FINAL REPORT
NOAA Award # NA09NMF4520413

Prepared by: Timothy Werner, Director, Consortium for Wildlife Bycatch Reduction
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Introduction

This is the Final Report under NOAA Award # NA09NMF4520413, "Consortium for Wildlife Bycatch Reduction," awarded to the New England Aquarium (Consortium Administrator), and covering the period October 1, 2009 to September 30, 2012. The Consortium consists of Blue Water Fishermen's Association, Duke University, Maine Lobstermen's Association, New England Aquarium, and the University of New Hampshire. It was established to support collaborative research and development of solutions to endangered species bycatch, focusing primarily in the US portion of the Northwest Atlantic but drawing from shared international experience in bycatch mitigation.

Projects supported by the Consortium come under three main categories:

- Global exchange of bycatch reduction technology
- Understanding wildlife interactions with commercial fishing operations
- Research and development of bycatch reduction approaches

The activities carried out under this project pertain directly to a principal mission goal of NOAA, namely, to *protect, restore, and manage the use of coastal and ocean resources through an ecosystem approach to management*.

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Organization of the Report

A detailed and separate report is included for each individual project supported under this grant to the Consortium for Wildlife Bycatch Reduction, of which there were nine. This introductory section includes summaries of the principal contributions made to bycatch research and mitigation by all these projects. For all projects, the intention was to have scientific manuscripts in peer-reviewed journals and other published materials serve as the principal deliverables and ultimate references for the research carried out here. For the majority of projects we achieved that objective, and relevant manuscripts have been referenced and some included in the appendices to this report. Each individual project report has its authors listed at the beginning of the report.

Additional Consortium activities supported by this grant, including a description and outputs from meetings and administration of its website (www.bycatch.org), are also included in this introductory section.

Background

The Consortium for Wildlife Bycatch Reduction brings together fishers, scientists, and engineers to pursue collaborative research and development of fishing gear and techniques that reduce the bycatch of non-target species and populations. The Consortium focuses primarily in the US portion of the Northwest Atlantic but draws from international experience in bycatch mitigation.

The Consortium includes but is not limited to the New England Aquarium, University of New Hampshire, Duke University, Blue Water Fishermen's Association, and the Maine Lobstermen's Association. The core objectives of the Consortium are addressed through: 1) an annual meeting and gear workshops designed to coordinate and develop plans for alternative fishing gear and practices; 2) the development and testing of new technology ropes, gillnets, and other potential bycatch-reducing devices or methods; 3) studies on animal behavior and sensory systems to better understand interactions between marine wildlife and fishing gear; and 4) fostering collaborations between industry, scientists, managers, engineers, and conservationists to provide the latest information on "best" fishing practices.

Projects supported by the Consortium come under three main categories:

- Global exchange of bycatch reduction technology
- Understanding wildlife interactions with commercial fishing operations
- Research and development of bycatch reduction approaches

The Consortium's underlying philosophy is that a science-industry partnership is the best way to identify effective and sustainable bycatch solutions. Further, its members recognize that change in fishing practices should be commercially viable, operationally practical, and use the best available science to evaluate the degree to which they will result in bycatch reduction benefits for non-target species. Equally important, even if a fishing technique is shown conclusively to reduce bycatch in a particular non-target species or population, it should not pose an increased threat to another endangered species. In this respect, the research and development priorities are in line with NOAA Fisheries' commitment to an ecosystem-based approach.

The New England Aquarium (Boston, MA) serves as the Consortium Administrator. As the administrative body, NEAq coordinates research activities to address wildlife conflict resolution (bycatch), the review of proposals submitted, and awards funds to approved proposals. The New England Aquarium is a 501c3 non-profit organization with a mission *to present, promote and protect the world of water through hands-on programs, live animal and interactive exhibits, public lectures and forums, and research and conservation projects.*

Report

Under this grant, the Consortium supported nine projects addressing the following critical bycatch challenges:

- Entanglements of baleen whales in fishing ropes (Projects 1-6)
- Bycatch of pilot whales in longline hooks (Projects 7-8)
- Bycatch of non-target elasmobranch fishes in longline gear (Project 9)

A detailed Project Report is included for each individual project. What follows is a brief summary of the outputs.

Entanglement of Baleen Whales in Fishing Ropes

Whale entanglements have been a major concern for roughly the past half a century. It is especially a problem for endangered species such as the North Atlantic right whale (*Eubalaena glacialis*).

In 2009 the Consortium convened an informal meeting among whale biologists from the New England region to discuss the persistent threat of entanglements and to identify research priorities. There was a consensus view that because we knew so little about the nature of interactions between whales and fishing gear, it was difficult to identify how to modify fishing techniques that would have the greatest potential for reducing bycatch. We therefore identified a critical need to carry out an in-depth examination of ropes retrieved from right and humpback whale entanglements (stored by NOAA Fisheries in a RI warehouse), and analyze the data in combination with information on whale scarring/injury/entanglement severity. These studies involved not only biologists and gear engineers, but also fishermen (Maine lobstermen in particular) who were essential for explaining temporal and spatial differences in the gear fished, and other details unfamiliar to non-fishermen.

At the same time, the Consortium supported research into two gear modifications identified by the Atlantic Large Whale Take Reduction Team as having potential to reduce large whale entanglements: (1) increasing the material stiffness or tension of vertical ropes; and (2) increasing the visibility of ropes to right whales. Finally, we began the development of a computer model intended to demonstrate how particular whale entanglements occur, and to provide a platform for testing the impacts of existing and future gear modifications on whale entanglements. Considering that entanglements are rarely observed or studied in nature, it seems critical to have a tool that can assist fishery managers understand the impacts of different gear modifications.

As a result of these projects, the Consortium and its collaborators determined that:

- Reducing the breaking strength of vertical lines would likely result in fewer fatal entanglements, and should be examined to determine if it would be practical to implement in some fisheries along the US east coast.
- Increasing rope tension may help whales avoid some rope entanglements, but it may also result in more severe lacerations, at least when considering whale-gear encounters in which the initial point of contact is the leading edge of the flipper.
- Right whales are likely color blind but objects that absorb light in the blue and green regions of the spectrum and reflect/transmit light in the yellow, orange or red region of the spectrum will provide the greatest amount of contrast to the background light underwater.
- Based on preliminary analyses of rope mimic trials off Cape Cod, there is a significant difference in the distance of first change of behavior by right whales confronted with black and green ropes versus red and orange ropes, with behavior changing sooner during the red/orange rope encounters. Although additional research will be carried out, this early work provides strong evidence that changing the colors of rope used in fishing gear may improve whales' ability to detect and avoid those ropes under daylight conditions.

Several deliverables were also produced as a result of these projects. Specifically:

- Detailed case studies of right (86) and humpback (22) whale entanglements, integrating (whenever available) a health assessment of the whale, the fate of the whale, an illustration of the gear configuration on the body of the whale, and the results of analyses of gear retrieved from by disentanglement teams. These case studies are completed and the Consortium intends to make them publicly available online in 2013.
- A first version of the Virtual Whale Entanglement Simulator, a computer program that models interactions between an anatomically accurate rendering of a right whale and fishing gear. Although the model needs additional work to improve its utility in studying whale entanglement dynamics, it so far can be used to recreate selected entanglements that are part of the case studies referred to above. These recreations provide insights into conditions that contribute to entanglement, including gear movement and right whale behavior during interactions.
- A comprehensive report on the temporal and spatial gear and vessel configurations of the Maine lobster fisher: *Lobster Pot Gear Configurations in the Gulf of Maine*.
- Scientific publications and presentations based on the research supported by these projects (see "Publications and Presentations", below).

<u>Bycatch of Pilot Whales in Longline Hooks</u>

In the Atlantic Pelagic Longline fishery, the two mammal species that typically interact most with fishing operations are pilot whales (*Globicephala* spp.) and Risso's dolphin (*Grampus griseus*) (Garrison, 2007). Both species are protected under the MMPA, and covered under NMFS' Final Rule to implement the Pelagic Longline Take Reduction Plan of May 19, 2009 (http://www.nmfs.noaa.gov/pr/pdfs/fr/fr74-23349.pdf). Presently the take of all three species is below PBR, although the difficulty in distinguishing short- and long-finned pilot whales means there is a possibility that bycatch of a single "stock" may exceed PBR (Erin Fougeres, *pers. comm*.).

Interactions presumably occur because these mammals are attracted to the bait, the catch, or both. Mouth hookings occur at roughly equal frequency to entanglements in the mainline, and the former tend to result in more serious injury (Garrison, 2007). In the Gulf of Mexico, the conversion of the fleet to circle hooks in order to reduce the number and severity of sea turtle bycatch may be increasing the rate of pilot whale hookings, presumably because these hooks are stronger that traditional J hooks (J. Watson, pers. comm.). Although progress has been made in reducing interactions of cetaceans with gillnet and trawl gears using pingers and other technologies, cetacean depredation in trawls, gillnets, and longlines remains a problem without any practical solution.

The Consortium supported two projects targeting the problem of pilot whale depredation, one involving fishermen operating within the Cape Hatteras Special Research Area and Dr. Dave Kerstetter of Nova Southeastern University, to evaluate the potential of a weaker hook designed to retain target catch but to straighten under the pull of a hooked pilot whale thus facilitating its escape. The other project, led by Duke University researchers, used stable carbon and nitrogen isotope analysis to address questions about the significance of depredation for pilot whales' diets, mostly within the same geographic location.

The principal findings from these projects were as follows:

- No evidence was found to support tuna as an important component of the diet of short-finned pilot whales in the study area.
- Indication of past fishery interactions observed on many stranded whales suggests that depredation may be a widespread behavior throughout the population; however, the lack of any stable isotope signature reflecting recent depredation in any of the whales sampled suggests that individual whales engage in this behavior only infrequently.
- There was no reduction in target catch, target catch weight, or bycatch during trials comparing weak and standard hooks.
- Although pilot whales were observed around the vessels during some trips, none were hooked by the gear.
- Weak hook technology is still a promising bycatch reduction technique warranting furtherl evaluation; in the trial supported by this grant, the intended research sample size was not achieved when fishermen deciding against participating in the last round of trials.

Bycatch of Non-target Elasmobranch Fishes in Longline Gear

In recent years there has been growing concern about the extent of shark bycatch. Elasmobranchs constitute a large percentage of pelagic longline (PLL) bycatch both in the Atlantic and elsewhere. Shark bycatch sometimes even surpasses the percentage of target tuna catch in the Atlantic (Beerkircher et al., 2002; Abercrombie et al., 2005). In some cases bycatch has been identified as a principal threat to species survival, as with the smalltooth sawfish (*Pristis pectinata*) that the US lists as endangered within its territorial waters (Endangered and Threatened Species, 2003).

Shark bycatch is also a problem for fishermen. There is the immediate problem to the fishermen of decreased profitability because hooks that could be used to catch target species are occupied by unwanted non-target species. In addition, there is the cost of damaged gear bitten through by sharks and reduced profitability as a crew spends valuable time removing and handling the bycatch. Closely related to this is a real potential for crew injury during attempts to release sharks that often thrash violently and possess very sharp teeth. Capture rates of target species are reduced through depredation and hook occupancy directly decreasing revenue. Gear damage, gear replacement, and shark handling time increase operational costs.

Examination of the potential for electropositive elements to reduce shark bycatch is an active area of research by the Consortium and other scientists, especially because that they have been shown to repel sharks from baits (Brill, 2008; Wang et al., 2008; Stoner and Kaimmer, 2008). In the most recent experiment, the Consortium supported Dr. Stephen Kajiura of Florida Atlantic University who combined behavioral and neurophysiological approaches to understand the mode of action of electropositive metals on the elasmobranch electrosensory system. The few previous studies on electropositive metals conducted by various investigators used different metals, variable study conditions (i.e. seawater temperature and salinity), behavioral assays and species, which limited comparisons.

- Results from these studies provide evidence that sensitivity to electric fields is comparable across elasmobranchs from different Orders and Families, however the behavioral responses to Neodinium varied between species and were influenced by hunger and competition.
- Nd may be a successful deterrent in fisheries where solitary species are the majority of the bycatch.

Workshops

The Consortium organizes at least one meeting each year to promote the exchange of information on bycatch reduction techniques and research.

In February of 2011, the Consortium held a workshop on large whale entanglements (see the individual report for Project 1).

In October of 2011, we organized the *International Marine Mammal - Gillnet Bycatch Mitigation Workshop*, held at Woods Hole, Massachusetts. The focus of the meeting was on marine mammal-gillnet bycatch mitigation, involving a workshop to review what we currently understand about available and potential techniques based on past and current research. The four-day workshop was organized into four themes: Acoustic deterrents; Non-acoustic deterrents (such as modifications to gillnet materials and methods of net deployment in the water column); Time-area closures; and Gear switching (for example, from gillnets to hook-and-line). Fifty participants from 14 countries attended the workshop, representing government, marine scientific institutions, and acoustic pinger manufacturers. The agenda included scientific presentations and breakout sessions during which participants produced summary reports on each category of bycatch mitigation approach listed above. Currently, these reports are being synthesized into a global review of techniques for reducing marine mammal bycatch in gillnet fisheries.

Individual papers presented at this workshop have already been published or are undergoing review in a Special Issue of Endangered Species Research. The ESR webpage for this issue, can be accessed at:
http://www.int-res.com/journals/esr/esr-specials/techniques-for-reducing-bycatch-of-marinemammals-in-gillnets/

Consortium Website

The Consortium developed a "Bycatch Reduction Techniques Database" to provide a clearinghouse of information on fisheries bycatch mitigation, focusing in particular on endangered species such as marine mammals, seabirds, sea turtles, sharks, and other groups. The database is a searchable collection of references and summaries, with currently over 150 bycatch reduction studies. The database allows users to search for bycatch reduction techniques by species of interest, fishing gear, or mitigation technique, view summaries about the effectiveness of methods for reducing bycatch and maintaining target catches, and consult a glossary of bycatch reduction techniques.

The Consortium designed the database so that registered users can upload new references using templates that make the process quick and easy, which helps keep the database up-to-date.

We have publicized the website on appropriate listservs, including Marmam, C-Turtle, Shark-L, Elasmo-L, American Fisheries Society, and DC Marine Community. We also correspond with registered users who have contributed to the database. Many users communicate to us that the database is very useful to their research or management applications because the database has captured a good portion of existing bycatch reduction research studies.

In addition to the Bycatch Reduction Techniques Database, the Consortium redesigned the www.bycatch.org site in 2011 where the database resides, to include general information about fisheries bycatch, information on Consortium research including reports and publications, profiles of our partner organizations, and to announce upcoming meetings and news stories.

We have tracked the use of the website using Google Analytics since April 2012. Since then, we have had:

5,532 visits
3,665 unique visitors
15,528 pageviews

The average visit duration was 3:04; new visits were 64.73% of the total.

The Consortium also uses twitter to collect and distribute information about fisheries bycatch at @bycatchorg. The account follows 588 organizations and individuals, is followed by 1,592 accounts, and has tweeted 1,720 times.

