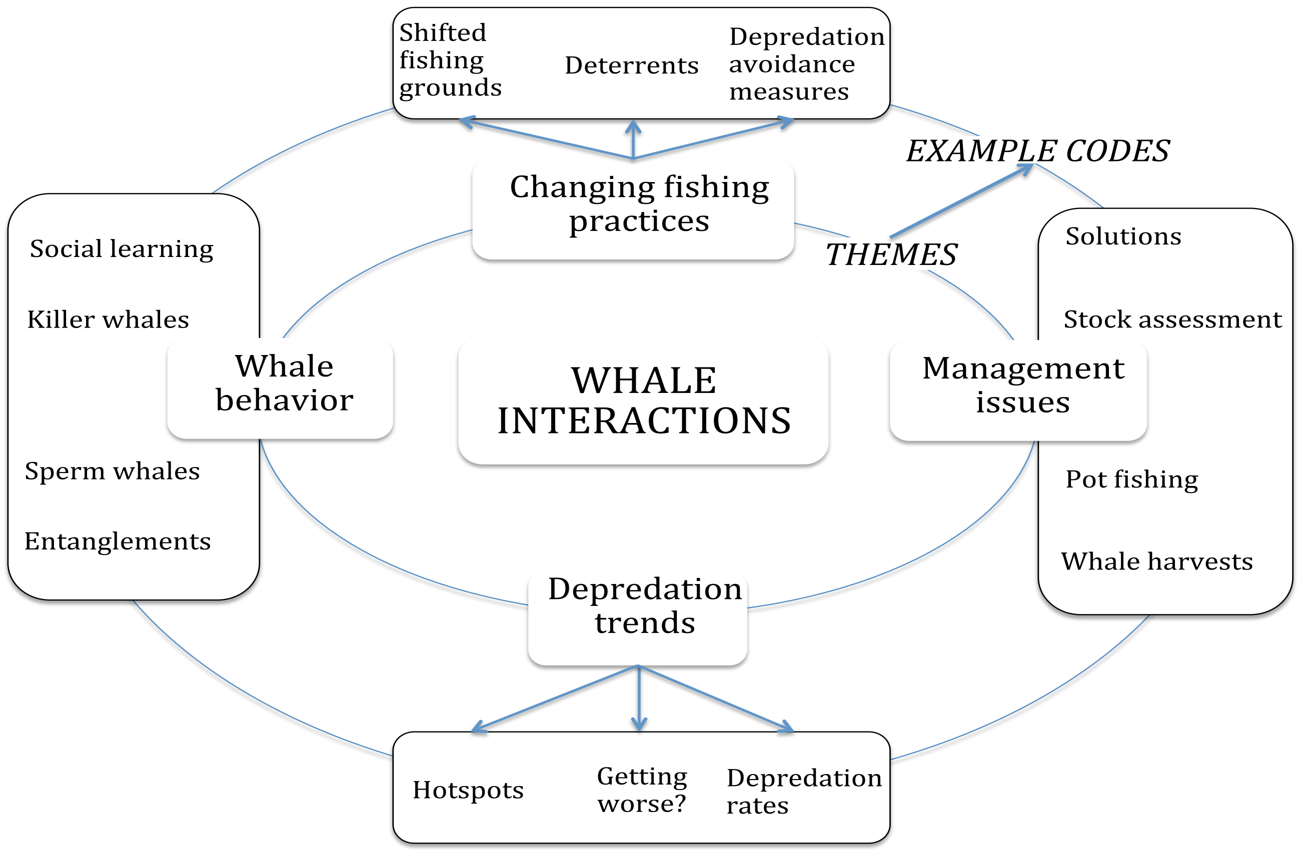

Figure 2.2 Themes and example codes. Themes and codes used during interview analysis.

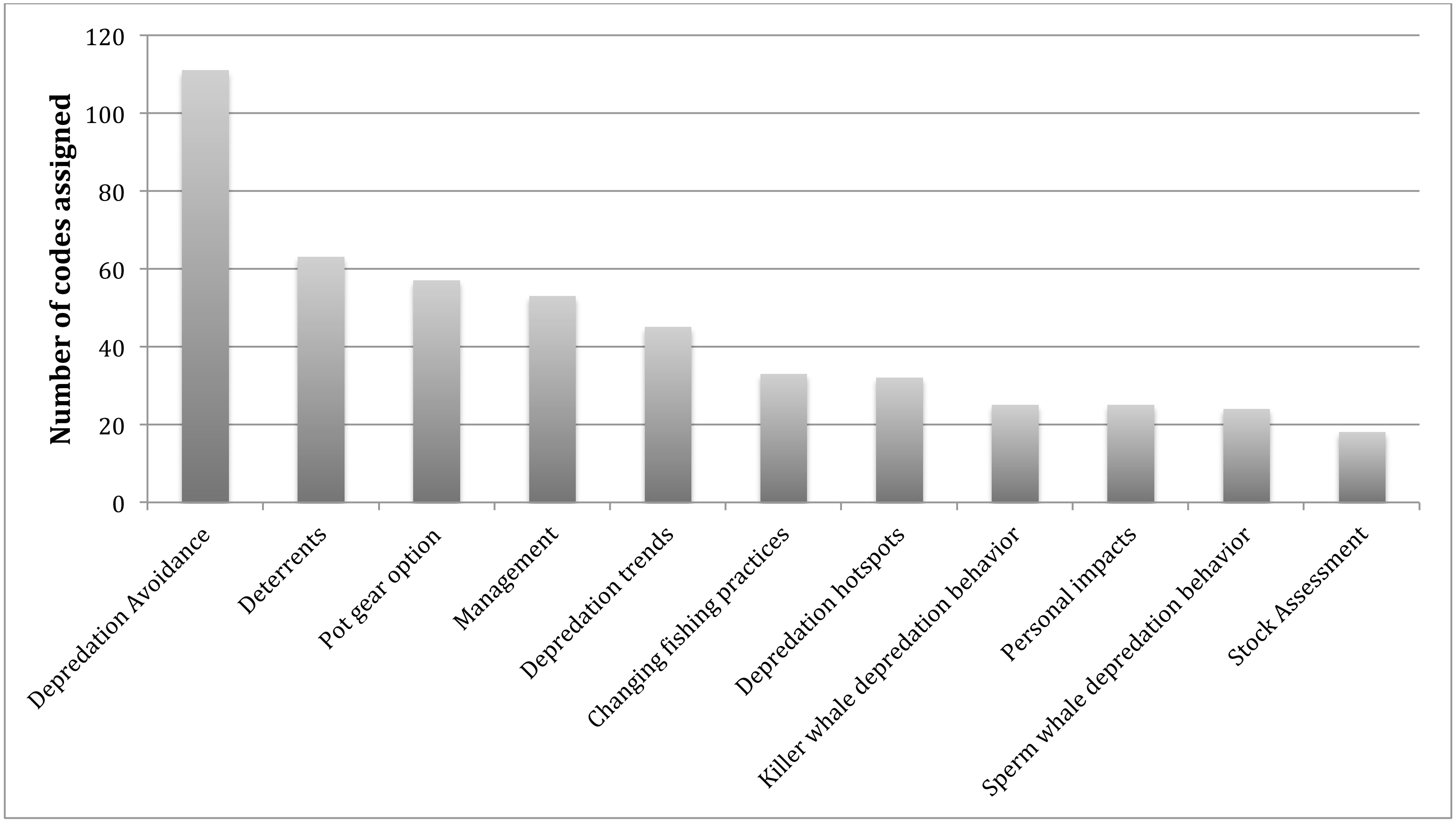

Figure 2.3 Code occurrences from transcribed interviews in combined text from 55 transcribed interviews (n=921 codes assigned).

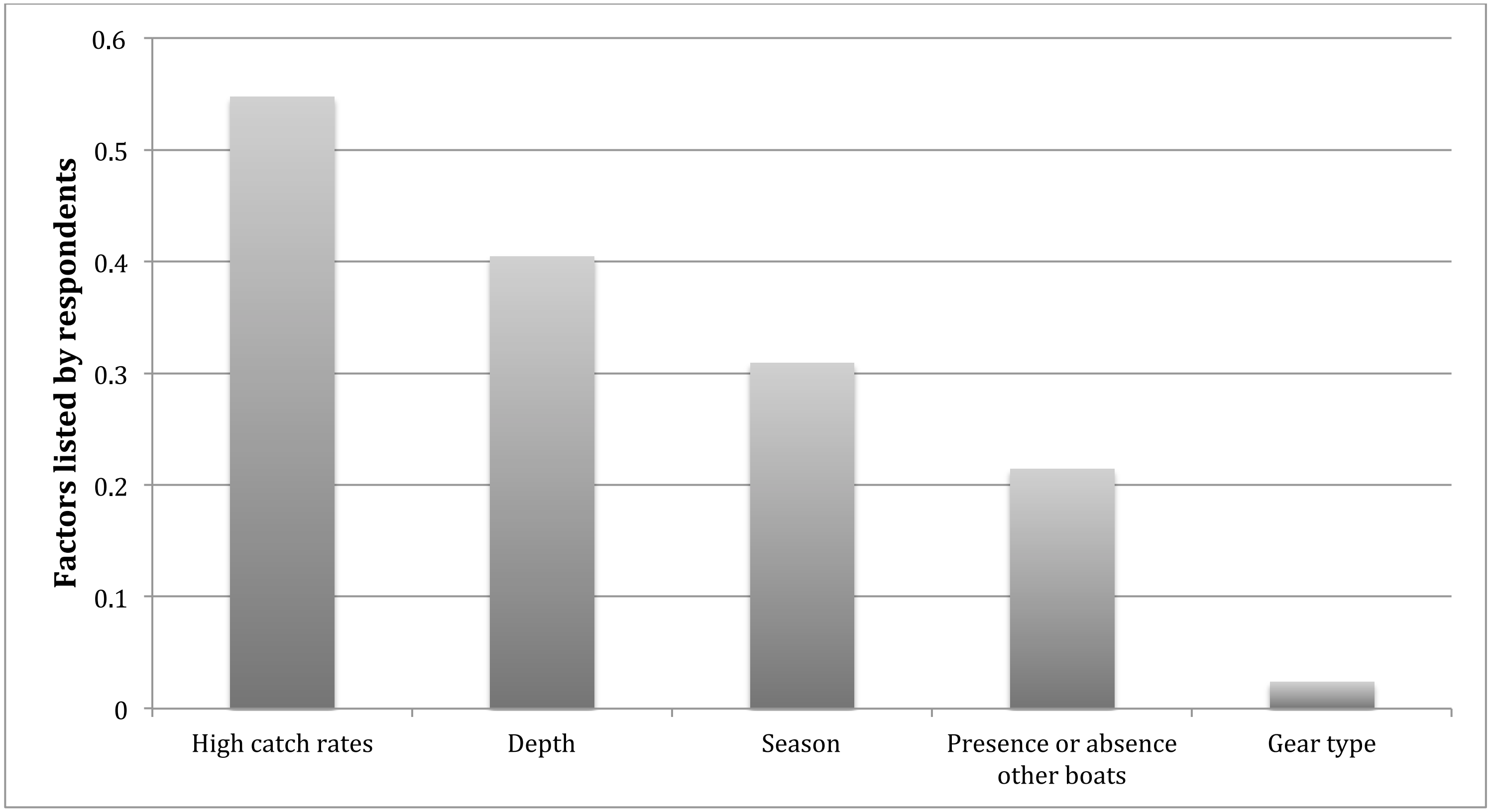

Figure 2.4 Commonly listed factors influencing interactions with whales. Proportions are based on the set of respondents that listed at least one factor.

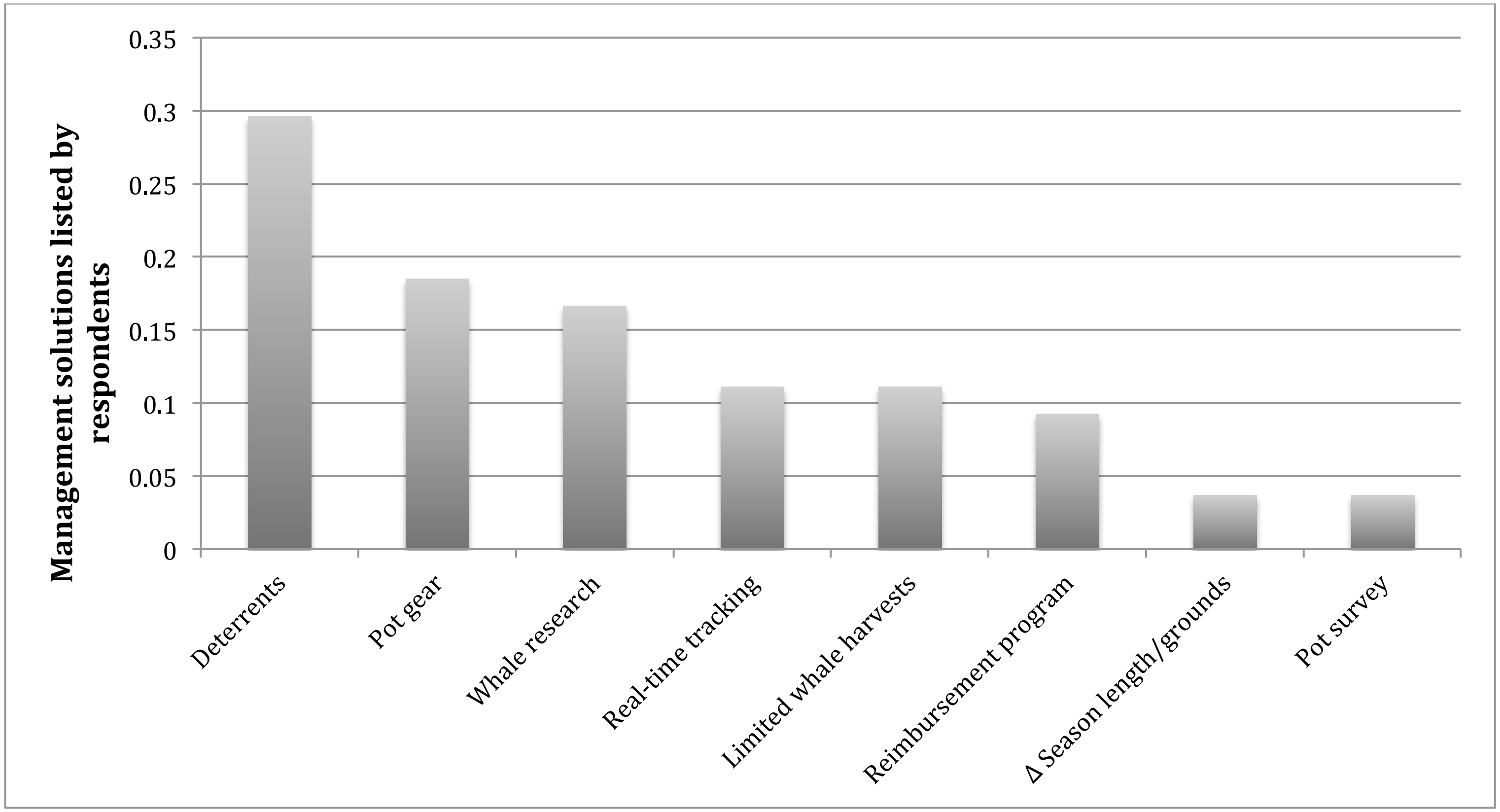

Figure 2.5 Commonly listed management solutions to reduce the impact of whale depredation. Proportions are based on the set of respondents that listed at least one suggestion.