Publications (Additional publications are in preparation or under review)

Bischoff, N, B Nickle, TW Cronin, S Velasquez, and JI Fasick. 2012. Deep-sea and pelagic rod visual pigments identified in the mysticete whales. Visual Neuroscience 29: 95-103

Fasick, JI, N Bischoff, S Brennan, S Velasquez, and G Andrade. 2011. Estimated absorbance spectra of the visual pigments of the North Atlantic right whale (*Eubalaena glacialis*). Marine Mammal Science 27(4): E321-331

Jordan, LK, JW Mandelman and SM Kajiura. 2011. Behavioral responses to weak electric fields and lanthanide metal in two shark species. Journal of Experimental Marine Biology and Ecology 409(1-2): 345-350

McCarron P and H Tetreault. 2012. Lobster pot gear configurations in the Gulf of Maine. Maine Lobstermen's Association

McCutcheon, SM. 2012. Lanthanide metals as potential shark deterrents. MS Thesis. Florida Atlantic University

Reeves, RR, McClellan, K, and Werner TB. (In Press) Marine mammal bycatch in gillnet and other entangling net fisheries, 1990-2011. N 481 http://www.int-res.com/prepress/n00481.html

Waples, D., K. Zelnio, H. Koopman and A. Read. 2011. The effects of DMSO preservation on stable isotope signatures of short-finned pilot whales (*Globicephala macrorhynchus*). Nineteenth Biennial Conference on the Biology of Marine Mammals, Tampa Bay, Florida

Additional Publications featured as papers at the Marine Mammal-Gillnet Bycatch Workshop and part of the Endangered Species Research Special Issue: Techniques for Reducing Marine Mammal Bycatch in Gillnets

Dawson SM, Northridge S, Waples D, and Read AJ. (In press). To ping or not to ping; the use of active acoustic devices in mitigating interactions between small cetaceans and gillnet fisheries. N 464 http://www.int-res.com/prepress/n00464.html

Erbe C, and McPherson C. (In press). Acoustic characterization of bycatch mitigation pingers on shark control nets in Queensland. Endangered Species Research 19: 109-121 http://www.int-res.com/articles/esr_oa/n019p109.pdf

[Ten additional manuscripts are under review or under revision as part of this special issue]

Papers Presented and Meetings Attended:

T. Werner, Consortium Director

5/3 – 5/4/11 - Presentation at the *Preliminary Report of the Dynamics of Large Whale Entanglements in Fishing Gear* at the *Workshop on Large Whale Behavior, Sensory Abilities, and Morphology in the Context of Entanglement in Fishing Gear*, New England Aquarium

10/11 – 10/12/11 – WWF Smart Gear Judges Workshop, Washington, DC.

11/15/11 – Invited speaker, The Nature Conservancy Fisheries Strategy Meeting, Boston, MA

11/26/11 - "Addressing bycatch in artisanal gillnet fisheries" Workshop, 19^{th} Biennial Conference on the Biology of Marine Mammals, Tampa, FL

S. Kraus, NEAq VP for Research

1/9-1/13/12 - Atlantic Large Whale Take Reduction Team Meeting, Providence, RI

Kraus, S. 2012. Assessments of vision to reduce right whale entanglements. Gulf of Maine Research Institute Summer Speaker Series. Portland, Maine

2012 - Assessments of vision to reduce right whale entanglements. Bigelow Labs Café Scientifique Speaker Series. Boothbay Harbor, Maine

2012 - Assessments of vision to reduce right whale entanglements. North Atlantic Right Whale Consortium. New Bedford, Massachusetts

K. McClellan, Associate Research Scientist

5/4-5/6/11- International Symposium on Circle Hooks in Research, Management and Conservation, Miami, Florida

10/27-10/28/11 – Northeast Consortium meeting, Portsmouth, NH

11/2- 11/3/11 - North Atlantic Right Whale Consortium Annual Meeting, New Bedford, MA

A. Knowlton, NEAq

2011 - Knowlton, A, S Landry, J Robbins, H McKenna, T Werner. Breaking strength and diameter of rope taken off entangled North Atlantic right whales in relation to wound severity and age. Nineteenth Biennial Conference on the Biology of Marine Mammals, Tampa Bay, Florida

S. M. McCutcheon, FAU

8/8-14/12 - Lanthanide metals as potential shark deterrents. 2012 World Congress of Herpetology and American Elasmobranch Society. Vancouver, BC.

References

Abercrombie, D.L., Balchowsky, H.A., and Paine, A.L. 2005. 2002 and 2003 annual summary: large pelagic species. NOAATechnical Memorandum, NMFS SEFSC-529, 33 pp.

Beerkircher, L.R., Cortes, E., and Shivji, M. 2002. Characteristics of shark bycatch observed on pelagic longlines off the southeastern United States, 1992-2000. Marine Fisheries Review 64(4):40-49.

Brill, R., Bushnell, P., Smith, L., Speaks, C., Sundaram, R., Stroud, E., Wang, J. 2009. The repulsive and feeding-deterrent effects of electropositive metals on juvenile sandbar sharks (*Carcharhinus plumbeus*). Fish. Bull. 107:298–307.

"Endangered and Threatened Species; Final Endangered Status for a Distinct Population Segment of Smalltooth Sawfish *(Pristis pectinata*) in the United States." Federal Register 68 (Tuesday, April 1, 2003):15674-15680.

Garrison, L.P. 2007. Interactions between marine mammals and pelagic longline fishing gear in the U.S. Atlantic Ocean between 1992 and 2004. *Fishery Bulletin* 105(3):408-417.

Stoner, A.W., Kaimmer, S.M. 2008. Reducing elasmobranch bycatch: laboratory investigation of rare earth metal and magnetic deterrents with Spiny dogfish and Pacific halibut. Fish. Res. 92:162–168.

Wang, J., McNaughton, L., Swimmer, Y. 2008. Galapagos and sandbar shark aversion to electropositive metal (Pr-Nd alloy). In: Swimmer, Y., Wang, J.H., McNaughton, L.M. (eds), Shark Deterrent and Incidental Capture Workshop.

Individual Project Reports

Project 1 – Dynamics of Large Whale Entanglements in Fixed Fishing Gear (New England Aquarium [NEAq], Maine Lobstermen's Association [MLA], Provincetown Center for Coastal Studies [PCCS], and Woods Hole Oceanographic Institution [WHOI])

Project 1 Final Report

A. Knowlton, T.B. Werner, and K. McClellan
New England Aquarium

The Relationship Between Fishing Gear and Large Whale Entanglement Severity

> *…the removal of gear from entangled right whales has been a primary source of information for the identification of gear types and fisheries that pose a risk to right whales; this information is critical to the development of appropriate mitigation measures.* (Reeves et al., 2007)

Project Overview

Mitigating bycatch in large baleen whales represents a continuing challenge to fisheries managers and others interested in reducing the often lethal and sublethal impacts of these entanglements. Many gaps in knowledge exist about when and where these entanglements occur and the relationship between the characteristics of the fishing gear used and the types of injuries observed. Despite over 15 years of dedicated efforts by the Atlantic Large Whale Take Reduction Team to develop and implement gear modifications and/or closures to reduce entanglement levels, a recently published paper analyzing North Atlantic right whale entanglement interactions documented from 1980-2009 indicate there has been no detectable change in the overall entanglement interaction rate, and the rate of severe entanglements has increased over the 30 year timeframe (Knowlton et al. 2012). In addition, entanglements of humpbacks and minkes in the western North Atlantic remain a conservation concern.

This project was undertaken to investigate in more detail the parameters of rope removed from disentangled or dead large whales, the resulting severity of their injuries and whether any linkage was evident involving species, animal age, entanglement complexity and injury severity. A second aspect of the project was to investigate rope manufacturing history and assess whether changes in rope resulted in changes to fishing practices or changes in entanglement complexity and severity.

This project report represents the summation of two years of work undertaken by multiple researchers to analyze and integrate both the whale biological information, rope parameter findings, and rope manufacturing changes. The principal results are provided as two separate deliverables:

- A scientific manuscript attached as Appendix 1 that in January of 2013 will be submitted to a peer-review journal for publication.
- A compendium of case studies of right and humpback whale entanglements (Appendix 2) integrating analyses undertaken for this project (injury severity, and examination of ropes retrieved from disentanglements), illustrations of the entanglements by PCCS, life history

information on the whales, photographs of the entanglement and/or its aftermath, and information from NOAA Fisheries examination of the retrieved gear.

This narrative includes much of what is reported in those deliverables, and also summarizes the activities carried out in producing them, organized into different work phases, described below.

Phase 1 – Development of injury and entanglement severity levels

The presence of scars and/or entangling gear show evidence of each entanglement interaction that a whale experiences. As part of the investigation of rope parameters on injury and entanglement severity, three different injury levels - low, medium, and high, and three different entanglement severity levels – minor, moderate, and severe, were developed and reviewed by veterinarian Dr. Rosalind Rolland. For each right whale[1] with evidence of entanglement interactions based on scars or presence of gear (1,032 events from 1980-2009), these entanglement severity levels were applied to each event. For all humpback whales reviewed for this study (animals with retrieved gear only), these entanglement severity levels were determined.

A description of the categories accompanied by images are provided below.

INJURY SEVERITY

Any wound/scar related to entanglement is reviewed using the criteria below. Injuries were coded at the highest severity level if any one of the criteria in the category was depicted. For a scar to be attributed to entanglement, it had to show evidence of the rope having "wrapped" on a given body part (see *Figure 1* for examples of injury severity).

LOW

- Small, linear wrapping scars or depressions in the skin that do not penetrate into the blubber and are less than ~ 2 cm in width, less than 2 cm in depth (approximate depth of epidermis).

  Note: Extent of depression/scar coverage in any given body area is low; these types of scars may fade altogether over time especially when found on calves or young juveniles.

MEDIUM

- Wrapping wounds or depressions that are bright white when healed and are greater than ~ 2 cm in width, and/or between 2 and 8 cm in depth, and/or penetrate the skin extending into the blubber (hypodermis layer) but not into muscle or bone.

- Broad areas of abrasion on a given body area that have removed a layer of skin but may not penetrate into the blubber.

[1] Unless otherwise indicated, the term "right whale" in this report refers to the North Atlantic right whale (*Eubalaena glacialis*)

- Wounds or bright white scars on the head, flipper or tail that extend beyond the skin but do not extend beyond blubber (actual depth of wound not measured at these areas as blubber layer is shallow).

  Note: The wounds may be raw (red) looking when fresh but typically heal within weeks leaving no raw areas.

HIGH

- Wrapping wounds on the body more than 8 cm in depth and/or extending into bone or muscle.
- Tail, flipper, or head wounds extending into the bone or muscle.
- Broad areas where skin and blubber tissue has been removed and muscle or bone is exposed. (Note: These wounds may also extend beyond 8 cm however this was often difficult to ascertain – often these wounds will heal but sometimes raw areas may still be evident months or years after the initial event).
- Significant deformity or discoloration of fluke or flipper, for example a twisted fluke caused by torquing by rope/gear, or evidence of a white flipper (indication of circulation impairment) that occurs in conjunction with a known entanglement event even if gear or wounds are not seen on the flipper. (This last criterion ["white flipper"] applies to right whales, only).

  Note: In cases of an animal carrying rope around the rostrum or taught over the blowhole where feeding or breathing is considered to be impeded, these injuries will be coded as severe; and if a juvenile has constricting wraps anywhere on its body and is still growing, these injuries will also be coded as severe.

OVERALL ENTANGLEMENT INJURY SEVERITY

Overall entanglement injury severity, herein referred to as "entanglement severity" refers to the maximum observed injury level across all body regions. Entanglement severity is categorized as minor, moderate, or severe and is determined by evaluating the injury severity determined for different regions of the body (rostrum/head, mouth, flippers, body, tail). For example, if the injury severity for any given body region was categorized as high, the entanglement severity is categorized as severe. If all the injuries seen on multiple body regions from a given entanglement event are determined to be low severity, the entanglement interaction is coded as minor. In some cases, the documentation was not adequate to reliably assess entanglement severity, particularly when the attachment site(s) were not well-documented. When the full extent of the injuries could not be adequately assessed, the case was listed as "Unknown".

Figure 1-1 (a-c). Entanglement severity level examples.

(a) Minor

(b) Moderate

(c) Severe

Phase 2 – Development of entangling gear complexity levels

Entangling gear complexity levels were developed to investigate how complexity may have changed over time, whether complexity was related to rope parameters, and what role complexity had on the fate of the whale.

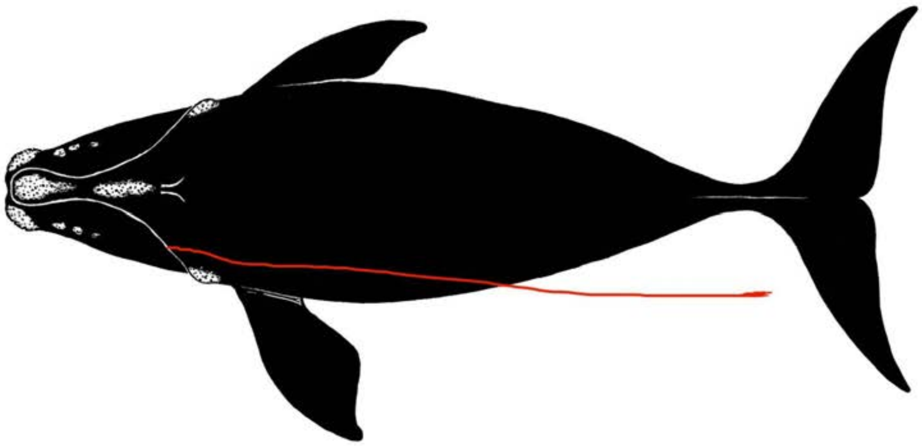
Two levels of entangling gear complexity were developed – high or low. Complexity was categorized as high if any one of the following criteria were met. If the whale experienced none of the following, complexity was categorized as low:

- More than one body area involved (potential attachment or anchoring points: mouth, flipper, body, tail)
- Dragging significant gear (greater than 1 body length trailing)
- Constricting wraps (anywhere on animal)

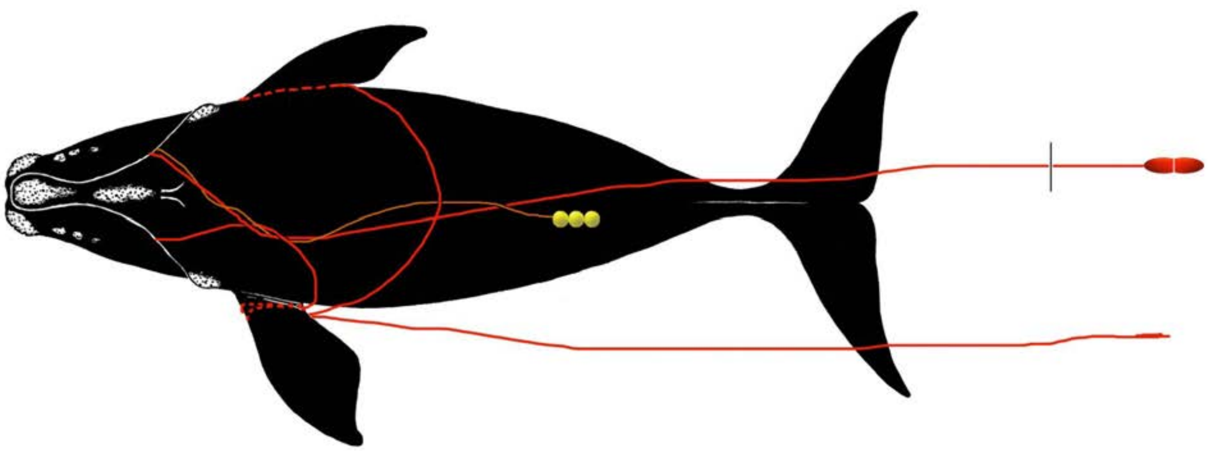
These criteria were developed based on known deaths or disappearances of both species when these types of entanglement configurations were observed.

All right whales with gear attached (including retrieved gear) and all humpback whales with retrieved gear only were categorized as high or low complexity.

Examples of whales with high versus low entangling gear complexity are provided in Figure 1-2.



(a)



(b)

Figure 1-2. Examples of entangling gear complexity for right whales: (a) Low entangling gear complexity; (b) High entangling gear complexity.

Phase 3 – Integration of whale and gear findings

This phase of the project involved the integration of the whale life history and fate data with the analyses on retrieved gear (Appendix 3) carried out by Hank McKenna, an expert in rope engineering, into whale entanglement case studies involving both right and humpback whales. In addition, the results of the combined analyses have been written up into a draft manuscript that we will be submitting for publication in January of 2013 (Appendix 1). A summary of the main findings described in this manuscript are provided below.

A second aspect of this phase was a survey of fishermen involved in the industry for several decades to see what types of changes had occurred in fishing practices between the 1980s and the present, and to also look at present seasonal variation in their fishing activity. An evaluation of rope manufacturing changes and how this might have influenced fishing activities was also explored. Methods and findings related to this study are touched upon in the draft manuscript (Appendix 1), but more details are provided in this report.

Case studies

To visually display the integration of the whale entanglement information with the gear configuration and rope parameters, case studies were developed for all right whales with gear attached (including cases where gear was not retrieved or analyzed) as well as all right whales with severe injuries from entanglement. Case studies were also created for humpback whales with retrieved and analyzed gear. Each case study is two pages in length – one page includes an entangling gear configuration diagram (created by Scott Landry) when the relative placement of gear on the body could be reliably determined, a description of the entanglement, life history information about the individual when detected with the entanglement, injury and entanglement severity, and details about rope parameters for those cases with retrieved and analyzed ropes. The second page shows images of the entangled whale. Appended to each case study, as available, are the associated gear reports developed by Hank McKenna and the Fishery Interaction Gear Analysis produced by John Kenney of NMFS.

A total of 86 right whale case studies and 22 humpback whale case studies were created. The right whale case studies are divided into three groups: whales with retrieved and analyzed gear (n = 29), whales with gear that was either not retrieved or not able to be analyzed (n = 44), and whales with severe entanglement injuries but no gear attached (n = 13). A total of 22 humpback whale case studies were created for those animals with retrieved and analyzed gear, only. An additional eight humpbacks and one right whale had retrieved gear but not enough information to create a case study, although rope information from these entanglements was included in all the analyses related to ropes.

Of the 73 right whales with gear attached, 47 cases had enough documentation to create gear configuration diagrams. The 22 humpback whale case studies all had entanglement configuration diagrams created.

<u>Findings of rope and whale analyses</u>

Methods summary

The following segments are brief summaries taken from the draft manuscript that should be consulted for clarification or more information (Appendix 1).

132 ropes from 69 individual whales (30 right whales [RW]), 30 humpback whales [HW]. 8 minke whales [MW]) and one fin whale were tested for a variety of parameters in particular estimated breaking strength and rope diameter. Because gear from only one fin whale was tested, this case was not included in any of the analyses below.

The estimated breaking strengths found on these 68 whales were compared between species and within species. Statistical differences in the average breaking strength of gear among different groups of whales were tested with a one sided Student's t-test. A one-sided test was chosen to evaluate the hypotheses that MW, HW, and RW would be found in increasingly stronger ropes because of their differences in size and weight, and whales of the same species with severe injuries, or that are older/bigger, or with higher entangling gear complexity would also be found in stronger ropes. Significance or non-significance findings are reported below and the related t-test results can be found in the draft manuscript.

To compare entangling gear complexity and entanglement severity in RW over time, two additional analyses were carried out: (1) A graph of the number of individuals seen with low or high gear complexity entanglements and visually comparing years and decades; (2) A comparison of the relative proportions of minor, moderate, and severe entanglement for all RW with either gear attached or with scars only as described in Knowlton et al. (2012). Entanglement events were combined for sequential three-year periods beginning in 1980-1982 through 2007-2009. This represented a total of 1,032 entanglement interactions. Visual differences between time periods were evaluated using a Fisher's Exact Test.

Findings

Comparison by species
No significant difference was detected in the rope breaking strengths between RW (mean = 3,292 lbs) and HW (mean = 2,952 lbs). Both HW and RW had significantly higher breaking strengths than MW (mean = 1,682 lbs).

Comparison by age
A significant difference was detected in the breaking strengths found on all juvenile RW (mean = 2,510 lbs) versus adult RW (mean = 6,184 lbs). No significant difference was found between juvenile and adult HW.

Comparison by entanglement severity
For RW, an increasing trend in breaking strengths versus severity was detected but was not significant. For HW, no trend or significant differences were found between breaking strength and severity.

Comparison by entanglement complexity
All RW cases with retrieved gear were coded as high complexity. RW are typically not anchored and few had single attachment points, therefore no comparison was carried out to investigate these parameters. Nearly all (88%) of the HW cases were coded as high complexity. A comparison of multiple attachment points vs. single attachment points was not significant. A comparison between anchored and non-anchored also was not significant.

Comparison by fate
No significant difference in breaking strength was detected for RW or HW in comparison to fate of the whale. However, most or all of the HW and RW cases respectively were considered high complexity. In most cases where the whale survived, it had been disentangled. Therefore, these findings are not surprising.
Boxplot comparison

An evaluation of the 1st quartile breaking strengths for all the different groups compared averaged 1,895 lbs with a range from 968-5,960 lbs. Interestingly for both RW and HW, the severe entanglement 1st quartile averaged 1,328 and 1,224 lbs, respectively.

Entangling gear complexity in right whales over time

The 73 cases of RW with gear attached were plotted by year and entangling gear complexity. During the 1980s and extending into the middle of the 1990s, the majority of detected entanglements had low entangling gear complexity and they were few in number. This changed from the mid-1990s onward with the majority of entanglements having a high entangling gear complexity and a concurrent, dramatic increase in the number of entanglement events. In addition, there were no detected cases of severe injuries in the 1980's, only three detected in the 1990's, and the remaining 10 documented between 2000 and 2009.

Entanglement severity in right whales over time
A graph of the relative proportions of minor, moderate, and severe entanglements (both with gear attached or with just scars) vs. the total entanglements detected within each three-year time period showed that from 1980-1982 through 1995-1997, the relative proportion of moderate and severe entanglements was below 20% of the total. Beginning in 1998-2000 and for every three-year time period thereafter, the relative proportion of moderate and severe entanglements exceeded 20%. A Fisher's exact test comparison of the tallies from these two different time periods indicated this increase was statistically significant.

Rope Manufacturing and Changes to Fishing Practices
To explore how changes in rope manufacturing may have led to changes in fishing practices, two different avenues of inquiry were followed. First, a web-based survey (Appendix 4) was distributed to fishermen by MLA The survey had a variety of questions focused on understanding where they fish, what gear types were used, the configuration and estimated weight of their gear and rope diameters used presently, seasonal changes to how and where they fish, and what changes in their fishing practices have occurred between the 1980s and the present. Many of the questions had multiple choice options. For example, the bottom depth where they fish was given in 10-fathom increments ranging from <10, 10-20, and on up to >150 fathoms. Similarly lobster configuration options were given as singles, pairs, triples, four, five, 6-10, 11-15, 16-20, 21-25, 26-30, 30-40, and 40 plus pots per trawl.

The second avenue of inquiry was to explore the internet for information related to ropes and fishing. Although we attempted to reach out to rope manufacturers (a list of four companies provided by NMFS), we did not receive enough responses to gain useful information. One responded to say they were in sales and were not manufacturers. The others could not be reached or did not return our calls or emails. Nevertheless, there were salient pieces of information found on the internet that provided some insight into changes in fishing practices. In addition, there was some useful information obtained from dialogues with fishermen and rope manufacturers during the two-day workshop held in Woods Hole in February 2011 (see below).

<u>Web-based Survey</u>

A total of 70 fishermen began the survey and 50 completed the entire survey (71.4%). For those fishermen that provided information on their home ports, most (45) were from Maine, 18 from Massachusetts, and one each from Florida and New York. Individual questions had response rates between 15.7% and 99%. Most of the respondents were lobster fishermen (70%). Others reported fishing gillnets, shrimp and crab traps, and longlines. Some of the questions apparently led to some confusion for the respondents and therefore an in-depth investigation was only carried out for those questions that had adequate information to analyze.

Years Fishing

To understand fishing practices in the past and how they have changed, we wanted to reach older fishermen, fishermen who had been fishing for many decades or fishermen who had knowledge about how fishing practices have changed. Most of the respondents reported that they had been fishing for more than 15 years (n= 52 of 67). This was corroborated by responses that the majority of the fishermen began fishing between the 1970s and 1990s.

Past Fishing Area/Time

Only 15.7% of respondents answered at least some of the questions about past fishing practices related to area and time. The first question was especially confusing about the years previously fished, because it was too similar to previous questions about years fished. The ports fished from were more numerous in the past, including locations from more southern states. Respondents also indicated that they mostly fished in state waters in the past.

Current Fishing Area/Time

The majority of respondents were fishermen working out of ports in Maine and Massachusetts, representing nearly all zones and statistical areas. Most of the fishermen spent the majority of their time fishing in state waters. Fishermen reported fishing in all months of the year, with the highest number reported between May and December.

Bottom substrate

Most lobstermen reported fishing on some type of rocky substrate at depths less than 100 fathoms although this would vary for most fishermen between seasons.

Gear Configuration and Water Depth Versus Season

Lobstermen reported setting a variety of gear configurations, from singles to 30-40 trap trawls. Most reported fishing doubles or 6-10 trap trawls, with 12-20, singles, and triples being in a distant 3rd, 4th, and 5th place, respectively. The range of total weight reported for these gear configurations was less than 50 to as much as 2500 pounds.

When each individual's response on gear configuration was categorized according to season and averaged, the data showed that for those who fish in the winter, during the winter months they shifted to longer trawls and into deeper water. The average trawl length in winter was 7.2 pots where as in spring and fall it was 6.7 pots, and in summer it was down to 6.3 pots. When the median was compared between seasons, winter had 8 pots, fall had 5 pots, and spring and summer both had 3 pots.

The average water depths fished by season was 50 fathoms in winter, 36 fathoms in fall, 34 fathoms in spring, and 25 fathoms in summer.

Current Buoy Line

More respondents answered some of the questions about current buoy lines (73%). Fifteen different answers were given for rope brand, which included multiple spellings and material instead of brand. This suggests that having provided a list of possible brands would have been more effective. The most frequently mentioned brands were Everson, Hyliner, and Manline (Mainline). About half of the respondents reported fishing with 3/8" diameter rope, with 11/32" and 7/16" also being popular.

Past Buoy Line

Fewer responded answered the questions about what buoy lines were used in the past (67%). One brand mentioned much more frequently as being used in the past than any other was Crow(e). Each individual's response was assessed to determine how rope diameter had changed from the 1980s to the present with the results shown in Figure 1-3. While the majority of respondents stated they used the same diameter presently as they did in the 1980s, seven respondents noted that the diameter they used was lower in the 1980s versus what they use now. None of the respondents said they used higher diameters in the 1980s.

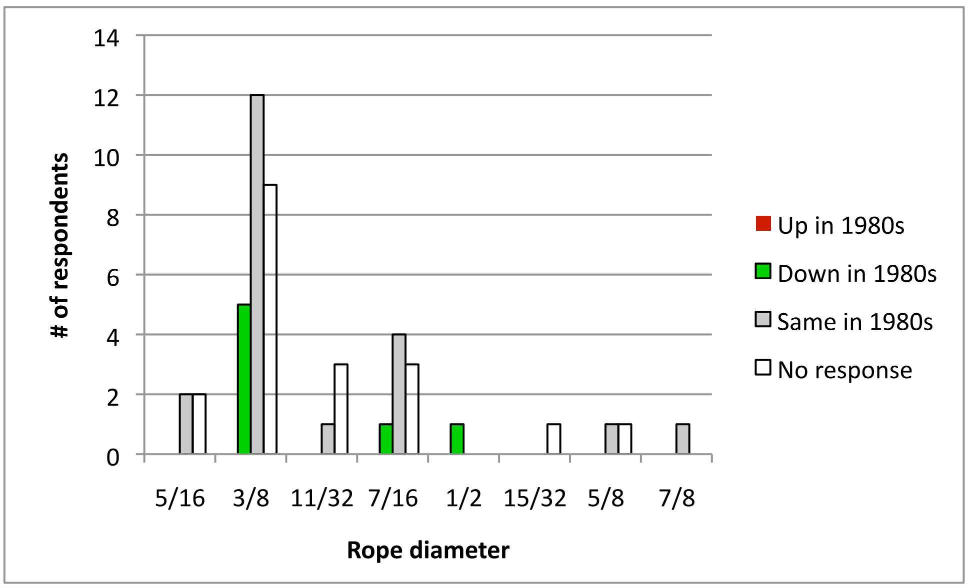


Figure 1-3. Diameters of buoy line used by individual fishermen presently and their response to whether the diameter used in the 1980s was higher or lower, the same, or if they did not respond (n = 47).

Current Groundline

Slightly fewer respondents answered questions about groundlines (67%). Everson remained the most popular brand, with Hy-liner being a close second. Again, most fishermen reported using 3/8" diameter rope, with 7/16" also being used frequently. The question about groundline configuration perhaps was not specific enough, so the responses varied significantly.

Past Groundline

Again, fewer fishermen responded to the question about past use of groundline (59%). Crow(e) was the brand used the most in the past, predominantly of 3/8" diameter.

An assessment of each individual's response comparing the 1980s to the present showed that a majority of those who responded used lower diameter groundline in the 1980s although three said they used higher diameter rope in the 1980s. (Figure 1-4).

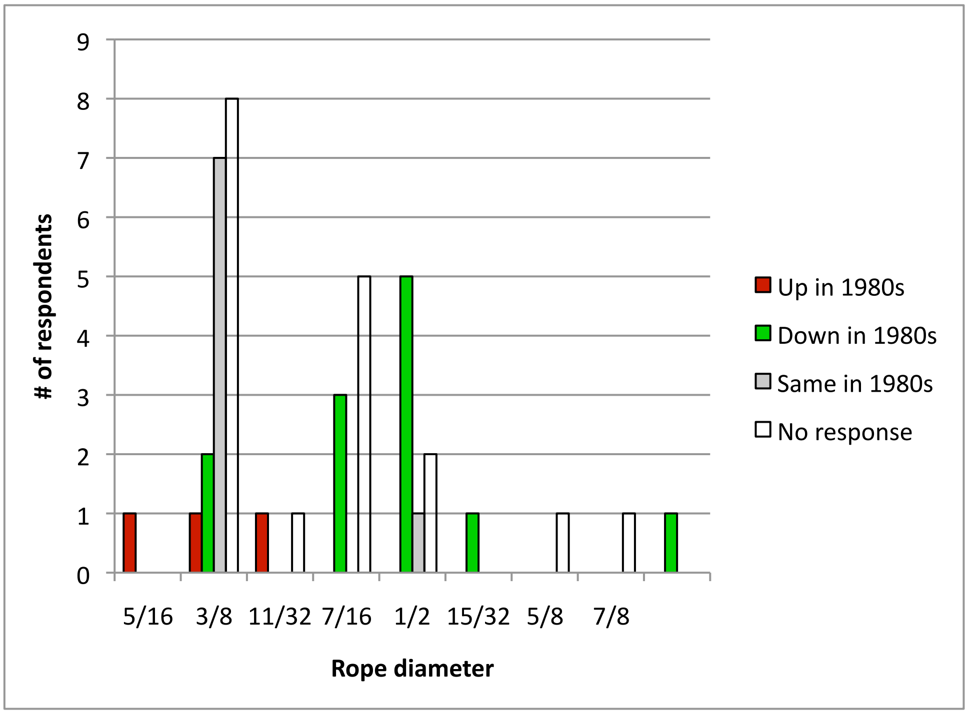


Figure 1-4. Diameters of groundline line used by individual fishermen presently and their response to whether the diameter used in the 1980s was higher or lower, the same, or if they did not respond (n=41).

Rope Characteristics (Question 14)

Most characteristics were deemed to be 'Very Important' for vertical lines (Figure 1-5). Durability was considered very important by nearly all of the respondents followed closely by breaking strength and abrasion resistance. Color was reported to be 'Not important' by most respondents. And noise was either not important or somewhat important by most respondents.