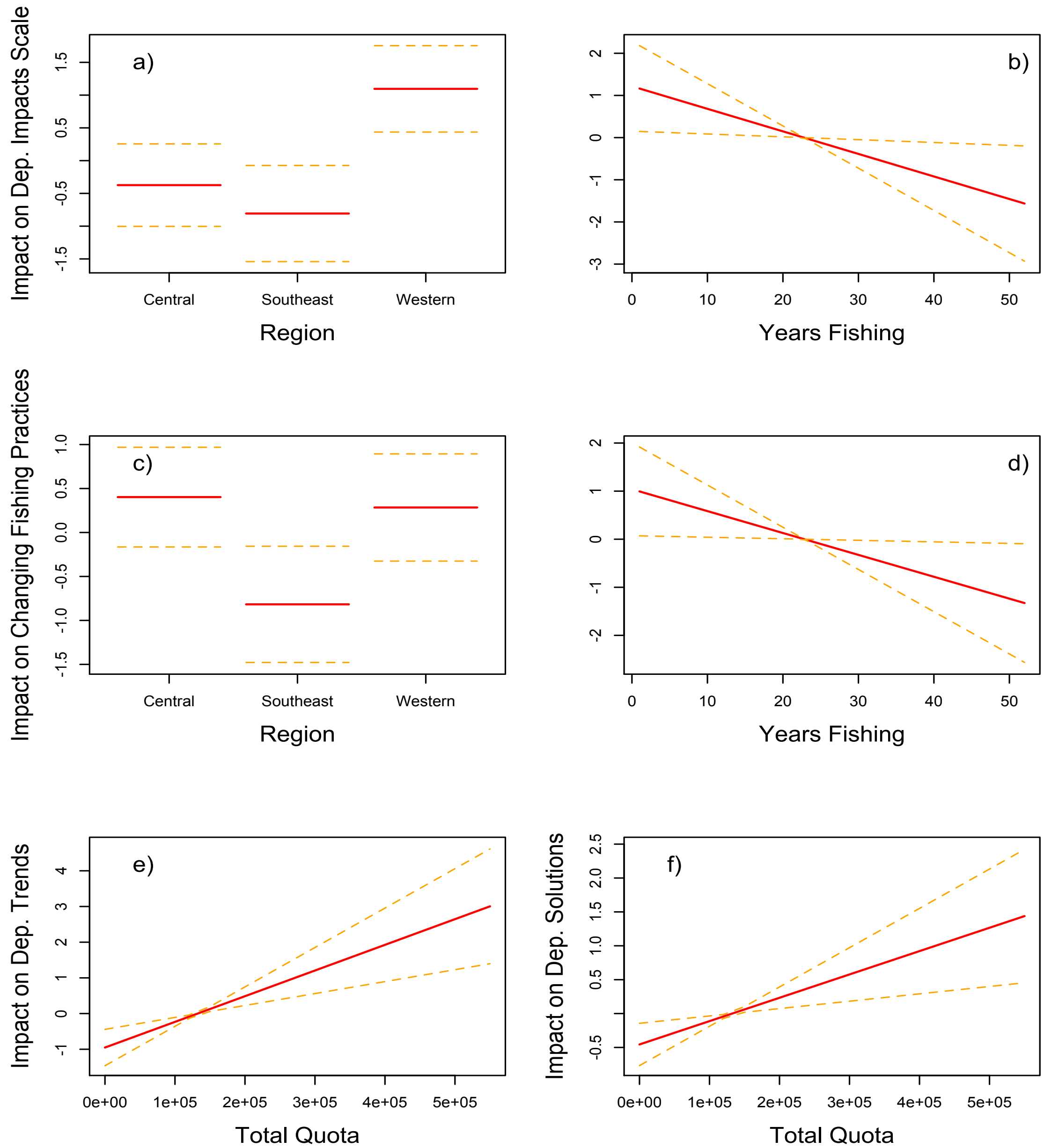

Figure 2.6 Standardized effects on Likert scales. Effects of region and years fishing on Likert scales “Depredation Impacts (a, b)”, “Changing Fishing Practices (c, d). Effect of total quota on Likert scales “Depredation Trends (e)” and “Depredation Solutions (f). Dotted lines denote standard errors.

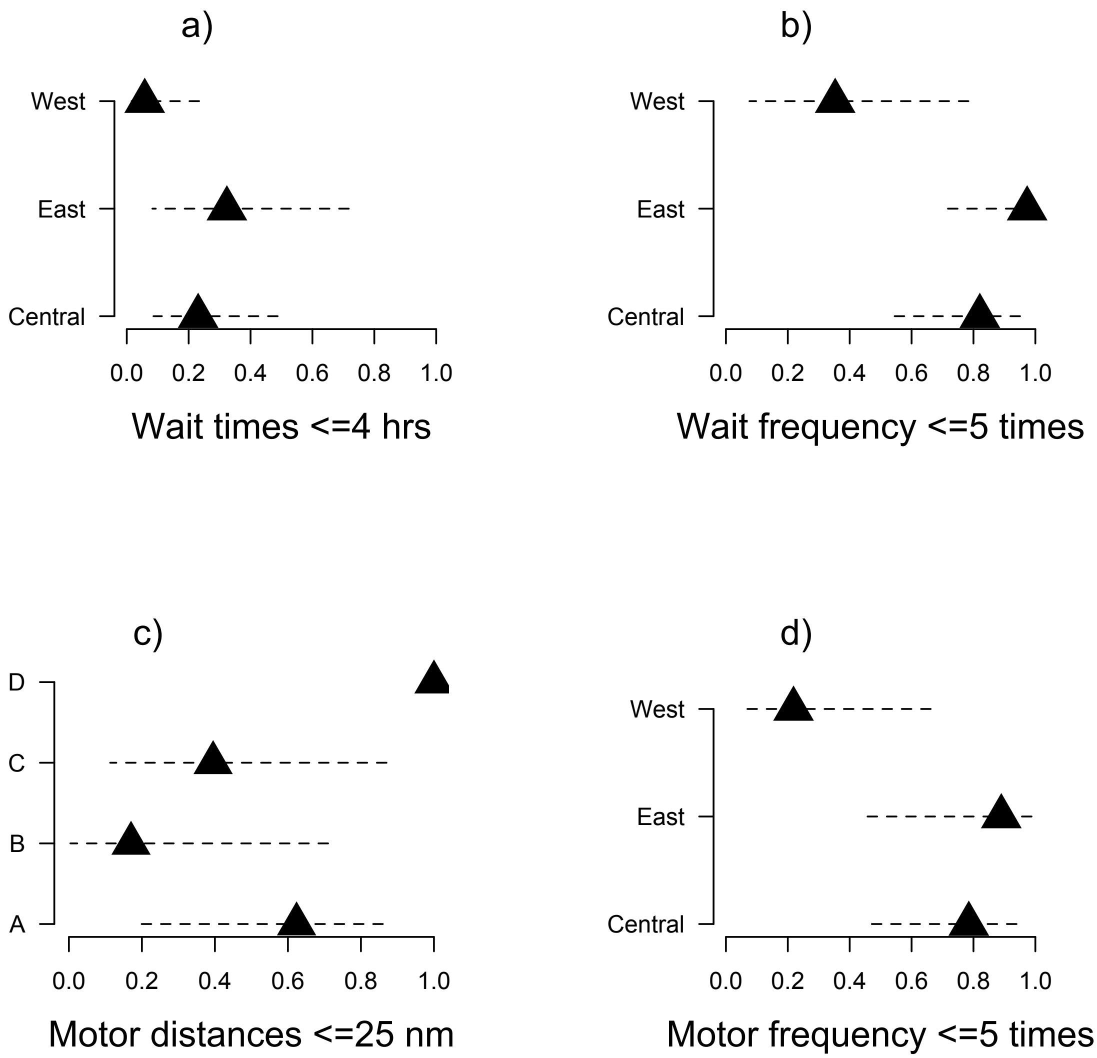

Figure 2.7 Model-estimated cumulative probabilities. Wait times ≤4 hours (a), number of waiting events per season ≤5 times (b), motor distances ≤ 25 nautical miles (c) and ≤5 motor events per season (d) broken down by region or vessel category (n=95) with 95% confidence intervals.

Table 2.1 Reported changes in fishing behavior from written surveys. Count of estimated wait durations, average number of wait events per season, estimated distances traveled, and average number of times distance traveled per season broken down by region primarily fished. Fisher's exact test results for each question and region.

	Estimated wait duration (hours)				**Average number of waiting events per season (times/season)**			
	0 - 3	**4 - 12**	**13 - 24**	**> 24**	**1 - 5**	**5 - 10**	**11 - 15**	**> 15**
West	3	10	7	9	6	11	8	2
Central	10	18	1	3	22	8	1	0
Southeast	8	7	1	1	14	1	0	0
Total	21	35	9	13	41	20	9	2
	Fisher's exact test, $p = 0.004$				Fisher's exact test, $p < 0.001$			

	Estimated distance traveled to avoid whales (nautical miles)			**Average number times distance traveled per season (times/season)**			
	< 25	**25 - 50**	**> 50**	**1 - 5**	**5 - 10**	**11 - 15**	**> 15**
West	9	12	8	7	12	7	3
Central	18	12	0	22	7	0	0
Southeast	13	5	1	16	2	0	0
Total	38	29	9	45	21	7	3
	Fisher's exact test, $p < 0.001$			Fisher's exact test, $p < 0.001$			

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Chapter 3

Killer whale depredation and associated costs to Alaskan sablefish, Pacific halibut and Greenland turbot longliners[3]

[3] Megan J Peterson, Franz Mueter, Keith Criddle, Alan C Haynie. In Review. PLOS ONE.

Abstract

Killer whale (*Orcinus orca*) depredation (whales stealing or damaging fish caught on fishing gear) adversely impacts demersal longline fisheries for sablefish (*Anoplopoma fimbria*), Pacific halibut (*Hippoglossus stenolepis),* and Greenland turbot (*Reinhardtius hippoglossoides*) in the Bering Sea, Aleutian Islands, and Western Gulf of Alaska. These interactions increase direct costs and opportunity costs associated with catching fish and reduce the profitability of longline fishing in western Alaska. This study synthesizes National Marine Fisheries Service observer data, National Marine Fisheries Service sablefish longline survey, and fishermen-collected depredation data to: 1) estimate the frequency of killer whale depredation on longline fisheries in Alaska; 2) estimate depredation-related catch per unit effort reductions; and 3) assess direct costs and opportunity costs incurred by longliners in western Alaska as a result of killer whale interactions. The percentage of commercial fishery sets affected by killer whales was highest in the Bering Sea fisheries for: sablefish (21.4%), Greenland turbot (9.9%), and Pacific halibut (6.9%). Average catch per unit effort reductions on depredated sets ranged from 35.1-69.3% for the observed longline fleet in all three management areas from 1998-2012 ($p<0.001$). To compensate for depredation, fishermen set additional gear to catch the same amount of fish, and this increased fuel costs by an additional 82% per depredated set (average $433 additional fuel per depredated set). In a separate analysis with six longline vessels in 2011and 2012, killer whale depredation avoidance measures resulted in an average additional cost of $494 per depredated

vessel-day for fuel and food. Opportunity costs of time lost by fishermen averaged $522 per additional vessel-day on the grounds. This assessment of killer whale depredation costs represents the most extensive economic evaluation of this issue in Alaska to date and will help longline fishermen and managers consider the costs and benefits of depredation avoidance and alternative policy solutions.

3.1 Introduction

Killer whale (*Orcinus orca*) depredation occurs when killer whales remove fish or damage fish during hauling operations [1,2]. While depredation by killer whales occurs in all ocean basins [2,3], the issue of killer whale depredation is particularly significant in western Alaska where high-value longline fisheries overlap with some of the greatest densities of "fish-eating" or resident killer whales in the world [4,5]. Killer whale depredation is most problematic in the Bering Sea (BS), Aleutian Islands (AI), and Western Gulf of Alaska (WGOA) fisheries management areas but also occurs in Prince William Sound [5-8]. These regions support major demersal longline fisheries for sablefish (*Anoplopoma fimbria*), Pacific halibut (*Hippoglossus stenolepis)* and Greenland turbot (*Reinhardtius hippoglossoides*), which are the main fisheries affected by killer whale depredation in Alaskan waters [5,8]. Killer whale depredation is less problematic in the Central and Eastern Gulf of Alaska and Southeast Alaska, where sperm whale depredation is the primary toothed whale interaction affecting demersal longline fisheries [9].

Killer whales can remove up to 30% of overall catches and up to 100% of catches on individual sets from longline fisheries targeting species including sablefish, Greenland turbot, and Pacific halibut in the North Pacific and Patagonian toothfish (*Dissostichus eleginoides*) in the Southern Ocean [5,10-13]. In addition to revenue reduction from lost catches, fishing fleets incur increased costs due to reduced catch per unit effort (CPUE) and changes in fishing practices to avoid depredating killer whales [7,14,15]. In a study evaluating changing fishing practices to minimize economic losses when encountering depredating killer whales, fishermen reported two primary methods to avoid killer whales: 1) dropping their gear back down to "wait the whales out," and/or 2) motoring to a different fishing site to "outrun the whales." In this same study, fishermen operating primarily in the BS, AI, and WGOA reported average wait times greater than 13 hours (hrs) and motoring on average at least 25 nautical miles (nm) to avoid depredating whales [7]. These changes result in higher costs due to extended trip durations, increased travel distances, and lengthened gear soak times. This increases operation costs and opportunity costs by increasing fuel consumption, bait costs, and crew expenditures, reducing the opportunity to engage in additional fisheries or other income-generating opportunities, and decreasing crew financial reimbursement.

The frequency of reported *odontocete* (toothed whale) interactions with longline fisheries increased globally from 1960 to 2010 [2]. This increase has been attributed to the modernization and geographic expansion of longline fishing during the mid- to late-twentieth century and the establishment of international conservation agreements to protect marine mammals, such as the International Convention on the Regulation of Whaling, and legislation enacted by individual nations, such as the U.S. Marine Mammal Protection Act and the U.S. Endangered Species Act [2]. There is a growing body of scientific literature investigating depredation frequency and catch removals by toothed whales; however, there are few studies examining the economic impacts of whale depredation on longline fleets.