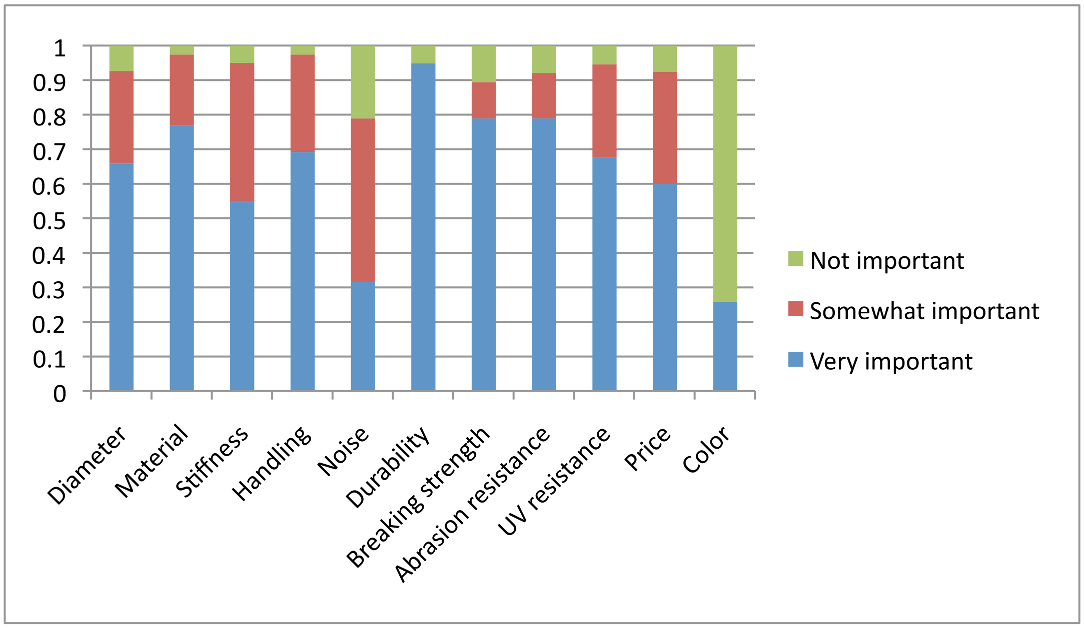


Figure 1-5. Relative ratios of importance for rope attributes.

Changes in fishing and ropes (Questions 15/16)

The last two questions invited unformatted comments how fishing practices have changed due to changes in rope. Many fishermen commented that the change to sinking groundline has been the main change in recent times with the change to synthetic ropes as the biggest change prior to that. Several noted that the sinking groundline chafes more quickly and they need to replace their gear more often. Others noted that because of sinking groundline they have shifted to less rocky bottom to avoid hangdowns. Others noted that they have increased the rope strength and diameter in groundlines to avoid gear loss. Another change noted by a couple of respondents was the shortening of groundline lengths between pots to save in cost. Lastly, several respondents noted that the change to sinking groundline has led to safety concerns. Perhaps the attention of respondents on groundline was related to when the questionnaire was administered, coinciding with the enforcement of a new regulation in which many who had previously used float rope as groundline were required to switch to sinking groundline.

Several commented that ropes are stronger and gear is heavier now than it used to be. Several respondents said that they now fish less on hard bottom and have increased the rope strength and diameter used to fish in response to the sinking groundline rule. Most respondents skipped the question about historical changes in rope use (n = 41). Those that did answer said that gear has gotten stronger and heavier because of the move to synthetic rope. Some said that they use larger diameter rope due to gear getting heavier.

Other interesting findings and recommendations

There have been several other interesting anecdotes learned from internet searches, and from conversations with rope manufacturers and fishermen over the years.

Changes in lobster pots

The vast majority of lobster pots used in the industry presently are wire traps with a plastic coating to prevent rusting. Prior to the 1970s and early 1980s wooden traps were used. As one trap manufacturer noted: "Once they caught on it changed everything, revolutionized the fishery. It allowed fishermen to fish large gangs of gear, in some cases year round, and the wire traps were found to fish better."[2]

Developing ropes at a standardized breaking strength

One rope manufacturer mentioned that a salmon fishery on the west coast that used small boats in a river requested ropes with breaking strengths of 250 lbs in order to reduce the chance of their boats capsizing if they got hung up in gear. This rope manufacturer was able to comply with that request.

Vessel loss due to gear entanglement

Recently, there have been incidents in which humans were killed and vessels lost after becoming entangled in fishing gear. The first event occurred in March 2012 off the coast of Washington state when the fishing vessel Lady Cecilia sank and four crew were lost.[3] Underwater footage has revealed that the vessel had crab pot gear entangled in its rudder and there is speculation that this entangling gear is what led to its demise. The second case occurred off of Cape Cod in November 2012 when a scallop vessel's dredge became entangled in lobster gear and the vessel capsized while the captain was trying to free it from the gear. The captain was lost.[4] These two vessels, probably similar in weight to an adult large whale, were not able to break free from the fishing gear they encountered, indicating that strong rope breaking strengths used in fishing can be deadly for both whales and humans.

Rope diameter reduction with increased breaking strength

One fisherman had mentioned that as rope strength increased, fishermen typically reduced diameter slightly to reduce cost. None of the survey responses however reported this.

Seasonal changes in gear configuration and water depth

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[2] Mike Wadsworth, manager of Friendship Trap in Friendship, Maine as reported in *Fishermen's Voice* June 2011, Vol. 16(6).
[3] http://m.dailyastorian.com/mobile/free/did-crab-pot-lines-cause-the-lady-cecelia-s-sinking/article_8ab55064-38c6-11e2-9adc-001a4bcf887a.html (accessed on 12-1-12)
[4] http://www.wickedlocal.com/provincetown/news/x1233652477/Underwater-robot-locates-sunken-Provincetown-fishing-vessel#axzz2E6OUYghB (accessed on 12-1-12)

The survey responses indicated that fishermen use shorter trawls and fish in shallower water during the summer. As fall progresses to winter, the trawls become longer and the water depth increases. Come spring, this pattern starts to shift back again. Although this question was not investigated for this report, there may be a higher incidence of severe right whale entanglements detected in the fall and winter as opposed to summer. This also could correspond with the opening of the Canadian lobster fishery in the Bay of Fundy in early November. There have been several occasions where retrieved gear has been able to be traced back to both the Bay of Fundy and to coastal Maine and the timing where the fishermen lost the gear has typically been in late fall or winter. A more in-depth exploration of the timing of detection of entangled right and humpback whales (especially anchored humpbacks), and the location of where the gear is traced back to and when the gear was lost may provide insights into whether there are seasonal differences in the severity and complexity of entanglements.

Historical natural fiber ropes

A study of the natural fibers ropes used historically in the sailing industry[5] showed that they used to be made at a higher quality and with better rope fibers than used presently in making natural fiber ropes. Hemp coated in pine tar was the rope of choice. Natural fiber ropes made today are typically made of manila or sisal, are prepared more coarsely, and are infused with chemicals and biocides. They are therefore difficult to handle and do not have as good breaking strength qualities as historical ropes.

Summary

Although the authors of this report are neither fishermen or rope manufacturers, the insights we have gained from surveying fishermen, talking with rope experts, and doing some web searches have helped us to better understand some of the changes that have been observed in the fishing industry and how these might be impacting large whales. The overarching finding is that the ropes used in fishing have become stronger and this fact may have resulted in an overall expansion of the industry into areas where large whales are more frequent. This in turn has led to more frequent serious entanglements and a higher severity of entanglement injuries for right whales and humpback whales. This increased level of takes by entanglement exceeds the levels allowed by Federal law. Based on our findings we believe that reducing the rope breaking strengths used in fishing to levels that a right whale and humpback could break free from without sustaining severe injury or complex entanglement is an important tool that should be examined as a complement other measures being developed by NMFS, i.e. the vertical line strategy, and would allow fisherman and large whales to co-exist.

[5] http://www.neropes.com/resources/history_of_rope.pdf (accessed on 12-27-12)

Dynamics of Large Whale Entanglements in Fishing Gear Workshop

From February 9-11, 2011 fishermen, whale scientists, fishing gear engineers, rope manufacturers, and marine wildlife disentanglement experts participated in a workshop to review and examine the dynamics of large whale entanglements in fishing gear. The *Consortium* organized this workshop to increase understanding about baleen whale entanglements and ultimately help improve the evaluation of methods for reducing their bycatch. We wanted to bring together important and varied points of view from individuals who too often in the past have not collaborated neither in studying the problem nor in solving it.

Much of the first day was devoted to reviewing what was known about baleen whale entanglements in the region, and sharing the results of the scarring/entanglement/injury severity results together with the findings of the analysis from ropes retrieved from entanglements. Dr. Laurens Howle of Duke/Bellequant Engineering also presented an early version of a computer model he was developing for simulating whale entanglements using engineering principles and information on whale swimming behavior.

Drafts of the whale entanglement case studies were assembled into a booklet distributed in advance of the workshop; the final versions are attached to this report (Appendix 2). The case studies were of 18 right whale and 22 humpback whale events that occurred from 1995-2006, and were intended to provide a comprehensive picture about the entangling gear and its impacts on individual animals. Other whales become entangled in fishing ropes but only right whales and humpbacks had cases of individuals with complete scarring records, illustrated wraps, and retrieved gear. Dr. Michael Moore of *Woods Hole Oceanographic Institution* (WHOI) contributed information from pathology reports for those cases that resulted in death and a necropsy had been performed on available carcasses.

In advance of the workshop, ten case studies were selected for groups to work up. They were selected to represent both right and humpback whales, a range of different gear and types of entanglement, and ones in which both retrieved gear and adequate scarring data were available. The cases selected were:

<u>Humpback Whales</u>

1. "Hat Trick" – PCCS Case WR-2003-11; NMFS Case E14-03
2. "Inferno" – PCCS Case WR-2003-21; NMFS Case E26-03
3. "Mosquito" – PCCS Case WR-2006-10; NMFS Case E13-06
4. PCCS-0208 – PCCS Case WR-2002-07; NMFS Case E11-02
5. "Tanith" – PCCS Case WR-2003-08; NMFS Case E10-03

<u>Right Whales</u>

1. Eg 1971 – NMFS Case E9-97
2. Eg 2030 – NMFS Case E4-99
3. Eg 3107 – PCCS Case WR-2002-12; NMFS Case E15-02
4. Eg 3120 – PCCS Case WR-2002-04; NMFS Case E07-02

5. Eg 3610 – PCCS Case WR-2006-28; NMFS Case E32-06

NMFS staff brought the fishing gear retrieved from these ten entanglements to the workshop, and were on hand to answer questions based on their understanding about them. Multi-disciplinary groups carried out detailed examinations of the gear, reviewed the body of evidence for these ten cases, and reported to the entire group on their overall assessments. Part of their assignment was to imagine whale-gear conflict scenarios that could have led to the entanglement observed ("reverse engineering"), and to consider what gear modifications might have prevented the entanglement or reduced its severity.

The majority of the workshop participants (20/50) consisted of fishermen from Canada and the northeastern US who fish primarily with pot, gillnet, and drag gear. The other major groups represented were from academia, non-profit marine science groups, government (the US and Canada, including disentanglement experts), and the rope manufacturing industry.

Results

A selection of observations made on individual case studies follows. Items 1-5 involve humpbacks; 6-10 right whales.

<u>Humpback Whales</u>

1*. Hat Trick* – This was a mouth entanglement involving trap gear and trailing buoys. The trailing polyballs were a unique ovoid shape. The fishermen linked this type of buoy to areas with strong currents and high tidal flows, such as downeast Maine, although no consensus was achieved and a range of areas suggested including offshore Maine, Canadian crab pots, and even perhaps Cape Cod offshore. All agreed however that based on the size of the poly balls and line diameter that it was almost certainly offshore gear. An assumption is that most likely the whale encountered vertical line while feeding. There appeared to be an abundance of splices and end knots and some examiners wondered if this wouldn't increase the probability of the line becoming fixed in the baleen.

2. *Inferno* – The whale in this case has never been re-sighted since it had partial disentanglement of very heavy gear (including an anchor) trailing from its peduncle and fluke. There appeared to be multiple gear involved in this entanglement; certainly gillnet was present, but it is conceivable that some of the gear was picked up after the initial entanglement event. During the disentanglement, Scott Landry reported that the team removed a high flyer for safety reasons, and to some examiners this suggested that the endline may have been attached to something well beneath the whale. Separate groups independently suggested that the whale may have become entangled in a vertical line and then picked up gillnet gear afterwards.

3. *Mosquito* – A mouth entanglement in lobster pot gear. One of the groups reviewing this case study recommended that disentanglement teams document on the PCCS illustrations where they

cut the ropes. The scarring observed on the leading edge of the fluke is not an uncommon result of trailing gear. One possible entanglement scenario is that the whale picked up the vertical line while feeding on its side, and then the line became stuck in its baleen. Subsequently, the pulling force of the whale resulted in the groundline parting between the first and second traps. Knots were observed in the vertical line, and may have increased the probability of the baleen entanglement. It was not clear however whether or not knots may have been made by NMFS staff who carried out tests on the retrieved gear. One recommendation is that if this occurs that it be documented and incorporated into the gear analysis and entanglement case study.

4. *PCCS-0208* – NMFS was unable to determine what kind of gear was involved in this entanglement. Rope was wrapped around the flukes on an animal never seen before or since in the Gulf of Maine. The entanglement had severely deformed the whale’s flukes, changing their normal orientation to a vertical one. Workshop study groups concluded that the rope was very probably endline given the mix of float and sink line used. One possible scenario put forward was that the whale may have hrolled when the line hit the body aft of the flippers, and the twisting movement could have explained the pattern observed. Reviewers wondered if a line with reduced scope could have helped avert the entanglement. They conjectured that a stiffer rope perhaps would have been more likely to slide off the leading edge of the fluke and avoided this entanglement.

5. *Tanith* – This was a mouth entanglement with trailing gear. At least a portion of the gear (gillnet) was traced back to its owner. The gear attached to the animal consisted of vertical line and a surface system with highflyer and tailer line attached to a bullet buoy. The line consisted of six different types sinking and floating line of various diameters. One explanation offered for why the entanglement occurred was that the whale encountered the vertical line on its side while feeding and the line become lodged in the baleen. The presence of a knot suggested to some reviewers that perhaps the line might have slipped through the baleen and an entanglement avoided had the knot been absent. The gear appeared to have been dragged through other gear that was incorporated into what the whale ended up dragging.

<u>Right Whales</u>

1. *Eg 1971* – This entanglement was assumed to be relatively straightforward, with a single anchoring point of rope within the upper jaw of the whale attached to a trailing vertical line and surface system. The simplest explanation of the entanglement was that the whale was feeding when it became entangled. Abrasions observed at the base of one of the flippers presumably was caused by the trailing gear scraping against it. This gear was previously determined to be offshore lobster gear, although the way the polyball was tied into the surface buoy--with a double spliced bridle– was a technique unfamiliar to all group members. The only alteration of gear suggested for avoiding this entanglement was the complete removal of vertical line from the water column.

2. *Eg 2030* - This whale had been entangled for at least 163 days and perhaps as many as 768. As a result, the gear was in a very degraded state. There were two sets of gillnet gear but it is not clear if they were part of the same gear. One of the reviewers who manufactures gillnet gear concluded it was likely from two different sets. Wrapping was extensive around the body and both flippers, and the whale eventually died from it. Reviewers postulated an entanglement scenario in which the

whale encountered the line first with its mouth but then rolling behavior produced the body wrap. Although there was no mouth entanglement observed, further examination uncovered that during the necropsy a small mouth wound was reported. In fact, one group of case study reviewers during the workshop wondered if perhaps most entanglements begin as a gear encounter with the mouth region of the whale.

3. *Eg 3107* – This was a peduncle entanglement that proved fatal to the whale. The gear involved was from an inshore lobster fishery, although fishermen remarked that the buoy present was one used for a large trawl uncharacteristically found in inshore waters. It was conjectured that perhaps a fishermen had lost the usual buoys and replaced them with a trawl buoy as a temporary measure. The reduced flotation with this buoy conceivably could have caused the line to have more of a horizontal profile that may contribute to an increased entanglement risk. The distance between the surface gear and where the line was wrapped around the peduncle was approximately 40', suggesting a possible depth at which the contact initially occurred, assuming the gear was actively fished.

4. *Eg 3120* - For this case it was known the location of where the retrieved gear was fished, although it was not clear when the entanglement occurred and therefore whether the gear was actively being fished or had become ghost gear. It did appear that the initial point of contact was between the vertical line and the mouth based on the first observation of the entanglement. Examination of the retrieved gear showed knots in the vertical line, perhaps increasing the risk of line becoming lodged in the baleen. Some reviewers pointed out that once gear becomes lost ("ghost gear") it has altered properties from when it is fished, so that even if fishing gear is designed to be "whale safe," as ghost gear it may no longer act as a bycatch deterrent.

5. *Eg 3610* – Unlike the other cases for which the gear type was identified, this entanglement involved longline gear of light duty, such as from a tub trawl. The location of the entanglement was the mouth. Reviewers struggled to match how the multi-colored lines were wrapped on the whale because the entanglement illustration used only one color to depict the rope.

Generally, all participants recognized that useful insights into whale entanglements can be acquired by having a group of fishermen and whale scientists collaboratively review entanglement events including the gear involved. It seems intuitive that the most accurate characterization of whale-gear entanglements would be achieved by engaging the fishermen who best understand the gear, and whale biologists who have studied whales the most, and the gear manufacturers who understand the material property and construction of the ropes involved. Yet prior to this workshop, there had not been a forum in which this exchange could occur purposefully and using the best available information on entanglement events together with the actual gear involved, corresponding information about the whales, and analyses involving both.

Separate breakout groups reviewing the same case studies often arrived at similar insights about particular cases. For example, two groups reported that rope knotting was a factor contributing to a higher likelihood that ropes would become lodged in a whale's baleen. Many also recognized the utility of combing multiple sources of data from individual entanglement events. One breakout group surmised that a particular entanglement originated in the whale's mouth but could only find corroborating evidence from a necropsy report that showed a furrowed scar in the jaw of the whale, the kind that would be produced by a rope.

Some breakout groups independently wondered if many of the entanglements characterized by wraps on the peduncle, flippers, or trunk of the body could be best explained as the result of an initial encounter of gear with the whale's mouth area. Computer modeling that incorporates the physical properties of ropes with whale behavior and biology can help test this hypothesis. Dr. Laurens Howle presented a first version of a computer model developed with a sophisticated custom software system to mathematically model the interaction between whales and fishing trap gear. The model presently allows an anatomically accurate whale model to move through a virtual environment with six degrees of freedom (three translations and three rotations). In addition, it includes a rope model to describe the rope mechanics in response to external forces such as axial current, cross current, weight, and tension. With further development and refinement, this model can provide a platform for studying whale-gear interactions and evaluating potential gear modifications, such as ropes fished under higher tension. Considering the inability to statistically validate gear modifications for whale entanglements, this tool could serve as a useful alternative.

Apart from contributing expertise on the gear and geographic differences in how gear is rigged, engaging fishermen in this workshop emphasized that hands-on examination of gear and how it entangled the whale can give them a better appreciation for how the range of gear types, as well as particular methods for configuring gear (such as the use of knots), are involved in actual whale entanglements.

Workshop Recommendations

The group suggested a number of recommendations on the final day of the workshop.

1. Many recommendations focused on improving the process by which gear is retrieved and documented from entangled whales. These included a request to thoroughly identify as much as possible the portion of the gear that was cut off during the disentanglement and/or as part of its examination by NMFS (the US National Marine Fisheries Service). Video documentation of gear above and below the water would be helpful in characterizing entanglements, and whenever it is safe to do so (for the whales as well as for disentanglement teams) it should be part of standard disentanglement procedure. Illustrations and photography should attempt to accurately capture the true color of the various ropes involved in the entanglement for aiding subsequent physical inspection of the gear. When gear is cut off from the whale, the location's GPS coordinates should be recorded, and every effort made to return to the site and retrieve gear removed at sea. This would help answer questions such as: Was there an additional gear component or another gear type involved in the entanglement? What drag force measurements might be estimated by knowing how much gear was trailing from the animal? Seeing as some entanglements appeared to involve multiple gear types (i.e., different sets and portions of the gear), it would be helpful to document how these different types became overlaid on the animal.

This would help determine which gear was involved in the initial contact and which may have been picked up subsequently. Finally, any alteration of the gear (such as knot-tying) by NMFS examiners should be documented.

2. This workshop demonstrated that insightful observations can be carried out post-disentanglement through collaborative exchanges among fishermen, gear experts, and whale scientists who are given complete information on entanglement events. Participants concluded these examinations of whale entanglements should be carried out on a regular basis by a small team of fishermen from different locations along the east coast of North America who have commitment and expertise in this subject, working alongside whale biologists familiar with fishing gear entanglements.
3. Considering the absence of data to indicate what impact regulated gear modifications are having on whale entanglements, it seemed surprising that reports from examination of retrieved gear were only available through 2007 [note: after the workshop, additional right whale samples were able to be made available for rope parameter analysis]. Many fishermen would like to see if retrieved gear can be used to create an historical benchmark and more real-time tracking of how entanglement dynamics may be changing as a result of regulatory changes to fishing gear and methods. Specifically, is there any way to use this process to evaluate the impact of weak links or sinking groundline?
4. Just as the study of individual entanglement cases and their associated gear can be insightful, examination of the body of evidence from all cases assists in identifying patterns that can help inform effective mitigation methods.
5. Workshop participants stressed the need for better gear marking so that entanglement events can be clearly attributed to the exact kind and components of fishing gear involved, which would include information on how and where it was fished.
6. Ghost gear is occasionally involved in entanglements, so any proposed gear modifications should consider the implications for lost gear, including both how the modifications might increase the probability that gear becomes lost and irretrievable, and any increased entanglement properties once it becomes ghost gear.
7. A website should give fishermen and other interested parties access to the complete set of photographic and other information on whale entanglement events, including retrieved gear, but excluding personal information of any fisherman.
8. Among the gear modification ideas worth evaluating is the use of fishing ropes that have higher tension while deployed underwater. These ropes might be less prone to wrapping around flippers and the peduncle region.
9. Including rope manufacturers at the workshop was useful given their knowledge of rope and expertise for evaluating the potential of innovative fishing ropes.
10. Necropsy data is extremely useful in understanding whale entanglement dynamics and needs to be better incorporated into the body of evidence assembled for relevant case studies.
11. A computer model with precise rendering of whale anatomy, behavior, rope characteristics, ocean current, and other critical factors that bear on whale entanglement dynamics would be a useful tool for studying various entanglement scenarios and evaluating gear modifications.

12. One recommendation is that if this occurs that it be documented and incorporated into the gear analysis and entanglement case study.

Project 1 Recommendations

The main findings from this project suggest ropes used in fishing are too strong for large whales to successfully escape in all cases, and rope strengths have increased since the mid-1990s resulting in more complex entanglements and severe injuries, especially for RW. If the fishing industry is to coexist with large whales without causing severe injuries to these endangered species, among the strategies that should be examined are reducing the breaking strengths of ropes used in fishing and ideally moving towards rope-less fishing especially in areas where more heavy-duty gear is required.

Based on the findings of this study, we have several specific recommendations as described below:

- The computer modeling effort undertaken by Laurens Howle at Duke University for the Bycatch Consortium should be used to simulate entanglements using the breaking strengths and configurations found on the entangled large whales presented in the case studies as well as age and estimated weight. When a reasonable simulation is created that results in the entanglement configuration observed, use the breaking strengths described below to evaluate how the entanglement configuration would change with the weaker rope.
- This study provides some of the first data on rope breaking strengths in relation to negative entanglement outcomes. For both RW and HW with severe injuries, the lower quartile measurements are just above 1,200 lbs. Although the average for all groups compared is higher at 1,895 lb, the data show that one fourth of the severely injured RW and HW were found in ropes below this 1,200-1,300 lb range, therefore we recommend that an examination be carried out to determine in what fishing areas north of Cape Hatteras a maximum breaking strength standard might be imposed at 1,200 lbs, to ensure that entanglements of all age groups of RW and HW would have a chance of breaking free from fishing gear before a complex entanglement develops. This analysis should include an assessment of how practical this measure would be for fishermen, and a projection of how much it might inadvertently contribute to the volume of ghost gear. Although this may not help MW (as well as leatherback sea turtles that also become entangled) as much as RW and HW, the limited data set does show the median and mean of rope breaking strengths found on MW to be at around 1,700 lbs suggesting they could also benefit to some degree from a reduced breaking strength. Any efforts to reduce rope breaking strengths used in fishing gear should be carried out to complement and strengthen the benefits that will be provided by the vertical line strategy under development by the NMFS and the ALWTRT for implementation by 2014.
- A recent analysis of RW growth rates indicates that calves experience rapid growth in their first year reaching three-fourths of adult size within 12 months (Fortune et al. 2012). Females typically give birth to calves between North Carolina and Florida during the winter months and remain resident there for several months before transiting north to spring feeding grounds. Two dead right whale calves have been found dead from entanglement in this region although there was no entangling gear attached and thus no information about the rope parameters in these cases. Only one RW calf was documented with gear and it had the lowest breaking strength of the 0-2 year old age group at 1,215 lbs. This whale (#2366) acquired the gear sometime between August and December of its calf year during which

time it would have been in the feeding grounds north of Cape Hatteras. Because newborn calves are considerably smaller than a calf at six months or more in age, we recommend an examination to determine if there are fishing areas south of Cape Hatteras where it would be feasible to use vertical lines with a maximum rope breaking strength of 600 lbs to give newborn calves a better chance of breaking free from entangling gear.

- For fishing situations where weaker rope cannot be used safely or effectively, develop and implement alternative bycatch-reducing gear alternatives, especially in light of the fact that new fisheries types and effort may change over time and other protected species (such as small toothed whales, pinnipeds and sea turtles) may not be able to endure even the whale-safer breaking strengths.
- Work with the rope manufacturing and fishing industries to develop, test, and implement lower breaking strength ropes that would work well within the industry (i.e., durable, abrasion resistant, easy to handle, safe, etc.). This should include an investigation of historical natural fiber rope-making technology as they were made at a better quality than today's natural fiber ropes.[6]
- Continue to remove and analyze gear from entangled whales to improve understanding of the types and nature of the gear that is involved, and promote multi-disciplinary examination of the gear involving fishermen, whale biologists, fisheries engineers, and gear manufacturers.

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[6] http://www.neropes.com/resources/history_of_rope.pdf

Project 2 – Assessing Right Whale Entanglement Risk Using Model Whale Flipper and Rope Interaction Experiments: Phase 2 (UNH, NEAq)

Project Goal and Objectives

The goal of this work was to use a full-scale model of a right whale flipper for evaluating the characteristics of different gear configurations and rope types on whale flipper/rope encounters. Specifically, the objectives were to:

- Test two ropes of different diameter (larger than previously tested under a previous project, including offshore lines or their equivalent)
- Test ropes with two different tension levels (higher than those already tested)
- Measure duration of entanglement and loads in all tests
- Analyze data to determine if increased line tension (such as what often occurs in downeast Maine inshore fisheries) might cause the whale flipper to shed the gear more rapidly
- Feed data from these experiments into the computer modeling work being carried out by Dr. Laurens Howle (Bellequant Engineering). Combining the results of these projects together will contribute to a broader understanding of whale entanglements and entanglement risk.

Project 2 Final Report

Taut Vertical Line and North Atlantic Right Whale Flipper Interaction: Experimental Observations

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[2] Blue Water Concepts

This report documents the experimental efforts of the University of New Hampshire, Center for Ocean Engineering and Blue Water Concepts investigating the interaction between a tense vertical line and a physical model of a North Atlantic right whale flipper.

Introduction

The critically endangered North Atlantic right whale, *Eubalaena glacialis*, is threatened by anthropogenic mortality from entanglements and ship strikes (Caswell et al., 1999; Fujiwara and Caswell, 2001; Kraus et al., 2005). Vertical lines used to mark the ends of mobile fishing gear, such as lobster traps, pose one of the leading entanglement threats to large whales. While the initial point of entanglement cannot always be identified, at least one third of right whales observed carrying gear had evidence of flipper involvement (Knowlton pers comm., 2012)

One problem with addressing gear interactions with endangered whales is that it is difficult to conduct meaningful field tests with fishing gear. Entanglements are extremely rare for any given location or fisherman, so testing the entanglement effects of an innovative fishing gear in a realistic manner with sufficient statistical power is not feasible. Thus the Atlantic Large Whale Take Reduction Team (ALWTRT) has attempted to move toward mitigation measures that intuitively reduce risk to large whales, but have not been supported by concrete evidence. In the face of this conundrum, we attempted to address one specific problem – what happens when a whale's flipper encounters a line in the water column? Defining the characteristics of this encounter may help to develop buoys and or lines that are less likely to entangle them or will do less damage to whales if encountered.

In addition, it is hypothesized that a “stiff” line or one with higher tension may reduce the number of entanglements from encounters with vertical lines. In Downeast Maine, vertical lines are taut due to the tension created by strong currents combined with the large surface floats and anchors used to keep gear in place and visible. This configuration also reduces the scope of the vertical line.

It was decided that experiments with a physical model of a flipper, deployed from a moving vessel, and towed into real vertical lines, could help us better understand how North Atlantic right whales interact with normal vertical lines and experimental high tension, “taut” vertical lines.

Methods

Flipper Model

The model flipper was constructed using data acquired from three different whales that included flipper outlines and bone measurements. From this data, a computer generated model flipper was developed. Sections of the flipper were extracted from this computer model and formed the basis of the flipper construction. The physical model of the flipper was covered with ½” neoprene rubber which was subsequently overlaid with 1/8” thick vinyl rubber sheeting. This was the same fabrication used the original flipper testing in 2007 (Baldwin et al, 2007). Other choices for material were investigated for the 2007 fabrication but were rejected due to high expense. We decided the neoprene/vinyl rubber combination was an adequate match for and emulated the outer surface of the NARW flipper. This was considered a cost-effective construction and duplicated in the new flipper so the response of the flipper to the slack vs. taut vertical line could be more readily compared.

This flipper and frame were successfully used in full-scale interaction experiments with vertical lines, which was documented in (Baldwin et al., 2007) and the presented at the North Atlantic Right Whale Consortium meeting in November 2007.

Figure 2-1. Completed flipper-whale body section while being weighed in air and water at UNH Chase Ocean Engineering Lab.

The experimental protocol called for adjusting the flipper angle relative to the 'whale side'. The forward/aft position and where the interaction happened along the flipper leading edge were key criteria. The three zones along the leading edge are indicated on Figure 2 as 'A', 'B', and 'C'. The angles (θ) are defined as**:** A: Acute (forward); N: Normal; O: Oblique (rear) relative to the whale body panel of the physical model.