Reported estimates indicate that whale depredation can be costly for longline fleets. Based on the market price of Patagonian toothfish per kilogram (kg) and catch losses, it was estimated that killer whales and sperm whales were responsible for $6.1 million in losses in the Crozet Islands Exclusive Economic Zone (EEZ) between 2003 and 2008 and an annual loss of $2.1 million in the Kerguelen Islands EEZ [13,16]. In dockside interviews conducted in Dutch Harbor, Alaska, during the 1988 fishing season, commercial longline skippers reported they lost an average of $2,300 per day due to killer whale depredation (based on lost catch and a 20% depredation rate) [14]. A more recent study of false killer whale (*Pseudorca crassidens*) and pilot whale (*Globicephala macrorhynchus*) interactions with swordfish (*Xiphias gladius*) and tuna (*Thunnus spp.*) longline fisheries off the Hawaiian Islands used lost catch and additional daily fuel and labor costs to estimate that tuna and swordfish fisheries could be losing an estimated $2,565 to $4,596 respectively per depredated set due to whale interactions [17].

Management and harvesting practices in the sablefish, Pacific halibut, and Greenland turbot longline fisheries have evolved over the last 20 years. The Pacific halibut and sablefish fisheries were converted to an Individual Fishing Quota (IFQ) system in 1995 to address problems associated with the "derby-style" short season and excess fleet capacity [7,18-20]. As a result of that transition, Pacific halibut and sablefish longline fisheries are typically open from March to November [21]. Fishermen may hold IFQ for both species in multiple regions. The majority of sablefish quota is harvested in May, whereas the majority of halibut quota is harvested in June [22]. The Greenland turbot fishery opens in May, but most of the longline harvest occurs between June and August to avoid killer whale depredation [23]. In lengthening the active fishing season, IFQs may have had the unexpected consequence of exposing the fisheries to increased levels of depredation [7].

The goals of this study were twofold: 1) to estimate the percentage of sets impacted by killer whale depredation in western Alaska in the commercial fishery, and 2) to evaluate costs incurred by the Alaskan sablefish, Greenland turbot, and Pacific halibut longline fleets operating in the BS, AI, or WGOA by exploring direct losses in increased operation costs through extended wait times and travel distances and the opportunity cost of lost time from extended fishing trips. This evaluation of killer whale depredation on commercial fisheries serves as a first step towards understanding the economic impacts of killer whale depredation and how these costs may be factored into future management and depredation mitigation strategies.

3.2 Materials and Methods

The goal of these analyses was to examine the frequency of depredation occurrence, CPUE reductions, direct costs, and opportunity costs for fishermen. CPUE-reduction analyses relied on National Marine Fisheries Service (NMFS) observer data; depredation-occurrence analyses relied on data from fishermen respondents and NMFS observer data. Cost estimates relied on a combination of the CPUE analyses and information provided by fishermen respondents. These methods are detailed in the following sections. The Institutional Review Board at the University of Alaska Fairbanks approved all research involving human subjects under this study (IRB # 221381-2).

3.2.1 Killer Whale Depredation Occurrence

The frequency of killer whale depredation was estimated using NMFS observer data from 1998 to 2012 for the BS, AI, and WGOA and depredation data collected by fishermen during the 2011 and 2012 fishing seasons. Additional depredation frequency data were included from previous studies using NMFS sablefish longline survey data [5] and written surveys conducted with longline fishermen [7]. In federal waters off Alaska, observers were required to monitor approximately one third of fishing operations of the Alaskan longline fleet for vessels over 60 ft. in length and to monitor all fishing operations for vessels over 125 ft. Observers monitored and recorded species-specific catch data, fishing location information and general gear performance. A total of 228,538 sets were sampled in the BS, AI, and WGOA. Each set was assigned a performance code ('no problem,' 'considerable killer whale predation,' 'gear entanglement,' 'crab pot in set,' etc.). Only sets with 'no problem' or 'considerable killer whale predation' as performance codes (227,785 sets) were included in the analysis. Per instructions in the NMFS observer manual, observers noted if there was considerable killer whale depredation based on visual evidence of killer whales interacting with the gear and feeding on catch [24].

The basic unit of gear for the NMFS observer data analysis was a set. Each set consists of one string of hooks ($\bar{x}$ = 12,165 hooks per set) fished end to end by an observed longline vessel. Following NMFS guidelines, the target species of each set was assigned based on whichever groundfish species was most prevalent in the set [25]. It was not possible to differentiate between a haul targeting a specific species (e.g. sablefish) from a haul that inadvertently caught more of a non-target species (e.g. targeting Pacific halibut but caught more sablefish). Consequently, this NMFS rule could result in a biased estimate of the number of sets by longline fishermen in the sablefish, Pacific halibut, and Greenland turbot fisheries. Nevertheless and in keeping with NMFS practices, the analyses described below are based on sets predominated by sablefish (5,716 sets, average bottom depth 320 m), Greenland turbot (5,915 sets, average bottom depth 336 m), and Pacific halibut (4,118 sets, average bottom depth 153 m). CPUE by species was estimated by dividing the total species weight (kg) per set by the total number of hooks per set. The proportion of sets depredated by killer whales was calculated separately for sets with sablefish, Pacific halibut, or Greenland turbot as the assigned target species.

Fishermen operating in western Alaska during the 2011 and 2012 fishing seasons also collected depredation frequency data. Participants in this study were selected based on semi-directed interviews conducted with approximately 70 longline fishermen in Alaska from 2010-2011 [7]. During the interview process, six key respondents (vessel-owners) were selected to collect depredation data on the fishing grounds throughout the 2011 and 2012 fishing seasons (March to November). Respondents were selected based on their long-term fishing experience, time spent on the fishing grounds, and willingness to participate. This purposive sampling method enabled researchers to work with particularly knowledgeable fishermen, but limited our ability to make larger, fleet-wide inferences [26,27].

Key informants were asked to report basic vessel and crew information for the entire season and to complete a "depredation sheet" for every day whale interactions occurred. On the daily depredation sheets, fishermen recorded the date, number of sets fished for the day, the number of sets affected by whales, fishing location, minimum and maximum estimates for numbers of whales present, and the estimated percentage of catch taken. Participating fishermen submitted the completed depredation sheets via mail at the end of 2011 and 2012 fishing seasons. Vessels from three size categories participated in the study: three catcher vessels less than or equal to 60 feet; one catcher vessel greater than 60 feet; and two catcher-processors greater than 60 feet. Depths fished ranged from 488 m to 822 m

($\bar{x}$ = 607 m) for sablefish, 119 m to 640 m ($\bar{x}$ =473 m) for Pacific halibut, and 713 m to 786 m ($\bar{x}$ =741 m) for Greenland turbot. The total number of sets fished for a given vessel was calculated by multiplying the reported days fished by the reported average number of sets fished per day for a given vessel. Altogether, these six vessels fished for 262 fishing days or approximately 846 sets in the BS, AI, or WGOA areas where killer whale depredation is prevalent. The proportion of sets or days impacted by killer whale depredation was calculated by dividing the number of reported sets or days affected by killer whales by the reported total number of days or sets fished.

3.2.2 Observed Fishery CPUE Reductions

A statistical modeling approach was used to evaluate CPUE reductions incurred by the longline fleet in western Alaska due to killer whale depredation. NMFS observer data from 1998 to 2012 was analyzed to compare CPUE between sets with and without significant killer whale depredation in each management area: BS, AI, and WGOA. A Generalized Additive Modeling framework (GAM; as implemented in the R package 'mgcv') was used to model sablefish, turbot, and halibut CPUE as a function of killer whale depredation and included additional non-parametric functions of potentially important covariates in each management area [28-30]. The response variable was log-transformed sablefish, turbot, or halibut CPUE. Explanatory variables considered included year, vessel, and killer whale depredation as categorical variables; and smooth functions of location (latitude, longitude) and bottom depth as continuous variables. Interaction terms such as an interaction between killer whale depredation and year or killer whale depredation and vessel, were also examined [31]. The maximum degrees of freedom for all smooth terms were restricted to 5 to limit the analysis to biologically reasonable relationships. The Akaike information criterion (AIC) was used to select the "best" model for each target fishery [30,32]. CPUE reductions due to killer whale depredation were calculated using the model-estimated killer whale depredation coefficients(kw), which represent the average difference in log(CPUE) of a given fish species with and without killer whales present. Thus, the full model (not including interactions) used in the analysis can be written as:

(1) $$\log(CPUE_{ij}) = year_i + vessel_j + kw * D + f_1(Lat, Long) + f_2(depth) + \varepsilon_{ij},$$

where $CPUE_{ij}$ is the CPUE of sablefish, halibut, or turbot of a given set by vessel j observed in year i and D is a binary variable that was set to 0 if killer whales are absent and to 1 if they were present. Confidence intervals were reported as ±1.96 times the standard error.

3.2.3 Direct Costs

3.2.3.1 Additional Fuel Costs

Direct costs incurred by the observed longline fleet were assessed by estimating additional fuel consumption due to lower CPUE on killer whale-depredated sets. In these lucrative longline fisheries, fishery participants generally fish until their full quota is caught or they lease their quota to other vessels. Fuel consumption was assumed to increase proportionally to the additional effort required to compensate for diminished CPUE. Diesel fuel prices per gallon were averaged by year for 1998 using US Energy Information Administration Alaska diesel industrial price data (http://www.eia.gov) and from 1999 - 2012 using EFIN Fisheries Economic Data Program historic diesel fuel prices for ports in Alaska (http://www.psmfc.org/efin/) [33,34]. The inflation-adjusted price of marine diesel fuel per gallon increased during the study period from a low of $1.18/gallon in 1998 to a high of $4.35/gallon in 2008, and Alaskan diesel fuel prices have remained fairly steady through 2013. The total fuel consumption for sablefish, Greenland turbot, and Pacific halibut sets was calculated using fishery effort data and a generic rate of fuel consumption for demersal longline vessels in Alaska [35]. Total fuel consumption for observed sets from 1998 to 2012 was estimated separately for vessels ≤ 100 ft (range 58 – 98 ft; $\bar{x}$ = 78 ft) and vessels > 100 ft (range 104 – 196 ft, $\bar{x}$ = 147 ft) using the following equation:

(2) $$Q_j = R_j * (avg\_hp_j * T_j)$$

where Q_j is the total quantity of fuel consumed (gallons) for the j-th year, R_j is the generic rate of fuel consumption (gallons/(horsepower*sea days), avg_hp_j is the average main engine horsepower for vessels ≤ 100 ft or vessels > 100 ft, and T_j is the total aggregate effort in days at sea for vessels ≤ 100 ft or vessels > 100 ft [35]. In order to determine an average rate of fuel consumption (R_j) to be applied to the observed longline fleet (for which total days at sea and fuel consumption data were not available), days fished and fuel consumption data were collected separately from a select group of longline fishing corporations and individual vessel owners operating in Alaska. In addition to vessel length and horsepower, detailed trip information was provided including: fuel consumed per trip, days fished per , and days steamed per trip. The rate R_j was estimated by regressing the actual fuel consumed during 26 fishing trips on vessels ≤ 100 ft and during 34 fishing trips on vessels > 100 feet against vessel horsepower times reported days at sea for 2011 and 2012 (Table 3.1, Figure 3.2).

The total number of sea days for the observed fleet was estimated by inflating the total number of days fished by a constant proportion of days for "steam time." The steam time to fishing time ratio varied according to vessel size based on results from the 60 fishing trips analyzed. Vessels ≤ 100 ft used on average 0.5 days of steam time for each day of fishing time [n=866 days total]; vessels > 100 ft used on average 0.25 days of steam time for each day of fishing time [n=981 days total]). The average engine power *(avg_hp)* for observed vessels ≤ 100 ft was 633 hp. For observed vessels >100 ft, the average engine power was 1378 hp. For observed sets impacted by killer whale depredation (n=819 sets), the amount of additional fuel consumed due to killer whales was estimated by multiplying the average fuel use per set (Table 3.1) by the model-estimated CPUE differences for each species and management area (Table 3.3). The additional fuel used due to killer whale depredation (gallons) was then multiplied by the average price per year of diesel fuel ($/gallon) to obtain an estimate of additional fuel costs. Additional fuel cost estimates to the observed longline fleet were adjusted for annual inflation rates [36].

3.2.3.2 Fishermen Respondent Direct Costs 2011-2012

Average direct costs due to killer whale depredation were also calculated based on information provided by the six longline skippers that collected real-time depredation data on fishing grounds in western Alaska during the 2011 and 2012 fishing seasons. In addition to depredation frequency data, fishermen respondents recorded all depredation avoidance measures they employed including: the use of deterrents, how long they waited if they dropped their gear back down (hrs), how far they motored if they moved to a different site (nm) and how long they traveled to get to that site (hrs). They also reported estimated gear damage due to straightened hooks and crew food expenditures for the season. Crew food was considered an expense to be taken from the skipper's or vessel's earnings. The additional time spent on the fishing grounds (hrs) due to killer whale depredation was calculated by summing the reported additional travel times and wait times (hrs). The additional time spent on the grounds (hrs) was divided by 24 to estimate the total and average additional days fishing vessels were forced to remain on the grounds due to killer whale interactions. Sets where a deterrent was used were not included in the analysis.

The additional cost of food was estimated by multiplying the average cost of food for the crew per day by the number of days each vessel reported extending its trip for a given year. The additional fuel expenditure due to killer whale interactions was estimated as the average fuel consumption (gallons of fuel burned per hour or GPH) multiplied by the additional travel time in a given year as reported by the vessel (hrs) multiplied by the average price ($) of diesel fuel in Alaska for that year [33,34]. Fuel consumption for each vessel was calculated by multiplying the established specific fuel consumption (sfc) for diesel engines (0.4 lbs per hp) by engine power (hp) of the vessel and dividing the result by the fuel-specific weight (fsw; 7.2 lbs per gallon)[37]. The average inflation-adjusted price-per-gallon of diesel fuel was $3.85 for 2011 and $3.93 for 2012 [33,36].

3.2.4 Fishermen Respondent Opportunity Costs 2011-2012

The opportunity costs in lost time incurred by the six longline vessels collecting real-time depredation data in 2011 and 2012 in western Alaska were estimated. This approach was based upon traditional time allocation theories linking the opportunity cost of lost time to foregone earnings [38]. This can be extended such that a relevant wage rate can be used as a proxy for the opportunity cost of lost time [39,40]. US Census data were used to estimate average daily income of male workers by reported vessel homeport city [41]. Opportunity costs in lost time per vessel were estimated as the average daily income of male workers multiplied by the number of crew per vessel multiplied by the number of additional days each vessel was forced to remain on the fishing grounds due to killer whale depredation. An alternative valuation approach based upon the Travel Cost Method

(TCM; generally used in recreation studies) was also considered. TCMs are often used in non-market valuation recreational demand models and typically assume that site visits are valued by out-of-pocket expenses and opportunity time costs of travel to and from a given site [38,40,42]. The opportunity cost for the TCM analysis was assumed to be 30% to 60% of the average wage rate, which brackets the likely range [42,43]. Given the commercial nature of this fishing, however, wages are considered as the appropriate opportunity cost. There may be additional opportunity costs, but this is a reasonable lower bound.

3.3 Results

3.3.1 Frequency of Killer Whale Depredation

A total of 15,749 sets targeting sablefish, Greenland turbot or Pacific halibut were sampled by NMFS on-board observers in the BS, AI, and WGOA between 1998 and 2012. A total of 5.2% of sets were affected by substantial killer whale depredation across all three management areas and species. The highest percentages of sets depredated occurred in the BS for each species (sablefish 21.4%, Greenland turbot 9.9%, Pacific halibut 6.9%; Table 3.2). The overall number of observed sets declined from 1998 to 2012, and the proportion of sets impacted also declined during the period (Figure 3.3). Sets targeting Greenland turbot had the highest level of depredation across all management areas combined as measured by the proportion of sets affected (8.9%; Table 3.2). The estimated proportion of skates affected by killer whale depredation during the NMFS sablefish longline survey [5] was higher than the estimated proportion of sets impacted based on the observer data (this study) (Table 3.2). From 1998 to 2012, a total of 60,720 skates (string of 45 hooks) were sampled on the longline survey in the BS, AI, and WGOA, and the percentage of skates depredated by killer whales across all years and areas was 21.7% (Table 3.2).

Written surveys and collaborative depredation research with longline fishermen were also used to evaluate the proportion of sets impacted by killer whale depredation. [7]. Six skippers onboard longline vessels completed depredation data sheets on the grounds for fishing days when interactions occurred with killer whales. A total of 81 out of 846 monitored sets (9.6%) were reported as impacted by killer whale depredation throughout the study period from 2011 to 2012, and depredation occurred on 57 days of the 262 days fished (21.8%). The percentage of sets affected differed among vessels, ranging from 4.7% to 15.4% in 2012 ($\bar{x}$= 9.1%) and from 11.1% to 26.7% ($\bar{x}$= 18.5%) in 2011. In an earlier study, 95 longline fishermen in Alaska completed written surveys estimating the proportion of sets affected by killer whales [7]. The majority of written survey respondents reported that 10-25% of sets were depredated (Table 3.2).

3.3.2 Observed Fishery CPUE Reductions

The estimated reduction in observed fishery CPUE associated with killer whale depredation, averaged across all depredated hauls and accounting for differences among vessels and years as well as for spatial patterns in CPUE, ranged from 35.1% to 69.3% among areas and species. The estimated killer whale coefficients were significant for all species in all areas ($p<0.0001$), with the exception of Pacific halibut in the WGOA ($p= 0.45$). Residual diagnostics did not indicate autocorrelation between years. The greatest CPUE reduction for depredated sets occurred for Bering Sea sablefish (69%), followed by AI Greenland turbot (67%), and WGOA sablefish (65%; Table 3.3). When averaged across all management areas, sets dominated by sablefish incurred the greatest CPUE reductions (63%), followed by Greenland turbot (60%), and Pacific halibut (36%; Table 3.3).

3.3.3 Costs Due to Killer Whale Depredation

3.3.3.1 Additional Fuel Costs for the Observed Longline Fleet 1998-2012

The average additional fuel costs per depredated set in the observed longline fleet between 1998 and 2012, as estimated from observer data, was $432.5 ± $147 (inflation-adjusted). The total time at sea (fishing days + estimated steam time) was approximately 3401 days (2267 + 0.5*2267) for vessels ≤ 100 ft and 7950 days (6360 + 0.25*6360) for vessels > 100 ft. Based on these values, the total fuel consumed for all years combined from 1998 to 2012 (Q_j) was 5.7 million gallons ± 333,815 gallons (Table 3.1). The additional fuel costs incurred by individual vessels due to depredation varied by two orders of magnitude, ranging from $263 to $34,795 ($\bar{x}$= $6,773). A total of 819 sets were impacted by killer whale depredation during this time, and the inflation-adjusted cost of the additional fuel attributed to killer whale depredation was $358,991 ± $122,223 for all vessels combined from 1998 to 2012.

Greenland turbot fishing operations accounted for 65% of the increased fuel consumption due to depredation across all three management areas, sablefish for 23%, and Pacific halibut for 12%. Additional fuel costs were concentrated in the BS; Greenland turbot operations in the BS alone accounted for 60% of the additional costs incurred due to killer whale depredation for all species in all three management areas. Despite the relatively low number of observed sablefish sets in the BS (n=252), the consistently high proportion of sablefish sets impacted by killer whales in the BS accounted for approximately 10% of the additional fuel costs. The total costs associated with killer whale depredation declined over time in concert with the proportion of sets depredated (Figure 3.4). Killer whale depredation accounted for an 82% increase in fuel expenditures to catch the same amount of quota when considering depredated sets only and for a 5% increase in fuel expenditures across depredated and non-depredated sets.

3.3.3.2 Fishermen Respondent Direct Costs 2011-2012

Based on data collected by fishermen respondents in 2011 and 2012, the proportion of effort and number of sets affected by killer whale depredation was highest in the WGOA, followed by the BS and the AI. The majority of sets were targeting sablefish in all three areas; however, Greenland turbot sets in the BS, and Pacific halibut sets in all three management areas were also included in the analysis.

The most fishing days with recorded whale interaction data occurred in May, but killer whale depredation data was recorded as early as April 1st and through July 20th. The minimum number of killer whales reported interacting with a vessel ranged from 1 to 30 ($\bar{x}$ =6.5) and the maximum number of whales ranged from 2 to 40 ($\bar{x}$ =12.1). When fishermen were forced to "fish through the whales" (generally due to weather or predation by "sand fleas"), respondents reported an average of 56% of catch lost to killer whales and minimal gear damage. On most (93%) of killer whale affected sets, fishermen opted to employ a variety of depredation avoidance measures. Respondents most frequently reported dropping their gear and waiting to set (50%), followed by moving to a new location (29%). Other reported measures included the use of acoustic or physical deterrents (14%) and fishing through the whales (7%).

Respondents' answers to depredation avoidance questions were used to estimate some of the direct costs a vessel experiences when avoiding depredating killer whales. Respondents reported waiting or traveling for a total of 809 hrs or 34 days (495 hrs in 2012, 314 hrs in 2011) due to killer whale depredation. Individual vessel wait times varied from 1 – 50 hrs ($\bar{x}$= 17.5 hrs) per set. Respondents reported motoring for a total of 1226 nm (889 nm in 2012, 337 nm 2011) and individual set motor distances by vessel ranged from 4 – 110 nm ($\bar{x}$= 36.1 nm). The average additional travel distance per vessel for a given season was approximately 204 nm (Table 3.4). One of the primary costs incurred by vessels participating in this study was associated with the increased fuel consumption to evade the whales ($\bar{x}$ =$4,677 per vessel per season or $\bar{x}$ =$411 per vessel per depredated day; Table 3.4). When killer whales interacted with a longline vessel during the study period, the estimated average direct cost of depredation avoidance (based on fuel and crew food) was $\bar{x}$ = $5,618 per vessel and $\bar{x}$ = $494 per depredated day.

3.3.3.3 Fishermen Respondent Opportunity Costs 2011-2012

Fishermen respondents recorded their additional wait and travel time when they avoided killer whales for a total of 809 hrs or 33.7 days due to killer whale interactions. Vessel wait/travel times resulted in an estimated opportunity cost of $522 per vessel per additional day spent on the grounds (n=33.7 days) or a total of $17,596 for all vessels combined in 2011 and 2012 ($\bar{x}$ = $309 per depredated vessel-day (n=57 days; Table 3.4). Reported wait times per vessel ranged from 75 hrs to 260 hrs ($\bar{x}$ =162 hrs) per season; however, examining the ratio of days waited to days fished (setting or hauling gear) may be a more relevant comparison and ranged from 0.053 to 0.264 ($\bar{x}$ =0.168).

3.4 Discussion

3.4.1 Frequency of Killer Whale Depredation

This study synthesizes analyses involving multiple data sources to estimate the frequency of killer whale depredation on commercial longline fisheries targeting sablefish, Greenland turbot, and Pacific halibut in western Alaska and some of the economic impacts these interactions are having on the fleets. The proportion of observed commercial fishery sets impacted by killer whales was highest in the BS (7 - 21%), followed by the AI (2 - 5%; Table 3.2). Fishermen respondents on the grounds reported that approximately 10% of monitored sets were affected in 2011 and 2012 in all three management areas. These results are fairly consistent across the two commercial fishery data sources used in this study, with the exception of the proportion of sets depredated in the WGOA region for the observed longline fleet (~1%). The low proportion of observed sets affected by killer whales in the WGOA may be attributable to a number of factors: killer whale depredation is a relatively more recent phenomenon in the WGOA region; there are gaps in the spatial distribution of killer whales in the WGOA [4,5]; or as suggested in this study fishermen in the WGOA may be less likely to fish through the whales [7].

The number of observed sets declined between 1998 and 2012 (Figure 3.3A), which may represent transitions in the sablefish and Greenland turbot fisheries in the BS. The BS sablefish fishery has recently experienced a shift away from longline gear towards pot gear, and the timing of the longline Greenland turbot fishery in the eastern BS has reportedly shifted to avoid killer whales [5,22,44]. Killer whale depredation may have played a role in shaping some of these operational and gear changes in the BS sablefish and Greenland turbot fisheries. The proportion of depredated sets also declined during the study period (Figure 3.3B), which could be indicative of spatial and temporal avoidance mechanisms employed in the fishery. For instance, only 4% of the days (n=445 days) that vessels fished through the whales on three or more hauls occurred after 2004. Lastly, the target species of each set was assigned based on whichever groundfish species was most prevalent in the set, and it is possible that this method may have resulted in a biased estimate of the number of sets impacted by killer whales.

The NMFS sablefish longline survey data consistently showed a higher proportion of skates affected by killer whale depredation in each management area (9.2 - 34.6%, Table 3.2). The NMFS survey records depredation at a more refined scale (per skate or 45 hooks); because killer whales will generally remain through the end of an entire set (multiple skates in a set), it is likely that one would observe a higher proportion of skates affected. However, this finding highlights the fact that commercial fishery operations actively avoid killer whales and generally will not fish through killer whale depredation. In this study drawing upon real-time depredation data on the grounds, longline captains chose to fish through the whales on only 7% of the sets when whales were encountered. Fishing through the whales was reportedly done out of necessity. Reasons for this included: “sand fleas were terrible,” “last set of the trip,” or “weather approaching.” The NMFS survey, on the other hand, is required to fish a given station irrespective of the presence of depredating whales to ensure consistent sampling over time. Thus, it is possible that the proportion of sets impacted on the NMFS sablefish survey may be indicative of the proportion of sets impacted if fishermen were to employ no depredation evasion measures. However, because fishermen target areas with higher concentrations of sablefish, it is not possible to estimate the degree to which depredation would occur without avoidance measures.

3.4.2 CPUE Reductions

CPUE reductions due to killer whales estimated as part of this study concur with a previous assessment of catch reductions in Alaskan waters using NMFS sablefish survey data 1998-2011 [5]. Sablefish CPUE was most heavily impacted by killer whale depredation, with reductions ranging from 55 - 69%, closely followed by Greenland turbot reductions (54 - 67%; Table 3.3). Pacific halibut CPUE reductions were relatively less severe, averaging 36% across all three areas. In the earlier study, killer whales were shown to selectively target sablefish (54 - 72%) and Greenland turbot (72%) in western Alaska [5]. In a separate study using Generalized Linear Models to estimate the killer whale effect on CPUE, killer whales depressed Patagonian toothfish CPUE by as much as 50% around South Georgia [10]. Alternatively, studies have examined catch damaged as opposed to CPUE depression. Comparing catches between depredated and non-depredated sets may be more effective for tropical, hard-billed fish species such as tuna or swordfish, where there is often evidence of a hooked fish damaged and left on the fishing gear. Killer whale depredation was associated with 12.4% catch damage off Southern Brazil [11,15]. Sablefish and flatfish such as Greenland turbot and Pacific halibut typically break away from the hook entirely, thus, estimating changes in CPUE is likely the most appropriate method to date for quantifying the killer whale depredation effect on Alaskan demersal fisheries.

3.4.3 Direct Costs and Opportunity Costs

The largest reported component of direct costs incurred by longliners was additional fuel consumption associated with moving to new fishing areas in response to the presence of killer whales or additional fuel consumption associated with fishing with lower catch rates due to killer whale depredation. The estimated cost of additional fuel used to move to avoid the whales (fishermen respondent data 2011 and 2012; $290 per depredated set) was lower than the estimated cost of additional fuel used to fish through the whales (observer data 1998-2012; vessel average $433 ± $147 per depredated set). It is important to note that the fishermen respondent-reported $290 in additional fuel used to avoid the whales does not take into account other direct costs such as food and the opportunity cost of lost time. Conversely, if an observed vessel fished through the whales on multiple sets per day it is likely the killer whales would remain with that same vessel for more than one set such that the overall cost per day would be significantly higher, especially if opportunity costs associated with longer sets were taken into account for the observed longline vessels. For example, there were 819 observed sets impacted by killer whale depredation over 445 days. Individual vessels fished between 2 – 4 sets per day on 40% of the total 445 days, and the maximum additional cost incurred by one vessel that fished three sets on one day was $2449 ± $805 based on fuel alone.

Additional direct costs and opportunity costs associated with killer whale depredation not taken into account in this analysis could result in an underestimation of the depredation costs incurred by the fleet. For instance, extra bait costs associated with lower CPUEs over time could result in substantial direct costs to the fleet. Bait costs were not included in this analysis as bait type (generally herring, squid, or pollock) and usage varies substantially across vessels and fisheries. Nonetheless, tracking bait costs and additional bait used would be a useful component to future depredation-costs research. Furthermore, baiting additional sets to make up for lost catch would take additional time on each killer whale depredated trip, which would lead to increased opportunity costs in lost time. There may be additional opportunity costs for the vessels if in addition to lost time they are forgoing opportunities to fish in other fisheries, but we do not have data on the value or prevalence of these potential opportunities. Reduced product quality due to killer whale interactions could also result in additional depredation costs not considered in this study. Diminished groundfish product quality due to extended gear soak times (sand fleas, damage from the seafloor or currents) is another potential depredation cost [45]. For instance, sablefish products are “graded” or priced based on quality and size, and fish that are torn or damaged will be graded and priced lower. Another important cost not considered in this analysis is the reduction in wages per fishing hour associated with longer trips for non-quota owning crew [46].

This analysis shows that fishermen often opt to let their gear soak longer so as not to feed depredating killer whales, but with this decision they risk reducing product quality and revenue. Fishermen also incur greater risk of losing their fishing gear with extended soak times, especially in areas like the AI where currents can be extremely variable. Alternatively, if fishermen are forced to fish through the whales, depredation can result in extra costs in gear damage in straightened and/or bent hooks. Depredating killer whales may target grounds with high fish CPUEs [5]. In response, fishermen may choose to fish in less profitable areas with lower CPUEs to avoid depredating whales. Additionally, whales may be effectively closing down certain fishing grounds where the likelihood of whale interactions is perceived to be high. It is possible a fisher location choice model could be implemented to estimate costs associated with fishing in less profitable areas [47,48], but more spatially and temporally refined information on expected whale depredation rates would be necessary.