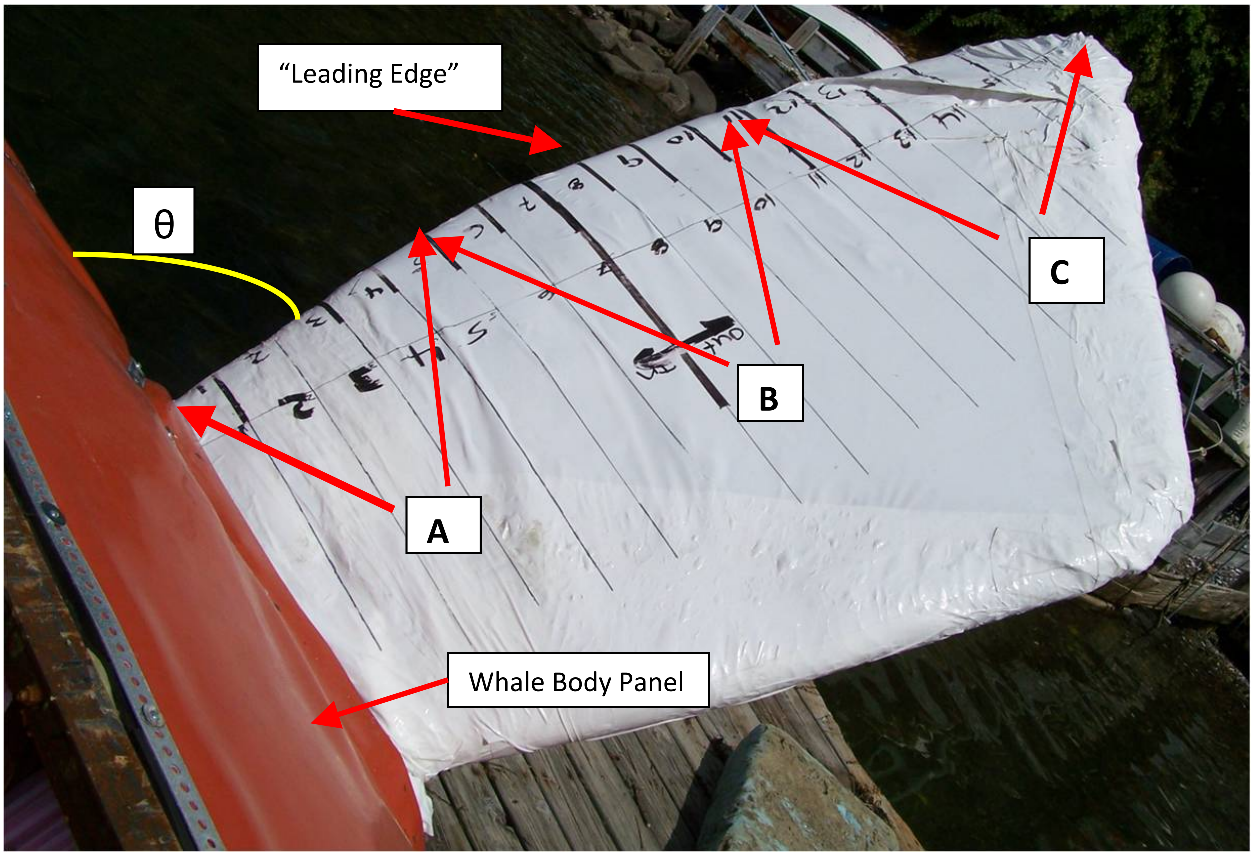

Figure 2-2. Position parameters for defining the zones along the flipper leading edge and the angle of the flipper relative to the whale body panel. 'A' : 0-50 cm; 'B' : 50-110 cm; 'c': 110 cm to the tip. (Adapted from Baldwin et al 2007)

Previous Trials

The results of previous trials (Baldwin et al., 2007) are summarized here:

- Line/flipper interactions were as anticipated: for angles 'A' & 'N' the line would snag and stay on the flipper, especially if it hit inside 80 cm
- For hits beyond 80 cm the buoy would remain above the water until all the slack expired, then the buoy would release under the flipper
- For angle 'O' the line mostly slid off the end of the flipper as the slack expired and the line gained tension
- The process was independent of line type used (i.e. sinking, polypropylene, nylon)

Taut Line Experiments

Salty Boat Company used the original flipper as a mold to fabricate a new physical model flipper for the taut line testing. The new flipper was made from fiberglass and was free flooding, rendering it lighter than the previous concrete ballasted model. The flipper's leading edge was covered with ½" neoprene which was subsequently covered with 1/8" vinyl-rubber. The flipper was marked with zones along the leading edge moving out from the body element to the tip of the flipper. The section from the body out to 60cm was ‘A’, from 60 – 120 cm was ‘B’ and from 120 out to the tip was ‘C’. These zones were marked in ten cm intervals.

The flipper was deployed approximately 12’ below the surface using a frame, attached to the *Jesse B* (Figure 2-3). This picture shows the frame without the flipper during a trial to observe the vessel behavior with the frame attached.

Figure 2-3. The flipper deployment frame mounted on the *Jesse B*. The flipper is lowered to a position under the vessel when the ‘arms’ are in a vertical position

A new mooring system was fabricated to create the taut vertical line using a large mooring block in the harbor in Eliot, Maine. The existing mooring block was fitted with a pulley and a swivel. The vertical line being tested was at least twice the water depth at mean high water (MHW) in length so the line could be changed by releasing the tension and replacing the experimental section with a different line. A 5/8” line was attached to a 28” diameter float, guided down through the pulley at the block, and attached to a longer sinking line which ran along the bottom to the shore. The float used to create the buoyancy was typical of those used by lobstermen. It was deployed at the test site at low tide and the line attached to it was pre-loaded at this point in time. The shoreline was surveyed earlier for a suitable ‘fixed point’ for securing the line when it was under tension. The line was terminated with an in-line load cell, attached to the fixed point, for measuring the tension in the line. A schematic of the mooring system is shown in Figure 2-4.

Line tension measurements were first recorded at low water (LW). The float was pulled under water from the shore and secured to the load cell at the fixed point on the shore. As the tide rose, the load was monitored until the float was completely submerged.

Experiments in the field began in August 2011. The flipper deployment frame was assembled on the *Jesse B*. A few trial runs were made without the flipper to get a feel for how the frame would affect boat steering. The flipper was attached and more trial runs were made until the crew was confident with steerage of the boat.

Two cameras were set up to observe the flipper-line interactions and a third was used to monitor the boat course. One camera was placed to look out along the flipper leading edge. A second was mounted to the flipper frame to look down along the flipper. A four channel DVR was used to record the video. The DVR was able to record and save the video on the internal hard drive.

After all the preliminary checks were completed, testing was delayed due to weather. Everything was removed from the water and boats were moved to safe locations or pulled from the water. The next testing date was October 1, 2011 after the weather improved and everything was reassembled. It should be noted that after large weather events, which produce a large run-off, the estuary is fairly turbid for up to two weeks.

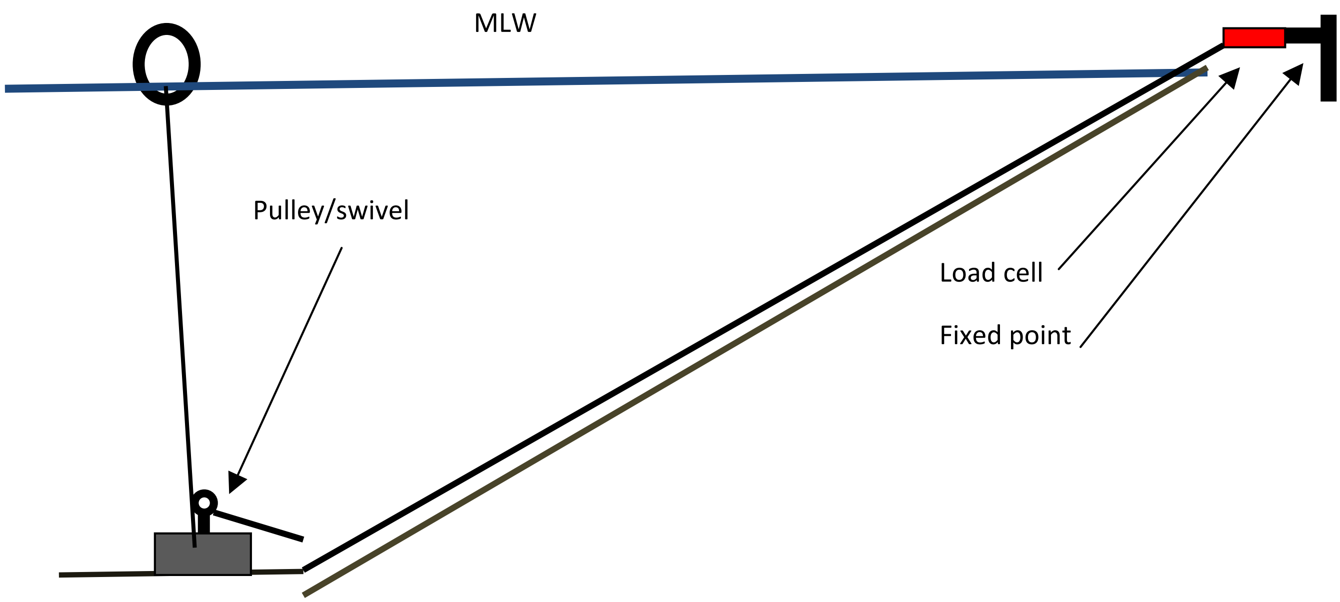

Figure 2-4. Schematic of mooring/taut line system indicating load cell placement at the fixed point.

Results

The tension of the line, with a fully submerged 28” in diameter float, was 415 lbs. This value is based on the displacement of a sphere 28” in diameter using water density of 62.4 lb/ ft^3. This value did not account for the weight of the float nor was the actual density of the water used, but the value was considered an acceptable estimate. The float was inflated in air at approximately 75° F and then submerged in water which was cooler (approximately 55° F) hence the sphere could easily have contracted. For these reasons, line tension measurements that were within 20% of this estimated value were deemed acceptable.

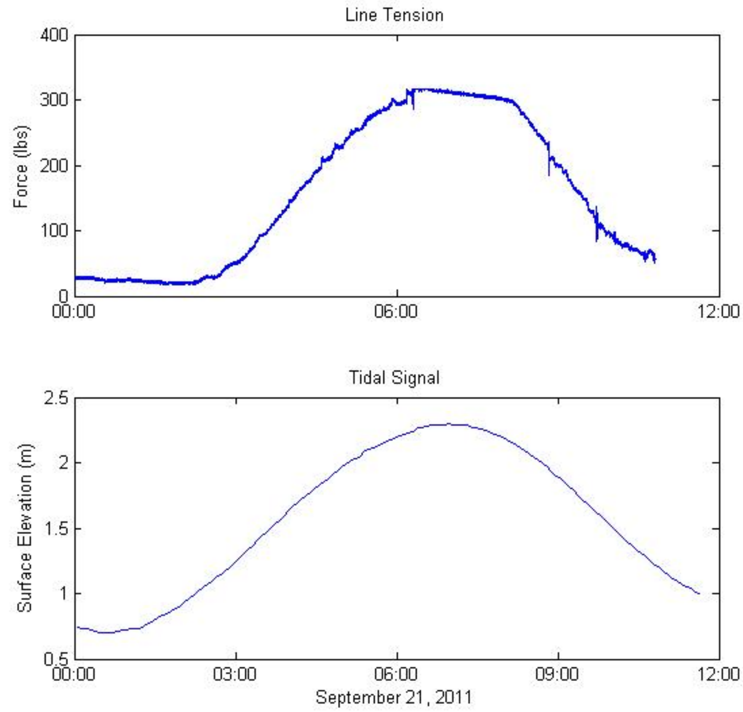

Figure 2-5. Measured line tension is shown in the top plot and the corresponding tide signal is shown in the bottom plot. The maximum tension was 325 lbs.

The line tension was continuously monitored over a 12 hour period. At high tide, the float was completely submerged, providing maximum line tension of 325 lbs (Figure 2-5).

Trials with the flipper began on October 1, 2010, in the afternoon during high tide and maximum line tension. The flipper was in the neutral, 'N', position relative to the body side panel. The boat was driven at 2 knots into the vertical line. Thirty-three interactions between the flipper and the line were recorded. The first group of 11 runs was mixed, hitting all areas of the flipper leading edge: A, B, and C. These trials were considered 'learning curve' observations.

Observations from the next 11 trials were recorded. Six events of that group were glancing interactions, in zone C, the outer edge of the flipper. These events occurred quickly, in less than two seconds. The remaining five interactions were at zones A and B areas. During these interactions, the float moved vertically down in the water column with a slight angle towards the back edge of the flipper (Figure 2-6).

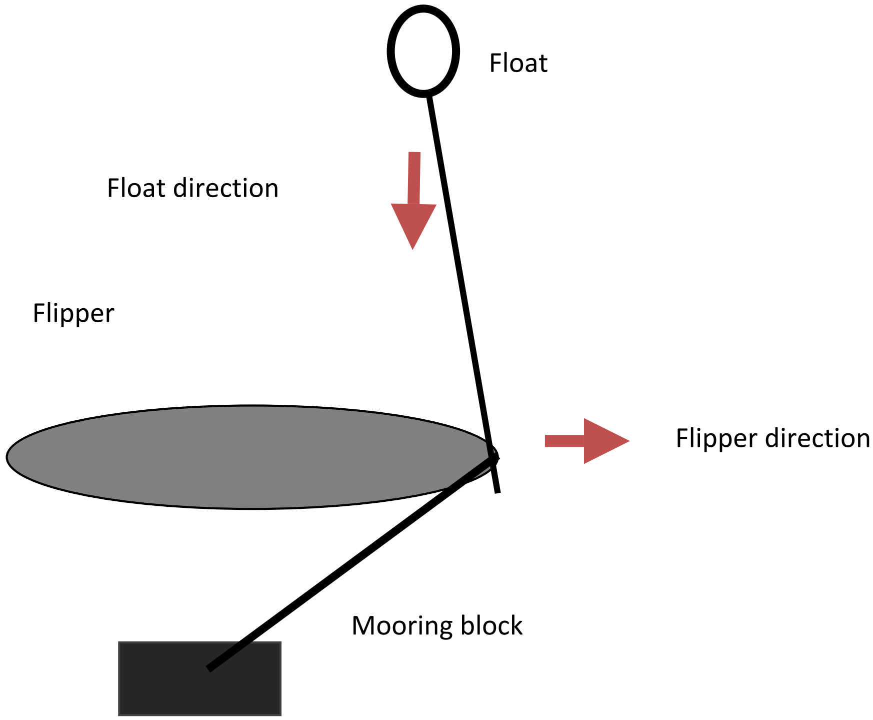

Figure 2-6. Schematic of the components of the line-flipper interaction. Red arrows indicate the motion of the flipper and the float.

The basic contact geometry resulting from zone A and B contacts showed a downward motion of the float as the dominant movement. After this group of events, it was observed that the material at the leading edge of the flipper was coming apart. Pieces of the vinyl rubber were moving about in the flow and pieces of the neoprene came to the surface. The resulting leading edge is shown in Figure 2-7.

The next eleven trails occurred in zone A and B, except one glancing event in zone C. During the A and B zone interactions, the float was observed to move downward as shown in Figure 6 in all cases. Some of the contacts that occurred in zone A caused the *Jesse B* to list starboard, leading the event to be terminated. Contact between the line and flipper was terminated by slowing the Jessie B, usually when the float reached the flipper edge. A summary of the events is displayed in Table 2-1.

The glancing events were 2 to 4 seconds in length and the line simply slid off the end of the flipper after contact. The events where the line snagged and the float submerged down to the flipper had an estimated 7 seconds maximum limit, based on the geometry of the mooring line and the speed (2kts) of the *Jesse B*.

Figure 2-7. A series of after the fact pictures showing the status of the leading edge of the flipper. The top two pictures show a scalloped edge which is most likely resulting from a ‘sawing action’ of the line as the float descended.

Table 2-1. The log book summary of the contact events is presented with an event number for correlating with the video and area of event, 'A', 'B', 'C'. The * indicates that the contact area is not clear. Some events were defined as 'A-B' in the notes

Event #	Event Area		
	'A'	'B'	'C'
1*			
2			X
3			X
4		X	
5		X	
6		X	
7			X
8			X
9*			
10			X
11	X		
12			X
13			X
14			X
15			X
16		X	
17			X
18			X
19	X		
20		X	
21	X		
22	X	X	
23*			
24	X		
25	X		
26	X		
27		X	
28			X
29	X		
30	X		
31	X		
32		X	
Total	**10**	**8**	**11**

Discussion

Observations from the video cameras and the final condition of the flipper's leading edge provide some insights into the nature of collisions between high-tension vertical lines and North Atlantic right whale flippers. When the line engaged the flipper in zone ‘A’ or ‘B’ along the leading edge a downward movement of the surface float was observed and an apparent ‘sawing action’ occurred which resulted in significant damage to the leading edge of the flipper (Figure 2-7). The damage to the flipper’s leading edge was clearly visible after 22 events, and 11 of these 22 events were just glancing events. It did not even take prolonged contact between the line and the flipper to cause this shredding. During each collision event, the *Jesse B* would list precariously starboard and each interaction event was therefore terminated only after 2-7 seconds had elapsed.

As shown in Figure 2-6, the line had little horizontal displacement before the vertical movement dominated and the line began to cut into the flipper. Vertical movement of a fishing rope across the edge of a baleen flipper can lead to the removal of epidermal tissue even under much lower tension than that used in this trial (Winn et al., 2008). In previous flipper-line collisions using a similar flipper model and under similar environmental conditions, there was more line in the water and a smaller toggle buoy at the surface such that the vertical line was far less taut (Baldwin, 2007). The additional scope provided more opportunity for the line to move along the flipper inward or outward relative to the body as the flipper moved forward under the propulsion of the *Jesse B.* These events were of much longer duration, ranging from 11.6 to 61.6 seconds.