A number of the direct cost estimations for the observed longline fleet as part of this study necessitated assumptions or generalizations about fishing behavior and fuel consumption for the observed vessels from 1998 to 2012. In particular, for this analysis we did not have access to the actual total days fished and steamed (total days out) by each vessel. This value was estimated for the observed fleet based on a subset of vessels (constituting 60 longline trips) for which days steaming and fishing data were available. The steam to fish ratio from this analysis was applied to the observed longline fleet to estimate the total days each vessel spent getting to or fishing on the grounds for vessels up to 100 ft and vessels greater than 100 ft. The estimate of total days per trip was then used to calculate the overall fuel consumption (and additional fuel consumed due to killer whales) for the observed fleet. Both of these methods are subject to many uncertainties that we were unable to fully quantify in this analysis.

Future studies should attempt to quantify or minimize uncertainties by obtaining more precise estimates of important quantities such as the steam to fish ratio and fuel consumption data. One approach to improving the ratio of fish to steam days and other parameters would be to account for differences among vessel categories, for example based on whether or not fish were processed on board. Fuel consumption rates were averaged based on vessel size, but it is likely that some vessels have improved or modified fuel consumption rates that were not reflected in the available data, which could have resulted in an underestimation of fuel consumed during the early part of the study period when fuel consumption was likely higher. Lastly, historic diesel fuel prices were averaged for western Alaska ports. Diesel fuel prices vary extensively based on port and price fluctuations throughout a season, and future studies evaluating depredation and fuel costs would benefit from improved fuel pricing data resolution. Despite the challenges inherent in working with these datasets, this study's estimated costs represent a thorough and well-supported approach in a data-limited situation.

3.5 Conclusions

In high-value longline fisheries managed under quota systems, such as the sablefish, Pacific halibut and Greenland turbot fisheries, there is typically incentive for fishermen to catch their entire quota, even if it takes longer due to killer whale depredation. In a limited-entry fishery, depredation can result in lower catches by a vessel for a given year. However, under the IFQ program in Alaska fishermen are able to fish longer to catch their entire quota. Thus, the main costs incurred by Alaskan longline fleets are associated with depressed CPUEs and an increase in time necessary to catch the vessel quota, not lost catch. The basic issue of fishery operators dealing with killer whale depredation can be simplified to consider the costs and benefits of fishing choices. Fishermen experiencing whale interactions essentially have two immediate choices: 1) fish through the whales and incur additional bait and fuel costs and potential gear damage, or 2) opt to move locations or wait to set and incur additional fuel and crew food costs plus opportunity costs in lost time. Findings from this study suggest that the additional fuel costs of depredation avoidance may still be cheaper than fishing through the whales. If a dollar value were assigned to lost catch, this difference in costs would be even more significant. It is important to note, however, that the opportunity cost of lost time associated with avoiding whales or fishing longer through the whales also represents substantial costs to the fleet. There is also incentive for fishermen to avoid feeding depredating killer whales to limit the spread of the learned depredation behavior and to minimize reinforcing the killer whales. The groundfish observer program has undergone restructuring, and since 2013 regulations mandate partial observer coverage on vessels 40 ft to 60 ft. These modifications to the observer program should generate additional depredation data for smaller vessels in the fishery. With this enhanced opportunity to collect depredation data, it is critical that fishery interaction reporting criteria be standardized and prioritized within the observer program. The substantial costs and depressed CPUEs associated with killer whale depredation provide strong incentive for fishery managers and fishermen to continue depredation research with special attention to depredation mitigation and potential management solutions.

3.6 Acknowledgements

We expressly thank Peter Tyedmers (Dalhousie University School for Resource and Environmental Studies), Joseph Jacobson (Alaska Seafood Marketing Institute), Jason Gasper (National Marine Fisheries Service), the Alaskan Longline Company and Central Bering Sea Fishermen's Association for assisting with data collection and analysis. This research was supported by the Rasmuson Fisheries Research Center, the National Science Foundation Marine Ecosystem Sustainability in the Arctic and Subarctic (MESAS) IGERT (Award Number DGE-0801720), and the National Science Foundation Arctic Social Sciences Program (Award Number 1107401). The authors would like to expressly thank the fishermen who collected invaluable data in 2011 and 2012

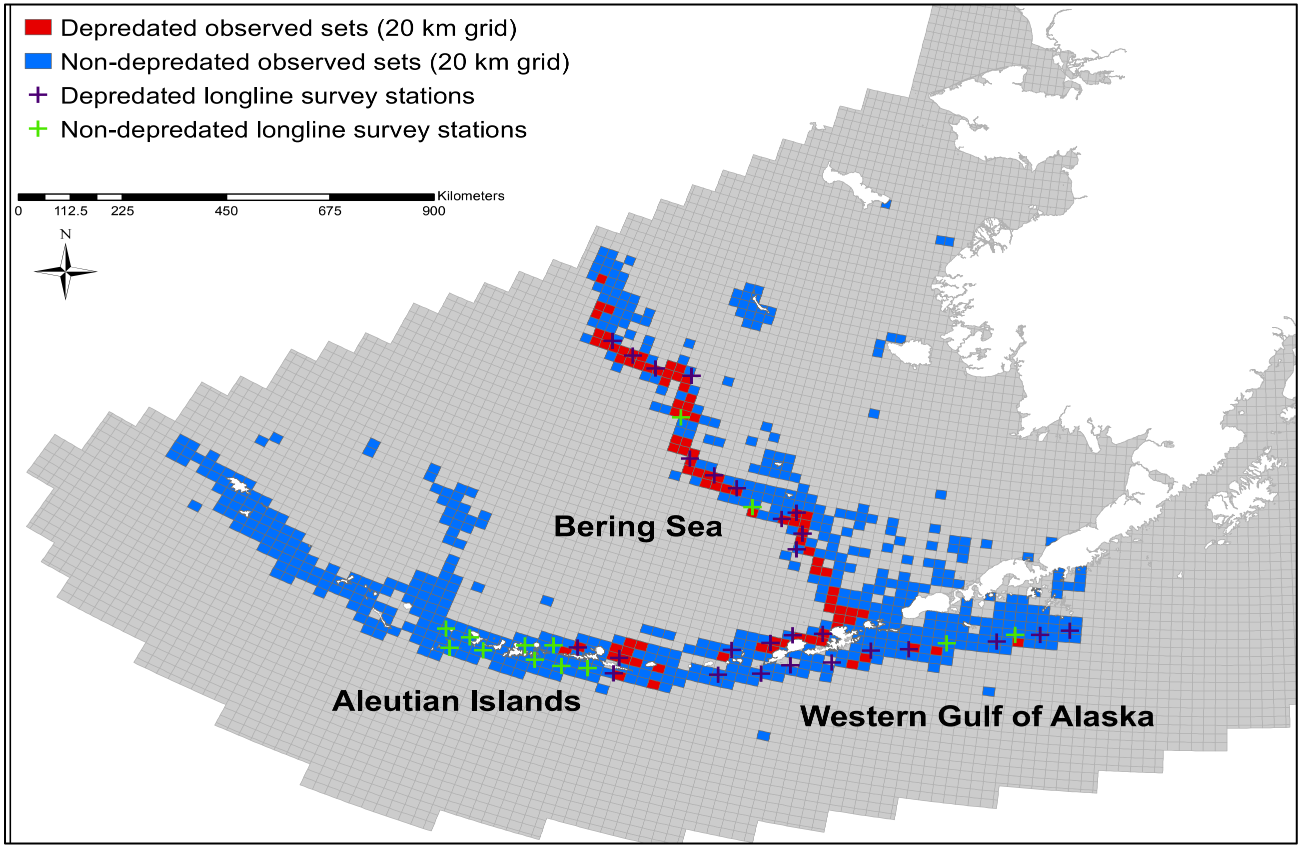

Figure 3.1 NMFS longline survey and observer sets sampled 1998-2012. Map of western Alaska regions with depredated and non-depredated sets based on NMFS observer data and depredated and non-depredated stations based on the NMFS annual sablefish longline survey. Observer data are aggregated by 20 km grids for confidentiality.

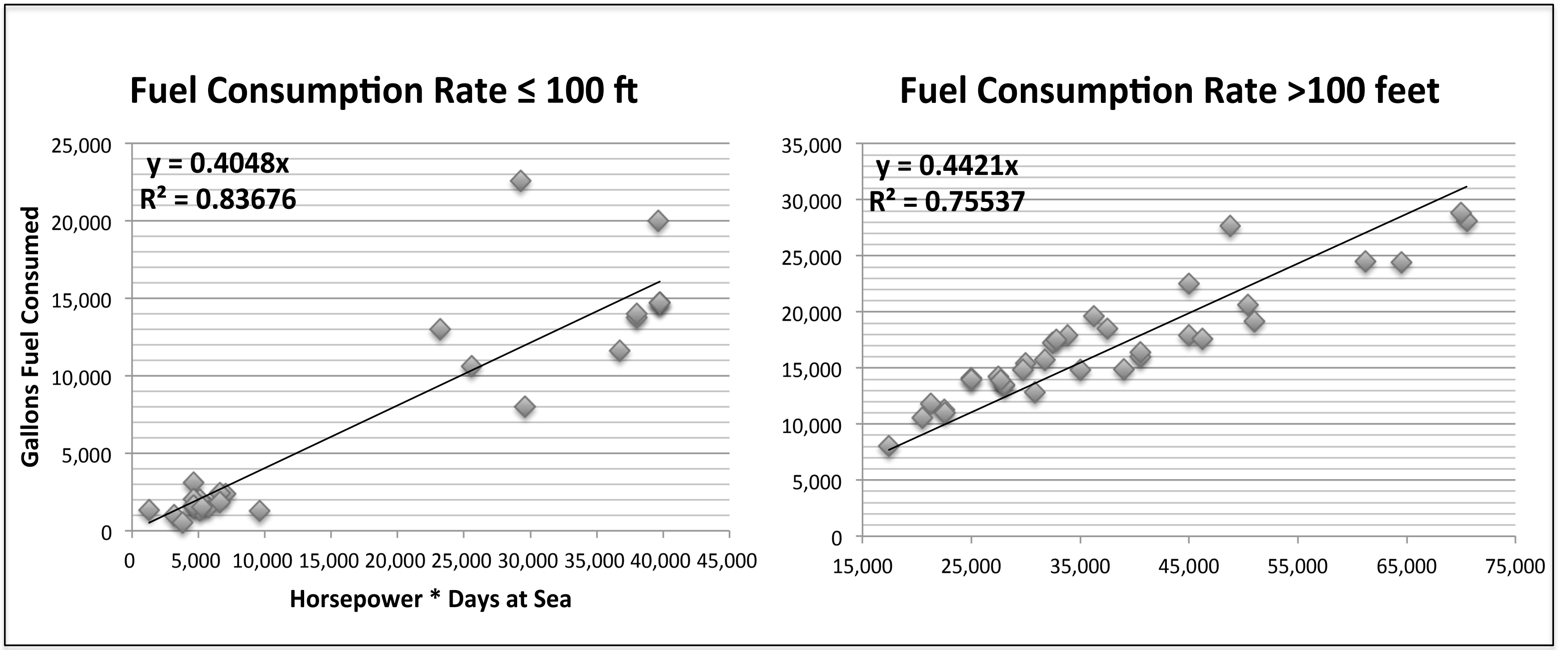

Figure 3.2. Fuel consumption relationships for longline vessels. These data constitute 60 fishing trips in Alaska in 2011 and 2012 (method from Tyedmers 2001) for vessels less than or equal to 100 ft and vessels greater than 100 ft.

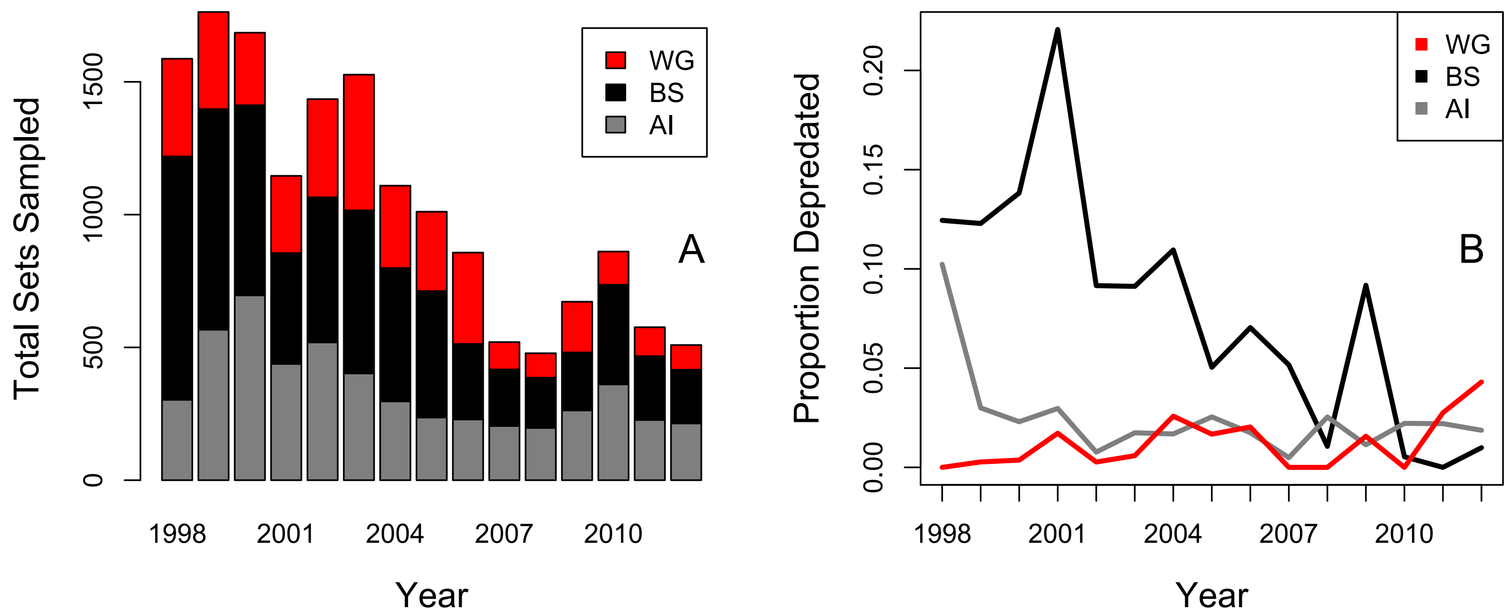

Figure 3.3 Number of sets sampled and proportion depredated by area. Total number of sets sampled (n=15,749) in all three management areas (A), and the proportion of sets depredated by killer whales over time by region (B).