The large surface float required to generate the high, ambient tension on the vertical line was not easily shed from the flipper. The float and the subsequent line tension essentially caused more snagging of the float as there was little room, temporally or spatially, for movement. If the experiments had been carried out in deeper water with longer, but still taut, lines, there would be more time for the float to move downward and possibly be shed from the flipper.

Originally, one goal of this project was to test two different diameter lines. The 5/8” diameter line was larger than lines tested in the 2007 experiments, and was the largest line planned for this series of experiments. During the trials, the 5/8” diameter line was observed sawing into the flipper leading edge. Due to this damage, it was decided that smaller line under similar tension would do more harm to the flipper, so no other diameters were tested. Support for this decision comes from abrasion tests using different fishing ropes and whale flipper tissue retrieved from entangled necropsied whales, in which ropes with lower diameters were more likely to cut into the epidermis (Woodward et al., 2006; Winn et al., 2008).

There are several obvious limitations in extrapolating the results of these trials to what actually occurs when right whales collide flipper first with vertical fishing ropes. Although the model flipper was constructed to be anatomically accurate and capable of slight sweeping movements both forward and aft, its covering, body attachment, and articulation were clearly different than what occur on a live animal. Furthermore, the rig is not appropriate for evaluating a more dynamic and prolonged interaction, such as were a whale to roll its body following contact with the gear, as was observed when a humpback whale came into contact with a gill net rope (Weinrich 1999). The results do suggest however that in evaluating the potential of stiff rope for reducing the incidence of large whale entanglements, consideration should be given to a possible increase in the probability that they would cause lacerations, at least for entanglement events in which the first point of contact is the whale flipper. This may especially be true if the intense force exerted against the flipper’s leading edge as a swimming whale moves into it may embed the line before it has a chance to slide off the outer tip. Although the results of this experiment should not condemn the potential bycatch reduction benefits of using a stiffer vertical line in trap and gillnet fishing, they do provide important insights that in combination with further research can help in its evaluation.

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Project 3 – Modeling Whale Entanglement Events (NEAq, Duke University, Bellequant Engineering)

Project Goal and Objectives
In the absence of direct observations of entanglement events involving baleen whales, the goal of this project was to better understand the dynamics of rope entanglements by drawing from hydrodynamic modeling involving actual and computer models.

Project 3 Final Report

Modeling Right Whale Entanglement Events

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Executive Summary

This final report summarizes our progress in generating an interactive virtual computer modeling system that will allow marine mammal scientists to reverse engineer entanglement events between whales and fishing gear. Although this is an ongoing project, this report summarizes our work under ending NOAA grant number NA09NMF4520413. As of the date of this report, we have completed the following tasks[7]: (3) research rope – cable models, (4) code FD/FE rope – cable models, (5) test rope model interaction with existing whale model, (8) install and learn Blender software, (9) compile a basic list of NARW motions, (10) create NARW bone mesh, (11) create NARW skin mesh, (12) code NARW motions, (15) install and test nVidia PhysX API, (16) code whale kinematics models (NARW), (17) code, test, refine, and optimize collision models, (20) generate and code whale – rope friction model. The first major task group, (2) Rope Model, the second major task group, (7) NARW Animation, and the third major task group, (14) Collision Model, are all 100% complete. The fourth major task group, (19) Friction Model, is 49% complete. Additionally, we were able to locate an open source software package to replace the commercial package we had originally budgeted for this project.

Abstract

The North Atlantic right whale (*Eubalaena glacialis*) is critically endangered. Population estimates put the number of North Atlantic right whales (NARW) in the range of 350 individuals with some indication of a slight upward trend [1]. The National Marine Fisheries Service (NMFS) has designated the summer feeding and nursing areas of Cape Cod Bay and Great South Channel as critical habitat areas. Several of the NARW areas are also productive for lobster and other fisheries. Entanglement of NARWs with lobster and other fishing gear is a major cause of mortality in the population (ship strike is another major cause of mortality) [2]. One recent study using photo-identification of NARWs found that greater than 75% of the NARWs had been entangled at some time in their lives and many NARWs had been entangled numerous times [3]. While there are many case reports on post entanglement and entanglement severity [2], there remains little documentation of first-encounter and how NARWs or other baleen whale species, such as the humpback whale (*Megaptera novaeangliae*) [4], become enwrapped after a first encounter with gear. In order to gain a better understanding of how entanglements might occur, and to aid in the analysis and design of fishing gear, we have developed an interactive simulator that allows the user to swim a virtual whale model through a gear field in an attempt to recreate (or reverse engineer) an entanglement given post-entanglement field observations or necropsy reports. Our entanglement modeling system is capable of running on either a PC or an Xbox 360 gaming console and uses a morphologically accurate whale model [5].

Introduction

The North Atlantic right whale (*Eubalaena glacialis*) has been fully protected from commercial hunting since 1935, but the species is still listed under the U.S. Endangered Species Act and as Critically Endangered on the International Conservation Union (IUCN) ‘Red List’. The number of animals in the species does appear to be slowly increasing [1], though continued serious injury and mortality from ship strikes and entanglement in fishing gear are certainly still slowing the recovery of the species [1, 3]. Becoming entangled in fishing gear is dangerous for whales for several reasons. Direct mortality from gear has been documented, but more common is the gradual decrease in body condition associated with gear being wrapped around body parts, including the mouth, reducing the animal’s ability to feed

[7] Task #s refer to those in the chart (Figure 3-7).

[2, 6]. Even when not involving the mouth, entanglements force animals to expend as yet unknown amounts of additional energy as they drag gear through the water.

To address the injury and mortality from ship strikes, several measures have been taken such as the shifting of shipping lanes in the U.S. and Canada and the recent implementation of a speed reduction rule around ports along the U.S. east coast. In an attempt to reduce entanglements in U.S. waters, the National Marine Fisheries Service implemented a rule requiring that lines joining fishing traps along the bottom must be neutrally or negatively buoyant (i.e., so-called 'floating' line is believed to entangle whales as they swim close to the bottom to feed) [7]. Even with the reduction of this threat, there are still thousands of lines in the water associated with traps as the ropes connecting the trap lines to the surface number in the hundreds of thousands. Another means of addressing the entanglement problem is to remove the gear from an entangled whale, an operation that is expensive and dangerous for both whales and humans. Even with the successful removal of gear, animals can carry life-long injuries [2], whose fitness consequences are poorly understood. Also, while disentanglement is sometimes successful, many more animals become entangled than can be helped and many entanglements are known to us through the existence of scars from previous entanglement events [3].

Given the prevalence of entanglement, its detrimental effects to the whales and the difficulties of treating the animals once entangled, the best strategy seems to be to prevent whales from becoming entangled. One way of preventing entanglements is to remove the gear from the water, and some measures have been taken to do this, but there is still a staggering amount of line in the water. Another strategy is to design gear that minimizes the chances that a whale will become entangled when it encounters the gear. In this vein there are been attempts to make different types of rope, or rope that disintegrates in a relatively short period of time, or rope that is somehow easier for the whales to detect. The method we have taken to contribute to this search for solutions is to recreate the sequence of events that lead to entanglements and to 'reverse engineer' the situation in hopes of gaining insight into some changes that can be made to the gear to reduce the likelihood that a whale will become entangled when it does encounter gear in the water. We have created a virtual whale entanglement simulator (VWES) to do this, and this environment also returns information on the forces (e.g., frictional, drag) experienced by the whale and the gear during an encounter. We report here on the second version of the 'virtual whale entangler', its outputs and directions.

Nomenclature

API	Application programming interface
CPU	Computer processing unit (computer hardware)
GPU	Graphics processing unit (computer hardware)
NARW	North Atlantic right whale
NEAq	New England aquarium
NMFS	National Marine Fisheries Service
NOAA	National Oceanographic and Atmospheric Administration
SAG	Surface active group
VWES	Virtual whale entanglement simulator
XNA	Microsoft managed DirectX API

Methods

Early in the development process for our VWES, we investigated several APIs for displaying the graphical output from the VWES system. Two of the more popular graphics APIs are OpenGL and Direct3D [8]. Direct3D was developed by the Microsoft Corporation and is a proprietary API for use with the Windows operating system. OpenGL was originally created by the Silicon Graphics Corp. and has become a widely-used open standard API. Both of these graphics APIs will take advantage of hardware acceleration if the capability exists on the computer's graphics card [8]. A third graphics API set, XNA, is a proprietary Microsoft system that provides a managed wrapper for the Direct3D and DirectX API sets [9-14]. XNA is the API most frequently used to program Xbox 360 and many Windows games. The XNA API set offers many advantages to the programmer when developing graphics-intensive applications such as native integration with the managed C# computer programming language. After a thorough review of these competing graphics APIs, we selected the XNA API set for graphics programming.
Although one paper documents the entanglement of the juvenile humpback whale with a fishing net [4], little is known about the behavior of whales when they encounter trap gear and how they become entangled after first encountering the gear. One of our goals in developing the VWES we discuss in this report is to generate a virtual system that marine mammal scientists can use to reverse engineer whale entanglement events. An additional motivation for this work is to create a virtual gear design software system which fishing gear designers and Marine Fisheries regulators can use to virtually test gear modifications before resorting to more expensive and time-consuming field tests. This could help the designers and regulators reduce the probability and/or severity of whale entanglement. In planning the development of the system with scientists at the NEAq and the NMFS, we decided that the most useful tool for our VWES is an interactive system that allows the researcher to control the whale's movement and test various "what if" scenarios. The XNA 4.0 Game Studio programming API provides a natural solution to our requirements. Another advantage of developing under the XNA API is at the modeling system can be deployed to either computers running Microsoft operating systems or to the Xbox 360 game consoles.

We developed our VWES so that the user controls the whale's movements using a standard Xbox 360 game controller. Currently, the whale dynamics are kinematic while the gear dynamics are kinetic. That is, the whale's movements are prescribed by the user without regard to the forces needed to generate those movements whereas the trap gear reacts to interactions with the whale and with the surrounding environment. In further refining our VWES, we will give the user the option of kinetic/kinetic dynamics. User input with the controller is as follows: whale swim speed is controlled by the left trigger; pitch and roll are controlled by the left joystick; left and right yaw are controlled by the right joystick; fast (cheat) swim speed is controlled with the right shoulder button; the start button restarts the simulation; the back button exits the program; the B button toggles first or third person (whale) point of view; and the Y button enables weak links to break the trap line if the line tension exceeds a set value. Additionally, the controller gives feedback to the user by vibrating if the whale collides with the seafloor, with another object, or attempts to breach the ocean surface.

The kinetic behavior of the gear and collision detection turned out to be one of the major areas of effort for this project. After much programming effort of the kinetic gear behavior and collision detection, we elected to use a commercial, off-the-shelf (COTS) game engine physics API [15] that included kinetic physics models, collision detection, and many other physics simulation capabilities. While other physics engine systems are available [16], the COTS game engine API that we chose was particularly well suited to this project due to its low cost, relative ease of programming, and the fact that this API did not require specific video hardware to operate efficiently. We also investigated the use of the nVidia PhysX game engine [17]. However, we decided not to use this game engine due to the fact that it includes native support for only the C++ programming language and does not include native support for the C# programming language. Therefore, we decided to continue to use our COTS game engine.

The 3-D right whale used in our VWES was created in several steps. First, a gaming programmer created an initial wire mesh whale in Lightwave, basing the shapes and dimensions of the whale parts on pictures and video. That model was then imported into Modeler Pro, where it was substantially revised it using empirical measurements obtained from necropsy reports and from photogrammetry efforts (for full details see [5]. After updating the 'base' model whale, we also created a pregnant whale model and a version with the whale's mouth open as it would be for feeding. In Figure 3-1, we show the open mouth and closed mouth versions of the North Atlantic right whale model used in our VWES.

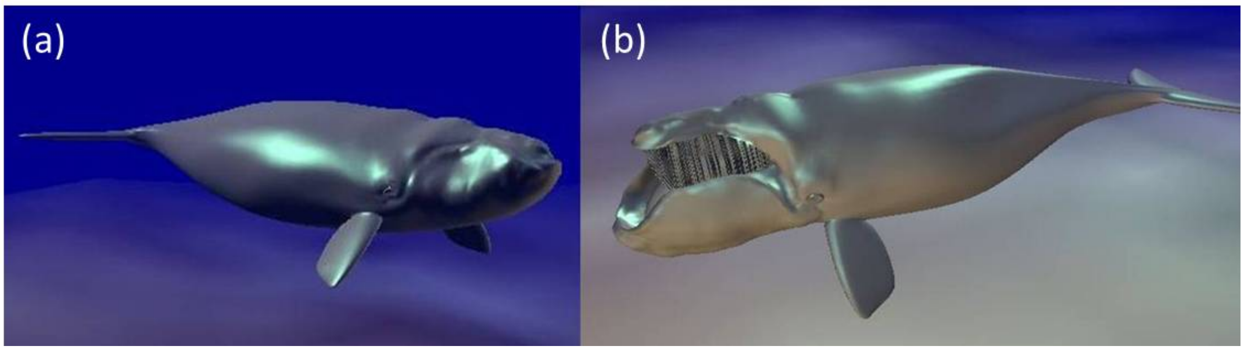


Figure 3-1. Closed mouth (a) and open-mouth (b) versions of the North Atlantic right whale used in our Virtual Whale Entanglement Simulator (VWES).

Much information on the properties of ropes such as strength, bending stiffness, elongation, friction, and wear due to internal and external damage is available in the literature for fiber [18-20] and wire [21, 22] ropes and will not be reviewed here. In this section, we will focus the discussion on the specific issues we faced with the rope and gear models used in the VWES. We begin with a discussion of static rope models. This is followed by information on the dynamical modeling of ropes under varying loads and with possible frictional contacts.

Solutions for the static shape of a rope under the effects of general body and surface forces are well-known and readily available [23]. We initially used these model solutions in the VWES for specifying the initial rope shape for some of our simulations. Later, we found it more practical to specify a simpler initial shape and let the rope settle to a steady-state configuration under the combined effects of current, buoyancy, and possible contact with other objects such as traps. Measurements of floating ground line elevation are also available [24] but we did not use this information in the VWES due to the fact that floating ground lines are not currently used in fisheries. We also built in the capability to have multi-part ropes into the modeling system. This allowed us to model the use of a floating endline portion connected to the trap and a sinking endline portion connected to the surface buoy.

The dynamic simulation of ropes (endlines, gangions, groundlines) is a subject that occupied a large fraction of our efforts for this project. Fast and accurate simulation of rope dynamics with time varying loads and time varying contacts is an active area of current research focus, particularly in the offshore structures [19, 20, 25, 26], and computer graphics [27, 28] fields. Some of the issues that one faces in generating an accurate rope model for interaction with other objects include the need to balance computational speed, accuracy, and stability. Rope models can generally be classified into two categories, continuum models and models that approximate the rope as a chain of rigid bodies [27]. In our VWES, we used the second of these two approaches. That is, we approximated the continuous rope by a series of rigid bodies, either spheres or cylinders, which were connected to one another with virtual springs. The springs allowed the force to be transmitted from one link component to the next and allowed for relatively easy collision detection calculations. However, if the spring constant was too large, the dynamic rope became unstable. Additionally, the use of spring connectors allowed the VWES to simulate weak links by specifying a spring tension force at which the link would break. An image from the VWES of the dynamic rope model along with and entangled NARW is shown in Figure 3-2.

Gear models used in the VWES consisted of traps, lines, and buoys. The trap models were approximated by rectangular boxes having all of the mass concentrated on the outer surface. This allowed the correct mass moments of inertia to be calculated so that the physics simulation involving the traps was more accurate. Additionally, collision detection between the rope and the traps was appropriately handled. In addition to the trap model we also used a buoy model in our simulations. The buoy model appropriately handled the physics calculations that resulted from its buoyancy and the hydrodynamic drag from an imposed current.