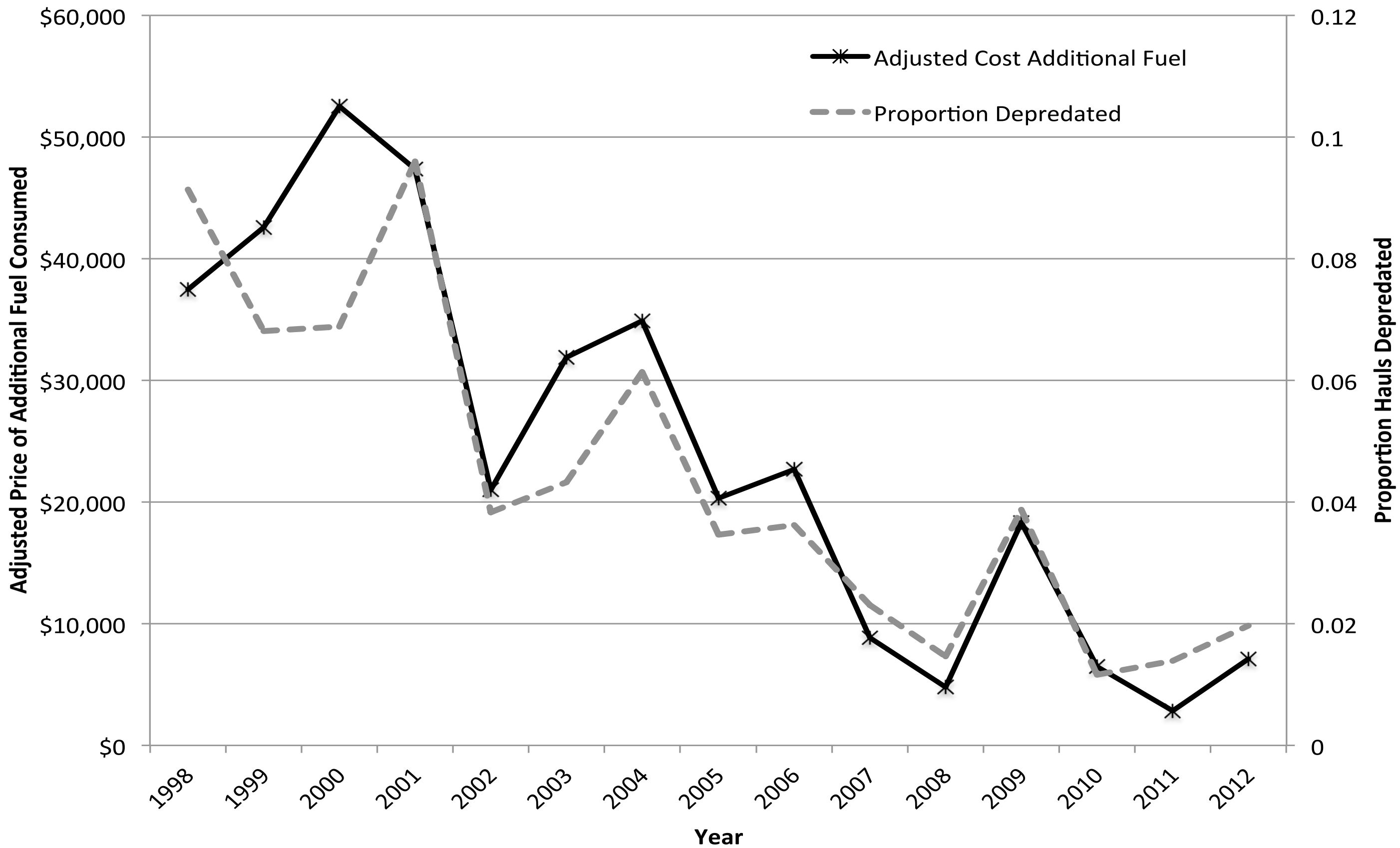

Figure 3.4 Additional fuel costs and proportion sets depredated. Additional fuel costs incurred by the observed longline fleet due to killer whale depredation and the proportion of sets depredated 1998-2012.

Table 3.1 Estimated fuel consumed and sea days for the observed fishery. Estimated rate of fuel consumption [gallons/(hp*days)], average engine power (hp), estimated time at sea (days) and estimated fuel consumption (gallons) for observed longline vessels from 1998 to 2012.

Vessel size	R_j	R_j 95% CI	Engine power (hp)	Estimated days at sea	Estimated gallons total	Number of hauls	Avg fuel use per haul (gallons)	Avg fuel use per haul 95% CI (gallons)
≤100 ft	0.405	0.359-0.451	633	3401	871,338	4,379	199	±23.1
>100 ft	0.442	0.421-0.464	1378	7950	4,843,249	11,357	426.5	±30.0

Table 3.2 Percentage of sets affected by killer whale depredation. The percentage of sets (NMFS observer data 1998-2012) or skates (NMFS longline survey data 1998-2012;h [5]) affected by killer whales by target species and management area, with sample size for each item. Results from written surveys [7] and depredation data sheets are also included.

	Bering Sea		Aleutian Islands		Western Gulf of Alaska		
	% Affected	Sample (n)	% Affected	(n)	% Affected	(n)	Overall % Affected
NMFS Observer data 1998-2012							
Sablefish	21.4%	252	2.3%	2614	1.0%	2850	**2.5%**
Greenland turbot	9.9%	4909	4.5%	963	NA	NA	**8.9%**
Pacific halibut	6.9%	1577	1.7%	1533	1.2%	1008	**3.6%**
NMFS Longline Survey 1998-2012 (Peterson et al. In Press)							
Sablefish	34.6%	19075	9.2%	17102	20.0%	23913	**21.7%**
Written survey results (n=95 resondents; Peterson and Carothers, In Press)							
Sablefish / Halibut							**10-25%**
Depredation data sheets 2011 & 2012 (n=846 sets)							
Sablefish/ Turbot/ Halibut							**9.6%**

Table 3.3 Model-estimated killer whale depredation coefficients (*1-exp^kw^*), with the percentage of deviance explained (%Dev) by the final model (Equation 1) and sample size (n).

	Reduction CPUE (kw)	95% CI (kw)	p-value (kw)	%Dev (full model)	n	% Sets Affected
Sablefish						
Bering Sea	69.3%	58.3 - 77.3%	p < 0.0001	65.9%	252	21.4%
Aleutian Islands	54.8%	45.9 - 62.2%	p < 0.0001	25.2%	2614	2.3%
Western Gulf of Alaska	64.8%	55.9 - 71.9%	p < 0.0001	25.6%	2850	1.0%
Greenland turbot						
Bering Sea	53.6%	50.1 - 56.8%	p < 0.0001	35.6%	4909	9.9%
Aleutian Islands	66.9%	57.4 - 74.2%	p < 0.0001	40.6%	1006	4.5%
Pacific halibut						
Bering Sea	35.1%	20.7 - 46.7%	p < 0.0001	49.7%	1575	6.9%
Aleutian Islands	56.9%	36.4 - 70.7%	p < 0.0001	38.9%	1533	1.7%
Western Gulf of Alaska	14.9%	NA	p = 0.45	49.9%	1008	1.2%

Table 3.4 Fishermen respondent collected depredation data. Reported additional distances traveled, extended trip times, calculated additional fuel expenses and additional crew food costs, and the estimated opportunity cost of lost time (wage rate) due to depredating killer whales (n=846 sets).

Additional Distance Traveled	**Extended Trip Time (travel and wait time)**	**Additional Fuel**	**Addititonal Crew Food**	**Opportunity Cost Not Working**
Avg per vessel (nm) per season	Avg per vessel (hrs) per season	Avg per vessel per day ($)	Avg per vessel per day ($)	Avg per vessel day ($)
204 nm	162 hrs	$411	$83	$486
		Total Additional Expenditures		
	Total ($)		**Avg per vessel per season ($)**	**Avg per vessel per day ($)**
	$45,685		**$9,137**	**$802**

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General Conclusions

This project advances our understanding of toothed whale interactions with Alaskan longline fisheries and associated impacts to the socio-economic sustainability of Alaskan longline fisheries. We refined estimates of catch removals by killer whales and resulting reductions in catch per unit effort (CPUE). We also developed a better understanding of how depredation affects fishing behavior and the economic costs fishermen incur due to whale interactions. This work builds upon earlier depredation studies and provides a template for future regional and international research examining apex predator interactions with fisheries.

CPUE reductions associated with killer whale depredation were estimated for groundfish species using two primary data sets: the National Marine Fisheries Service (NMFS) longline survey and NMFS commercial catch data in the Bering Sea (BS), Aleutian Islands (AI) and the Western Gulf of Alaska (WGOA) management regions. In all three management areas, killer whale depredation was more common on standardized longline survey skates (9.2-34.6%) than commercial sablefish fishery sets (1.0-21.4%). The NMFS survey records depredation at a more refined scale per skate (string of 45 hooks), whereas the commercial fishery records depredation per set ($\bar{x}$=5900 hooks). More frequent killer whale depredation on the longline survey relative to commercial operations is consistent with other findings reported in this dissertation that commercial fishery operations actively avoid killer whales and generally will not continue to retrieve their gear when killer whales are present.

Killer whale depredation had a significant effect on NMFS longline survey catch rates for five of the six groundfish species evaluated: sablefish (*Anoplopoma fimbria*), Greenland turbot (*Reinhardtius hippoglossoides*), Pacific halibut (*Hippoglossus stenolepis*), arrowtooth flounder (*Atheresthes stomias*) and Pacific cod (*Gadus macrocephalus).* Catch reductions were consistent between the NMFS survey and commercial fishery data despite different modeling approaches (Negative Binomial Generalized Linear Models and Generalized Additive Models, respectively), averaging 35-69% for sablefish, Pacific halibut and Greenland turbot in the commercial fishery and 51-73% for the same species in the survey. Trends in predicted mean catch or CPUE reductions associated with killer whale depredation also concurred with previous regional assessments conducted in the 1980s in the Bering Sea and Prince William Sound. The impact of killer whale depredation on a commercial fishery was studied in Alaska state waters fishing in Prince William Sound in 1985 and 1986, where it was estimated that 25% to 35% of overall sablefish catch was lost to killer whales. Individual sets were affected by as much as 80% to 90% for sablefish (Matkin, 1986; Matkin, 1988), consistent with our findings that average reductions for individual sets in the three management areas ranged from 54% to 72% for sablefish. Model-based estimates of catch reductions in the NMFS survey and in the commercial fishery were also consistent with fishermen's estimates from the written surveys and depredation data collected on the fishing grounds (Peterson and Carothers, 2013; Peterson et al., 2013). Fishermen respondents also reported that catch rate reductions were most severe in western Alaska and the Bering Sea, consistent with modeling results.

Based on the NMFS longline survey data, sablefish CPUE, gear haul time and location were significantly associated with the proportion of skates or sets depredated. Killer whales were more likely to depredate stations with higher average sablefish CPUE, which may be consistent with optimal foraging efficiency and maximizing net rate of energy gain (Estes et al., 2003). This finding concurred with data collected from written questionnaires and interviews (Peterson and Carothers, 2013). Survey respondents were asked, in an open-ended question, to list any marine environment characteristics they associated with whale depredation. The majority of respondents (55%) listed "high catch rates," supporting the hypothesis that the whales target fishing grounds with higher CPUEs. Results from both interviews and written surveys, as well as model results from the NMFS survey data, indicate that killer whales targeted areas southwest of the Pribilof Islands and north and south of Unalaska and Umnak Islands. The relatively high prevalence of killer whale-fishery interactions may be related to higher abundances of killer whales in these areas (Fearnbach, 2012), although abundance data for killer whales are limited in these region.

Based on the NMFS survey data, it appears that the frequency of killer whale depredation has increased since the late 1990s in the AI and during the mid-2000s in the WGOA. These findings were consistent with fishermen's observations from these regions and results from semi-directed interviews and written surveys

(Peterson and Carothers, 2013; Peterson et al., 2013). However, these results did not concur with NMFS observer data, which suggests that killer whale depredation was relatively uncommon for the commercial longline fishery in the WGOA during the same time period (~1%). The low proportion of observed commercial sets affected by killer whales in the WGOA may be attributable to a number of factors including: killer whale depredation is a relatively more recent phenomenon in the WGOA region; there are gaps in the spatial distribution of depredating killer whales in the WGOA (Fearnbach, 2012; Peterson et al., 2013); fishermen in the WGOA may be less likely to fish through the whales; or estimates are complicated by changes or inconsistencies in observer reporting over time (Peterson and Carothers, 2013; Peterson et al., In Review).

Despite advances made by this study, a number of important questions remain that could be addressed in future research. Both the commercial fishery and standardized longline survey data indicate whale interactions are highly variable in frequency and catch reductions severity (Hanselman et al., 2010; Peterson et al., 2013). Estimating and accounting for the high degree of spatial and temporal variability in killer whale depredation will continue to pose statistical and practical challenges in determining depredation effects on CPUE indices. Additional exploration of factors influencing the frequency or severity of depredation events is needed. For instance, this research demonstrated that certain regions and areas with high sablefish CPUE experienced killer whale depredation more frequently (Peterson et al., 2013).

There are other factors, such as killer whale ecology (e.g. distribution, regional abundances, group-specific foraging patterns) that may influence the likelihood or severity of interactions. The number of killer whales depredating on a set may also impact the severity of catch removals, as was indicated in a recent study in the Crozet Exclusive Economic Zone (EEZ) Patagonian toothfish (*Dissostichus eleginoides*) longline fishery (Tixier et al., 2010). Future studies in Alaska should seek to include the number of depredating whales in analyses. An additional gap in our knowledge of killer whale depredation in Alaska is the behavioral dynamics of individual depredating groups (pods or matrilines). For instance, are some groups becoming "depredation specialists" during the fishing season? Using photo-identification, Tixier et al. (2010) demonstrated that four out of eleven pods (35 out of 97 individuals) were involved in over 80% of the documented interactions with longline fisheries in the Crozet EEZ, indicating a degree of specialization. Lastly, whale abundance could influence the frequency of longline fishery interactions. Because we do not currently have reliable population estimates for sperm whales in the GOA or killer whales in western Alaska, it is difficult to determine how changes in whale abundance may be influencing interactions with the fleets. These aspects of killer whale ecology should be components considered in future depredation research in Alaska and elsewhere.

Investigation of potential acoustic deterrents and fishing gear modifications should also be a priority for future research. Catch protection devices such as the "umbrella-and stone" Chilean longline system were tested on Patagonian toothfish fisheries in the Southwest Atlantic. Although these devices did reduce depredation, there have been some indications that the modified gear may also reduce CPUE (Moreno et al., 2008; Goetz et al., 2011). Alaskan fisheries would benefit from similar gear modification studies to evaluate killer whale and sperm whale deterrence. Additionally, research into killer whale acoustics and communication may shed light on the development of more effective deterrent devices. There is likely no single remedy against killer whale depredation to date, and it is possible that a combination of gear modifications, deterrents and adaptive management (such as modified fishing seasons and adoption of pot fishing gear) will be necessary to reduce the frequency of killer whale interactions.

This study confirmed that killer whale depredation has significant economic implications for longline fishermen operating in Alaska. The main costs incurred by Alaskan longline fishermen due to killer whale interactions are associated with depressed CPUEs and an increase in time necessary to catch quota. Fishermen can opt to fish through the whales, but findings suggest that the associated additional fuel, food, and bait costs (and opportunity costs in lost time) may be more expensive than depredation avoidance measures. If a dollar value were assigned to catch consumed by the whales, this difference in costs would be even more significant. There is also a risk of exacerbating the spread of the depredation behavior by reinforcing whales with fish each time they interact with the gear. However, avoidance is also costly in the short run; killer whale depredation avoidance measures resulted in an average additional cost of $494 per depredated vessel-day for fuel and crew food. Opportunity costs of time lost (based on lost daily wages) by fishermen averaged $522 per additional vessel-day on the grounds.

The impact to individual vessels and fishermen varies per trip and per season. However, if one vessel experiences killer whale depredation on multiple trips in a given year, their individual vessel costs would be substantial, and this could impact the long-term viability of a fishing operation. This study provides the most thorough evaluation to date of economic costs incurred by longline fishermen due to killer whale depredation; however, additional bait cost, refined fuel consumption and fish quality degradation data would contribute to an improved estimate of costs incurred by commercial fishery operations due to whales. This study also did not take into accout potential losses incurred by the crew in reduced earnings.

Interdisciplinary Research

Whale interactions with Alaskan longline fisheries are an example of a conflict that arises when two apex predators (humans and toothed whales) compete for access to a prey or other resources. This interaction impacts fishermen, fishery managers, stock assessment scientists and killer whale/ sperm whale ecology. The complex nature of this research topic, therefore, necessitated an interdisciplinary approach to integrate the ecological and socio-economic components of whale depredation, fishery operations, and fishery management. Conducting a large-scale research project within an interdisciplinary framework yielded many rewards and just as many challenges. The following section will discuss some of the benefits and costs associated with trans-disciplinary research and recommendations for future work integrating multiple disciplines.

Complex issues with biological and socio-economic components in many cases cannot be fully captured with one data set or one study group. In this research, quantitative analyses of survey and commercial fishery data were assessed in conjunction with results from written surveys and semi-directed interviews with fishermen. Written survey findings concurred with quantitative analyses on a number of topics including: whales targeting high CPUE areas, interaction rates and catch removals by depredating whales. Conversely, findings from the NMFS commercial fishery data analyses did not always concur with fishermen respondent accounts. For instance, fishermen operating in western Alaska reported higher interaction frequency than suggested by NMFS fishery observer data. Understanding these differences in the survey and fishery data informed the economic analysis and assessment of changing fishing practices in the third chapter. Including multiple disciplines and both qualitative and quantitative approaches helped to identify consistencies and discrepancies.

An additional benefit of conducting this research in an interdisciplinary format was the incorporation of differing fields of study and the cross-fertilization of ideas that resulted. Collaborations with people from other disciplines expands our frame-of-mind and the levels at which we can ask and answer different types of questions. For instance, estimating the costs incurred by individual longliners avoiding killer whales necessitated an innovative approach and cooperation with fishermen, economists and statisticians. Working together, we were able to develop a new approach to estimate depredation avoidance costs. International marine mammal-fishery interaction researchers have subsequently expressed interest in future collaborations regarding this novel economic model. Thus, the scope of this project was more comprehensive than it would have been without involving theories and methods from different disciplines. However, it is too simplistic to argue that interdisciplinary research will always lead to better and more thorough studies. Effective interdisciplinary research requires a strategic and deliberate approach in tandem with clearly defined goals and work products. As policy and scientific arenas work to transition towards ecosystem-based management approaches (ongoing in the eight U.S. regional fishery management councils), effective interdisciplinary research will be key in understanding different socio-ecological mechanisms and how they relate to and affect one another.

Interdisciplinary research facilitates integrating fishermen's ecological knowledge and the development of more comprehensive and relevant research projects or, as Johannes (2000) noted, "ignore fishers' knowledge and miss the boat." Many biological or ecological fishery assessments fall short when they do not consider the perspectives and experiences of fishery participants. For example, depredation mitigation tools must be practical for fishery participants to use. It is important that a researcher seeking to develop a depredation mitigation device consult with fishermen during product design and evaluation phases regarding the feasibility/efficacy of the device's use on the fishing grounds. Fishermen are the ones who spend the most time on the fishing grounds and directly experience interactions and competition with other fishers and marine species.

Fishermen's knowledge is especially useful in studies examining social-ecological interactions, such as whale depredation, where data can be deficient. Fishermen's knowledge was integral to this research project at all stages through informal conversations with fishermen, semi-directed interviews, written surveys and eventual depredation data collection on the fishing grounds. It is important to note that fishermen's knowledge can be difficult to document effectively. Fishermen may be wary of sharing fishing ground information or harvesting practices with an investigator and may misrepresent information. Such risks are inherent in working with fishermen's ecological knowledge; however, these risks can be mitigated through effective and transparent relationship building.

Fishery and marine mammal biologists are tasked with basing their research and management upon the best available scientific information to ensure the long-term health of a managed stock(s). Nonetheless, there is value in also considering anthropology or economics to inform scientific understanding and management responses. By beginning this project with over 70 interviews with longline fishermen across the state, I had the chance to recognize and appreciate the very real human elements that were intricately connected to the depredation issue. Biologically-based conservation concerns should be balanced with the needs of resource users to support long-term socio-economic, cultural and marine ecosystem health. Talking with fishermen helped to understand that there were many sides to the depredation story, and that the human component was as scientifically relevant as the ecological aspects.

Despite the many benefits of interdisciplinary research, there are also major challenges inherent in synthesizing findings from multiple data sources based on quantitative and social research methods. Data often differ in spatial or temporal scales. For example, fishery independent data, such as the NMFS longline suvey data used in this study, are often standardized and randomly designed to facilitate analyses, extrapolation and prediction. Conversely, the fishery dependent data from this study were collected opportunistically by fishermen, and consequently it was more difficult to make fleet-wide inferences.

Although interdisciplinary research is gaining traction in many fields, it can still be challenging to present interdisciplinary results in more conventional scientific forums unaccustomed to transdisciplinary analyses. More specialized biological or statistical audiences may not be willing to accept findings from different methodological approaches presented together. In order to address these challenges, it is important that researchers presenting interdisciplinary work find the commonalities and core messages across disparate data sets and consider innovative presentation formats, such as interactive online websites or video and audio presentations, to best convey interdisciplinary results. Systematic and detailed documentation of methods in manuscripts and presentations free from jargon will help to improve audience reception of interdisciplinary results.

Finding the right balance of depth and breadth is a challenge with any research project, but this issue is amplified when trying to incorporate different fields of study, perspectives and approaches into one project. In trying to include multiple disciplines in a marine science research project, one runs the risk of a work product too broad for practical application. Results that are intangible, vague, or too general do not provide a basis for meaningful advice. These challenges can be alleviated through systematic study design and clearly defined research goals.

In sum, this dissertation benefited greatly from an interdisciplinary approach, enabling me as the researcher to examine whale interactions in Alaska from a number of angles, all equally important. I am excited to support the development of interdisciplinary marine research throughout my career, and I look forward to being a part of the field's progression going forward.

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Appendix 1 IACUC approval form and permit information.

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
Silver Spring, MD 20910

APR - 8 2011

Ms. Janice Straley
University of Alaska Southeast
1332 Seward Avenue
Sitka, Alaska 99835

Dear Ms. Straley:

Thank you for your request to add Ellen Chenoweth, Megan Peterson, and Lauren Wild Co-investigators (CIs) to Permit No. 14122 to conduct all research activities on cetaceans, excluding tagging and biopsy under your permit. Pursuant to General Condition C.6 of your permit, these personnel have been included as CIs and are authorized to act on your behalf for the activities specified during field research for the duration of your permit.

Please note that as Permit Holder and Principal Investigator (PI), you are ultimately responsible for the activities of individuals operating under the authority of this permit. In your absence, CIs will assume this role during field research. Please attach this letter to your permit and ensure all CIs receive a copy of the letter and permit.

As a reminder, please ensure that the NMFS Assistant Regional Administrator for Protected Resources is notified of planned fieldwork as specified in your permit. Notification must be made at least two weeks prior to initiation of a field trip/season and must include the locations of the intended field study and/or survey routes, estimated dates of research, and number and roles of participants.

If you have any questions, please contact Amy Sloan or Kristy Beard at (301) 713-2289.

Sincerely,

for P. Michael Payne
Chief, Permits, Conservation and
Education Division
Office of Protected Resources

cc: Kaja Brix, F/AKR

Appendix 2 IRB approval form.

(907) 474-7800
(907) 474-5444 fax
fyirb@uaf.edu
www.uaf.edu/irb

UNIVERSITY OF ALASKA FAIRBANKS

Institutional Review Board

909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

June 3, 2010

To: Courtney Carothers, PhD
Principal Investigator

From: Bridget Watson
Research Integrity Administrator
Office of Research Integrity

Re: IRB Protocol Application

Thank you for submitting the IRB protocol application identified below. This protocol has been administratively reviewed and determined to meet the requirements specified in the federal regulations regarding human subjects' protections for exempt research under 45 CFR 46.101(b)(2) for research involving the use of educational test, survey procedures, interview procedures or observation of public behavior, unless: (i) information is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects, and (ii) any disclosure of the human subjects' responses outside of the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing employability, or reputation.

Protocol #:	10-24
Title:	*Qualitative and quantitative investigations into cetacean depredation on Alaskan longline fisheries*
Level:	Exempt
Received:	April 29, 2010 (original)
Exemption Date:	June 3, 2010

If there are major changes to the scope of research or personnel involved on the project, please contact the Office of Research Integrity. Email us at fyirb@uaf.edu of call 474-7800. Contact the Office of Research Integrity if you have any questions regarding IRB policies or procedures.

Appendix 3 Written consent form.

Informed Consent Form
Cetacean Depredation Impacts on Longline Fishermen

IRB #: 221381-2 Date Approved: June 3, 2010

Description of the Study:
We are asking you to take part in a research study about killer whale and sperm whale depredation on fisheries in Alaska. The goal of the study is to learn about the effects that killer whale and sperm whale depredation has on longline fishermen and fisheries management in Alaska.

You are being asked to take part in this study because you were identified as particularly knowledgeable about this subject. Please read this form and ask any questions you have before you agree to be in the study. If you decide to participate, we would set up a 30-60 minute interview with you. We will ask you broad questions about your fishing history and interactions with marine mammals. We will ask you to reflect on depredation events, avoidance or deterrent measures and potential solutions.

To better enable us to record the information we collect accurately, we would like to audiotape or videotape our interview(s) with you. Audiotaping or videotaping, like participation in the study, is completely voluntary. If you prefer not to be audiotaped or videotaped, you will not be pressured to do so.

Risks and Benefits of Being in the Study:
We do not expect any risks for you if you take part in this study. You may feel uncomfortable being interviewed and/or audiotaped. We will make every effort to accommodate the interviews in a place that is most comfortable for you. You can ask for any sensitive information to be excluded from the official transcript and/or study.

There is no monetary compensation for participating in this study. You may not receive any benefits from taking part in this study. The knowledge that we collect in this study might help to better understand and explain the effects of marine mammal depredation on Alaskan longline fisheries. This may also lead to a discussion of potential ways to reduce the negative impacts of depredation.

Confidentiality:
If you are comfortable with us audio-taping and video-taping our interview to help us in note-taking, the researcher, Megan Peterson will keep a copy of the audio and video files in a locked office at the School of Fisheries and Ocean Sciences in Juneau, AK. If requested, she will provide you with a CD copy. Any information we collect for presentation or publication will not be linked with your name without written permission (for example, if we would like to quote you, we would contact you again and ask for your permission to so).

Voluntary Nature of the Study:
Your decision to take part in the study is completely voluntary. You are free to choose not to take part in the study or to stop taking part at any time during the interview or after it is completed. If you would like to erase the recording after the interview you may choose to do so.

Contacts and Questions:
If you have questions now, feel free to ask. If you have questions later, please contact:

Megan Peterson, PhD Candidate/ MESAS Graduate Fellow
School of Fisheries and Ocean Sciences
University of Alaska Fairbanks
530-219-4093, mjpeterson6@alaska.edu

Courtney Carothers, PhD/ UAF Faculty
School of Fisheries and Ocean Sciences
University of Alaska Fairbanks
907-474-5329, clcarothers@alaska.edu

If you have questions or concerns about your rights as a research subject, please contact the Research Coordinator in the Office of Research Integrity at 907-474-7800 (Fairbanks area) or 1-866-876-7800 (outside the Fairbanks area) or fyirb@uaf.edu.

Statement of Consent:
I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been provided a copy of this form.

________________________ ________________________
Signature of Participant & Date Printed Name of Participant

____
Signature of Person Obtaining Consent & Date

To enable us to send you a copy of your audiotaped interview, please provide your mailing address and contact information. As mentioned above, prior to using your name with any quoted material, we would contact you at this address for permission.

________________________ ____________________
Street or PO Box Telephone

________________________ ____________________
City, State, Zip Email

Appendix 4 Written questionnaire.

Whale Depredation on Longline Fisheries in Alaska

How is it impacting fishermen today?

We want to understand the impacts that whale depredation has on longline fishermen. This survey collects information on changes in fishing practices and avoidance techniques associated with depredation. We believe that fishermen knowledge and experience is important to understanding depredation and working towards future solutions.

This research is part of a University of Alaska Fairbanks student's doctoral thesis funded by the National Science Foundation and MESAS program.

Whale Depredation Survey

Personal Information: *Can be completed anonymously if desired.* ***Personal information will NOT be shared in results.***

Name ______________________ **Date** ______________________

Email ______________________ **Home residence City, St** ______________________

Phone ______________________ **Vessel Name** ______________________

Age_________ **Gender** M | F **Vessel homeport City, St** ______________________

Fishing Information

Please circle only the answer that most applies to you.

B1 What best describes you as a fishermen in the longline fishery?

1 Skipper *owning* quota
2 Skipper *leasing* quota
3 Crew without quota
4 Crew *owning* or *leasing* quota
5 Hired skipper *owning* quota
6 Hired skipper *leasing* quota
7 Used to own quota
8 Other: ______________________

B2 What year did you start fishing for halibut or sablefish? ______________________

B3 What length boat do you typically fish? ______________________

B4 Do you primarily fish on a catcher processor? 1 Yes 2 No

B5 How many days (approximately) did you fish in the in 2011 season?
Approx. number of days: ______________________

B6 How many days per season (on average) have you fished each year in the last 5 years?
Average number of days: ______________________

B7 What is the appoximate amount of your sablefish quota? ______________________ lbs

B8 What is the appoximate amount of your halibut quota? ______________________ lbs

B9 Where do you primarily fish for sablefish/halibut?

1 Bering Sea
2 Aleutian Islands
3 Eastern Gulf of Alaska & Southeast
4 Western Gulf of Alaska
5 Central Gulf of Alaska

B10 How many sets (on average) will you haul in a day provided conditions are decent?
Average number of sets: ______________________

B11 Do you ever fish pots for sablefish? 1 Yes 2 No

B12 If yes, what percentage of the time do you fish pots for sablefish or halibut?

1 <10%
2 10-29%
3 30-60%
4 >60%

Whale Depredation Survey

Depredation Information

Please circle only the answer that most applies to you.

D1 Which type of whale generally depredates on sets where you fish?
- 1 Sperm whales
- 2 Killer whales

D2 Have you ever seen killer whales and sperm whales depredate *on the same set*?
- 1 Yes
- 2 No

D3 How many ***sperm*** whales do you usually see around the vessel when depredation occurs?
- 1 1-2 whales
- 2 3-5 whales
- 3 5-7 whales
- 4 >7 whales

D4 How many ***killer*** whales do you usually see around the vessel when depredation occurs?
- 1 1-5 whales
- 2 6-10 whales
- 3 11-20 whales
- 4 >20 whales

D5 My biggest concern with whale depredation is….
- 1 Loss of catch
- 2 Increased risk of lost/damaged gear
- 3 Loss of time (less efficient fishing)
- 4 Inaccurate stock assessments (sable/hal)
- 5 Other: ____________________

D6 Please list some of the *other* main effects/concerns associated with whale depredation.

____

____

____

D7 What species fish is most heavily targetted by depredating whales?
- 1 Arrowtooth
- 2 Halibut
- 3 Sablefish
- 4 Skates

D8 What other species are often taken by whales? ____________________

____

____

D9 What would you estimate the *overall* percentage is of sets subject to whale depredation?
- 1 <5% of sets
- 2 5-10% of sets
- 3 10-25% of sets
- 4 >25% of sets

D10 What would you estimate the depredation rate is on *individual* sets when whales are present?
- 1 <10% of catch
- 2 10-20% of catch
- 3 21-40% of catch
- 4 >40% of catch

D11 In your experience, are there any obvious characteristics *(e.g. topography, depth, season, high CPUE areas)* that may be associated with depredation events?

____

____

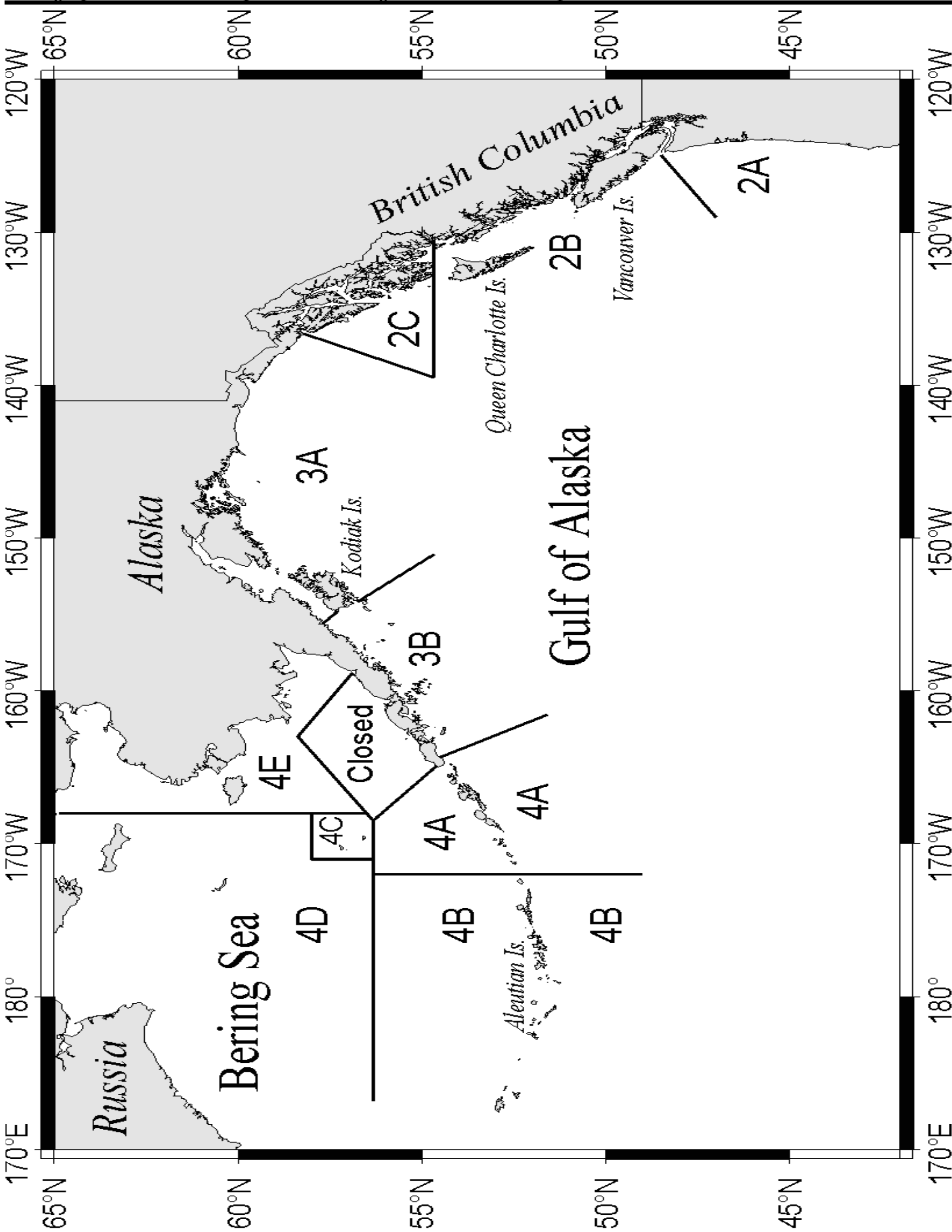
____

____

Whale Depredation Survey

Depredation Hot Spots

Please circle hot spots where you have experienced the most severe whale depredation. *Write "S" by sperm whale hot spots and "K" by killer whale hot spots.*



Whale Depredation Survey

Fishing Experience

Please circle one to indicate the extent to which you agree or disagree with each statement. (Strongly Agree, Mostly Agree, Undecided, Mildly Disagree, Strong Disagree)

LS1	Whale depredation has gotten worse over the last 20 years.	SA | MA | UND | MD | SD
LS2	Finding an effective deterrent is the *only* way to reduce depredation rates.	SA | MA | UND | MD | SD
LS3	When I fish, I am always on the look-out for whales.	SA | MA | UND | MD | SD
LS4	I *don't* get frustrated at depredating whales.	SA | MA | UND | MD | SD
LS5	Whales are teaching the depredation behavior to younger generations.	SA | MA | UND | MD | SD
LS6	"Waiting the whales out" is the only avoidance technique that seems to really work.	SA | MA | UND | MD | SD
LS7	I will often try and pass the whales off on another vessel.	SA | MA | UND | MD | SD
LS8	Whales tend to depredate in areas where CPUE is highest.	SA | MA | UND | MD | SD
LS9	Whale depredation is the main reason fishermen switch to pots for sablefish/halibut in Alaska.	SA | MA | UND | MD | SD
LS10	I would be interested in real-time tracking of groups of depredating whales by fishermen.	SA | MA | UND | MD | SD

F1 The main reason depredation has gotten worse is...

1 Ban of high seas drift net fisheries
2 More whales
3 Longer fishing seasons
4 Whales learning behavior
5 More people fishing
6 Other: ____________________

F2 To avoid whale depredation, my first choice is to....

1 Change target species
2 Fish through the set
3 Drop the gear/wait the whales out
4 Move to a different site
5 Other: ____________________

F3 Another depredation avoidance technique that may work is...

1 Dummy sets
2 Hauling gear quickly
3 Ditching the whales on someone else
4 Fishing in tandem with other boats

F4 Has anyone ever intentionally driven by to ditch whales on your vessel? 1 Yes 2 No

F5 If you decide to wait, what is the average time you wait to haul a set to avoid the whales?

1 0-3 hours
2 4-12 hours
3 13-24 hours
4 >24 hours

F6 If you had to estimate, how many times a season are you forced to wait the whales out?

1 1-5 times
2 5-10 times
3 10-15 times
4 >15 times

Additional comments: ____________________

Whale Depredation Survey

F7 If you decide motor away from the whales, what is the average distance you travel?

1 <25 nm
2 25-50 nm
3 >50 nm

F8 If you had to estimate, how many times a season are you forced travel to avoid whales?

1 1-5 times
2 5-10 times
3 10-15 times
4 >15 times

Additional comments: ______

F9 I think this kind of deterrent has the best chance of being successful…

1 Explosives
2 Acoustic deterrents
3 Gear modifications
4 Air bubbles
5 Other: ______

F10 I think this type of management solution may help reduce the effects of depredation on fishermen.

1 Depredation loss risk pools
2 Better communication with managers
3 Real-time tracking of depredating whales
4 Rotating/changing fishing seasons
5 Other: ______

Please circle one to indicate the extent to which you agree or disagree with each statement. (Strongly Agree, Mostly Agree, Undecided, Mildly Disagree, Strong Disagree)

LS11	Whale depredation is costing fishermen a lot of money.	SA | MA | UND | MD | SD
LS12	Depredation could affect my decision to continue fishing a quota.	SA | MA | UND | MD | SD
LS13	Switching to pot fishing is a realistic option for me.	SA | MA | UND | MD | SD
LS14	I am concerned about decreasing quotas.	SA | MA | UND | MD | SD
LS15	Managers have been proactive and up-front in dealing with whale depredation.	SA | MA | UND | MD | SD
LS16	I often have to fish less efficiently to avoid depredating whales.	SA | MA | UND | MD | SD
LS17	Whale depredation is reducing the accuracy of fish stock assessments.	SA | MA | UND | MD | SD

Q1 What could managers do better to assist fishermen in dealing with depredation?

______

Q2 Please add anything at all *(anything)* you think should be included! *More room on page 6.*

Whale Depredation Survey

Thanks so much for your participation!

Please mail completed surveys to:

Megan J. Peterson
17101 Point Lena Loop Road
Juneau, AK 99801

You will be reimbursed $15 for completing the survey. Please provide a return mailing address and the funds will be sent to you. ****You can elect to not receive payment if you do not feel comfortable providing social security information.*

Return mailing address:

In order to pay respondents for completing the survey, the University of Alaska Fairbanks requires that each person sign, date and provide their social security number on this form. ***This information will remain confidential and will not be distributed.*** **Please sign to confirm that you are receiving $15 as reimbursement for your time for completing this survey.**

Signature: ______________________________ **Date:** ______________

Social Security: ______________________________

Additional Comments:

Please contact Megan Peterson at 530-219-4093 or mjpeterson6@alaska.edu if you have any questions.

Appendix 5 Indirect costs survey form.

F/V ____________________

Data Collection: Tracking Whale Depredation, 2012 Season

Thank you very much for collecting data as part of this study. The goal of this survey is to gather baseline data for quantifying indirect costs fishermen incur as a result of interactions with depredating whales. This survey will focus on the increased operating costs associated with avoiding whale depredation (e.g. extended travel distances, increased soak times, damaged gear). This information will be used in conjunction with NOAA observer and survey data to estimate direct costs to fishermen (catch loss) and indirect costs (increased operating costs) over the 2011 and 2012 fishing seasons.

Please fill out the first page at the beginning of the season and the final page of the survey towards the end of the season. In an attempt to keep this as easy as possible, the majority of the data collection occurs on days when whales interact with the vessel during fishing operations. It will be important to track the total number of days fished at the end of the season (and the number of sets if possible).

**On whale interaction days, I ask for Latitude/Longitude (remains confidential). If you are more comfortable, please feel free to provide statistical landing area instead.*

Please don't hesitate to contact me (Megan Peterson, mjpeterson6@alaska.edu, 530-219-4093 if you have any questions or concerns.

Please complete this section at the BEGINNING OF THE SEASON to provide basic information on the crew and fishing vessel.

Basic Information Pre-Season
Crew

Data Collection Completed by (name): ____

Contact Number:____________________ Email:______________________________

Additional skippers or crew (please list names and role): *e.g. Bob Blue (crew with/without quota)*

____

____

____

____

____

____

____

Total Sablefish quota owned (for all skippers/crew) for vessel (lbs):_________________

Management Areas where sablefish quota held (e.g. BS, AI):_____________

Total Halibut quota owned for vessel (lbs):___________________

Management Areas where halibut quota held (e.g. 3a and/or 3b):_____________

Vessel

Vessel Length (ft):___________________

Gross tonnage of vessel:___________________________

Fuel tank size (gallons):___________________________

Engine type:________________________

Engine horsepower:______________

Auto-baiter on board: Yes ☐ No ☐

Hook type used **sablefish**:______________ Hook type used **halibut**:______________

WHALE INTERACTION SHEET (*please complete one sheet per day when whale interactions occur during fishing operations*).

Date gear set: ____________ Time gear set:_____________ Target: Black Cod ☐ Halibut ☐

Haul date:_____________ Time haul start:___________ **Time whales sighted:_____________**

 # Sets for day: _____________ # Sets affected by whales:________________

Lat/Long (*will remain confidential*):_____________________ ***or*** Statistical Area:________________

Approximate water depth (fathoms):__________ Photographs taken: Yes ☐ No ☐

Regional Area (e.g. WGOA, BS):_________ Species: Sperm whale ☐ Killer whale ☐

Gear operations when whales arrived (e.g. hauling, approaching gear to haul):_______________
____

Minimum # of whales on gear (*e.g. 1 shows up and other whales arrive later*): _________

Maximum # of whales:__________ Other boats fishing in area (~20 nm): Yes ☐ No ☐

Type of deterrents or avoidance measures used (*please describe*):__________________________
____
____

If you continued hauling with whales present…

Evidence of damaged fish Yes ☐ No ☐

Estimated % catch lost (based on previous sets):_____%

Evidence of straightened or damaged hooks: Yes ☐ No ☐

If damage to gear occurred, please estimate the value of the damaged gear: $_________

Comments/description:____
____

If you dropped the gear back down due to whales….

Amount of time hauling delayed due to whales (e.g. 3 hrs):__________________

Comments/description:____
____

If you traveled to a different site to fish to avoid depredating whales….

Distance traveled to evade whales and fish a new site/alternate set (e.g. 25 nm):____________

Time spent traveling (e.g. 3 hrs):_______________ Change target species (y/n):____________

Comments/description:____
____

Please complete this sheet at the END OF THE SEASON.

Please estimate the following for the 2012 season…

Number of days fished (setting or hauling gear) by area:

Bering Sea:______________________ Aleutian Islands:_____________________

Western Gulf:____________________ Central Gulf:________________________

West Yakutat:____________________ Southeast Outside:____________________

Number of days of vessel transit (traveling to grounds or to port):_____________

Average number of sets on a given day when fishing **sablefish**:______________________

Average number of sets on a given day when fishing **halibut**:______________________

Average # of hooks per set **sablefish**:_____ Average # of hooks per set **halibut**:_____

Total Quota Caught (lbs) by all crew on-board during the 2012 fishing season:

Sablefish:___________________ Halibut:_____________________

Average number of skippers & crew onboard throughout 2012 season:_______________

Estimated total cost of food for the crew for the 2012 season ($): $__________________

Estimated amount of fuel used for the 2012 season (*gallons or $*):___________________

Please estimate overall percentage of catch lost due to whales for the 2012 season:

Killer whales:__________% catch lost Sperm whales: __________% catch lost

During the 2012 season, did you avoid setting/fishing areas where whale depredation is thought to be most common? Yes ☐ No ☐

If yes, what percentage of the time did potential whale interactions impact your decision to fish grounds farther away to avoid whale depredation? _________%

Please add any comments or suggestions…____

____

____