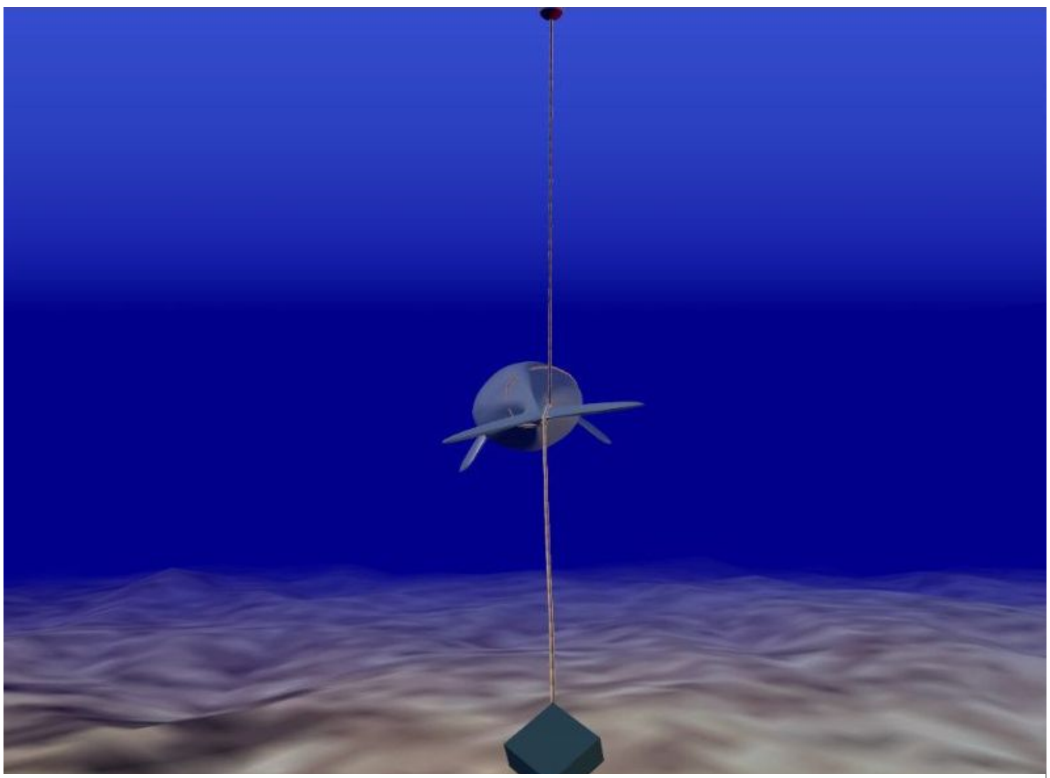


Figure 3-2. Dynamic rope model shown attached to a trap under the combined influences of current, buoyancy, and contact with a NARW.

Whale movement, particularly at the moment of initial entanglement, is likely an important factor in understanding the entanglement mechanisms and severity. While observations of initial entanglements are quite rare [4], video footage of surface active groups (SAGs) is available [29]. It is possible that the same motions displayed during SAG activity would also be displayed upon initial entanglement with fishing gear. As a portion of this project, we compiled and programmed a list of basic SAG motions and have programmed these into our VWES.

There is currently at least one model of whale articulation for a swimming NARW [30]. However, this model is restricted to swimming motions only and does not include other motions such as those observed during SAG activity or pectoral flipper movement. A more general, computationally expedient and interactive whale animation model was created for our VWES. Modern computer games create character animation by considering a bone mesh and a skin mesh [31]. Each vertex in the skin mesh is connected to up to four bones in the bone mesh with weights assigned to the connection between the skin mesh vertex and each bone according to the desired influence of that bone on the skin vertex position [32]. The computer program creates model animation by specifying the positions of the bone mesh relative to a "root" bone. Then, the skin mesh deforms as a function of the bone mesh position and the local skin mesh vertex weighting. Model animation by this method allows for arbitrary model motion according to user input and does not rely on a set of pre-scripted animations. This type of model animation is likely to be the most useful for studying whale entanglement events as it will allow the user to create various motions and test the influence of those motions on entanglement severity and probability. This type of model animation is highly computationally expedient because the model is loaded once onto the video graphics card. Then the model animation calculations take place on the massively parallel graphics card hardware (GPU computing) rather than on the CPU.

Fast and accurate calculation of collision mechanics, particularly the calculation of collisions between a trap rope and a whale fluke or flipper, turned out to be the single most effort-consuming task of this project. When a whale flipper or fluke encountered a model rope, the control spheres on the rope could tunnel through the whale surface, producing inaccurate results. In order to mitigate this tunneling problem, we employed dynamic collision detection in the program.

The static collision detection between two objects, for example, a triangle and a sphere is a relatively straightforward calculation [33]. However, for large collections of objects, the calculation can be computationally expensive. With our high-resolution model of the NARW, we had approximately 14,000 triangles making up its outer mesh. The rope model typically consisted of more than 500 control spheres or cylinders. In order to reduce the calculation effort, we used a number of hierarchical searches so that each rope control sphere would not need to be tested against each surface triangle. The hierarchical search first tested for collision between the rope control spheres and a sphere completely bounding the whale. Only those rope control points found to be within the whale's bounding sphere were then retained for further collision calculations. Next, we tested for collision between the rope control spheres retained from the previous step and a number of local bounding regions containing a subset of the whale's surface triangles. Finally, only the rope control spheres found to be within the local bounding regions were tested for collision using the more computationally expensive test between a sphere and a triangle. Using this hierarchical method significantly reduced the computational effort of collision detection and allowed the simulation to run in real-time.

A collision detection problem can occur when there was rapid relative motion between the whale and rope. In this case, during a single time step, we can have situations in which a rope control sphere moves completely from one side of a whale surface triangle to the other in a single time step. Thus, the collision detection algorithm would not register a collision event between the sphere and triangle. In order to mitigate this problem we use dynamic collision detection techniques [33]. In dynamic collision detection, an object is assumed to propagate along its current trajectory during the current time step. If there is a second object in the path of the first object, and if the two objects will collide at any time during the current time step, then a collision event is registered. This prevents a fast-moving object from moving completely through a second object during a single time step, thus dealing with the tunneling problem. We implemented this dynamic collision detection in the VWES.

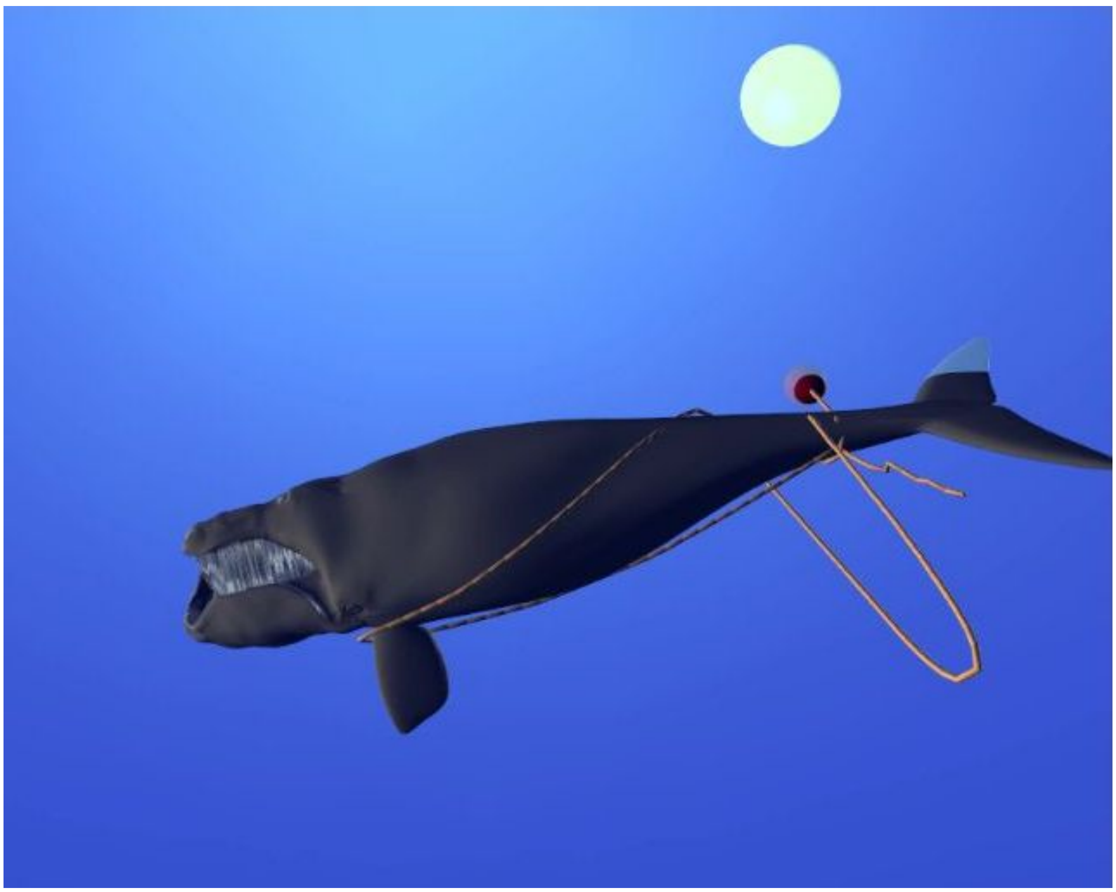


Figure 3-3. Dead, floating NARW showing flipper and peduncle wraps.

As we mentioned in the introduction section of this report, the primary goal of developing our VWES is to give marine mammal scientists a tool that can be used in an attempt to reverse engineer whale entanglement events. In Figure 3-3-3, we show a screen-capture of the VWES graphical display window. This figure shows a NARW with flipper and multiple body wraps. In this particular simulation the rope tension exceeded the breaking strength of the weak link so the trap broke free. These particular entanglements, that is, pectoral flipper wraps, and wraps around the caudal peduncle are entanglement types that are frequently observed with this whale species [2]. This entanglement scenario was generated by the VWES user in an effort to understand what motions the whale must have generated in order to become so entangled. Thus, we feel that our VWES has the potential to become a useful tool for marine mammal scientists studying the problem of whale entanglement.

Whale Articulation

We originally proposed to purchase and use Autodesk's Maya software for generating whale articulation motions. These motions would then be imported into our VWES system. Instead, we found that the Blender open-source software package allowed us to accomplish the same objectives. Therefore, we chose to use Blender rather than Maya. The Blender software system was used to build the articulated whale model and program it with a catalog of known whale motions. In Figure 3-5, we show the bone armature used for our computer animation. Computer animation of the model articulation is accomplished by programming the motion of the bone Armature rather than programming the time-dependent motion of the skin mesh. The animation of the skin mesh is accomplished by suitably weighting the movement of the skin mesh to as many as four bones per skin vertex.

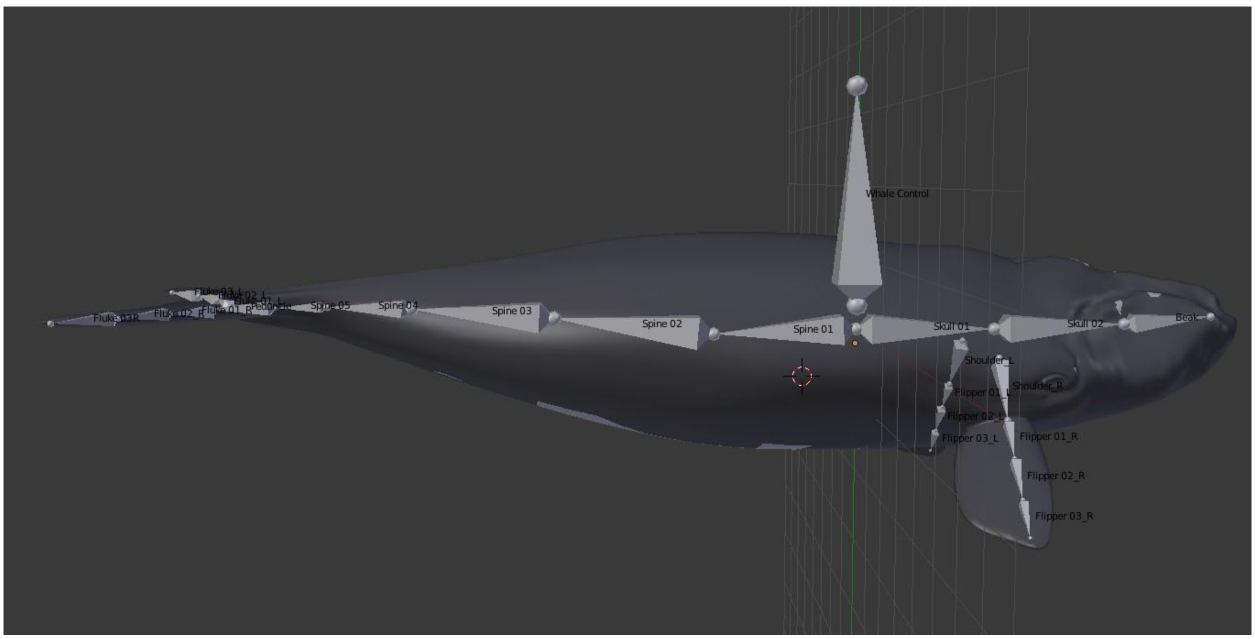


Figure 3-5. Armature (virtual skeleton) used for whale articulation. The armature consists of a single control bone (the vertical dorsal bone) for model placement in 3D space, multiple deform bones (shown) and inverse kinetics bones (not shown). As the deform-bones move, the skin mesh deforms according to mathematical weighting from nearby deform-bones.

In Figure 3-6, we show two still images of the basic swimming motion of a NARW. The left-hand frame, image (a), shows the whale near the top of its upstroke just before beginning the downstroke whereas the right hand frame, image (b), shows the whale at the bottom of its downstroke. A complete swimming cycle is generated by producing a small number of keyframes. Each keyframe contains the desired shape of the whale at that point in the swimming cycle. The computer then generates smooth motion by interpolating between the keyframes.

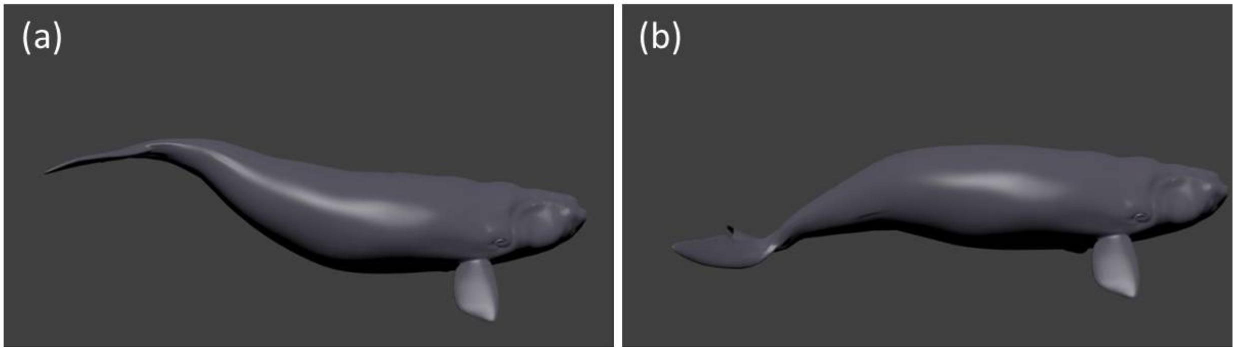


Figure 3-6. Images showing swimming motions (a) near the top of the upstroke before starting the down stroke, (b) at the bottom of the down stroke.

Since the pectoral flipper is one of the critical entanglement locations on the NARW, we also spent a considerable amount of time programming the articulation of the flippers. This flipper articulation is shown in Figure 3-7. The frames in this figure show abduction (a), adduction (b), pronation (c), and supination (d). Programming these flipper motions will allow marine mammal scientists to interrogate whether flipper motions required for maneuvering exacerbate entanglement severity.

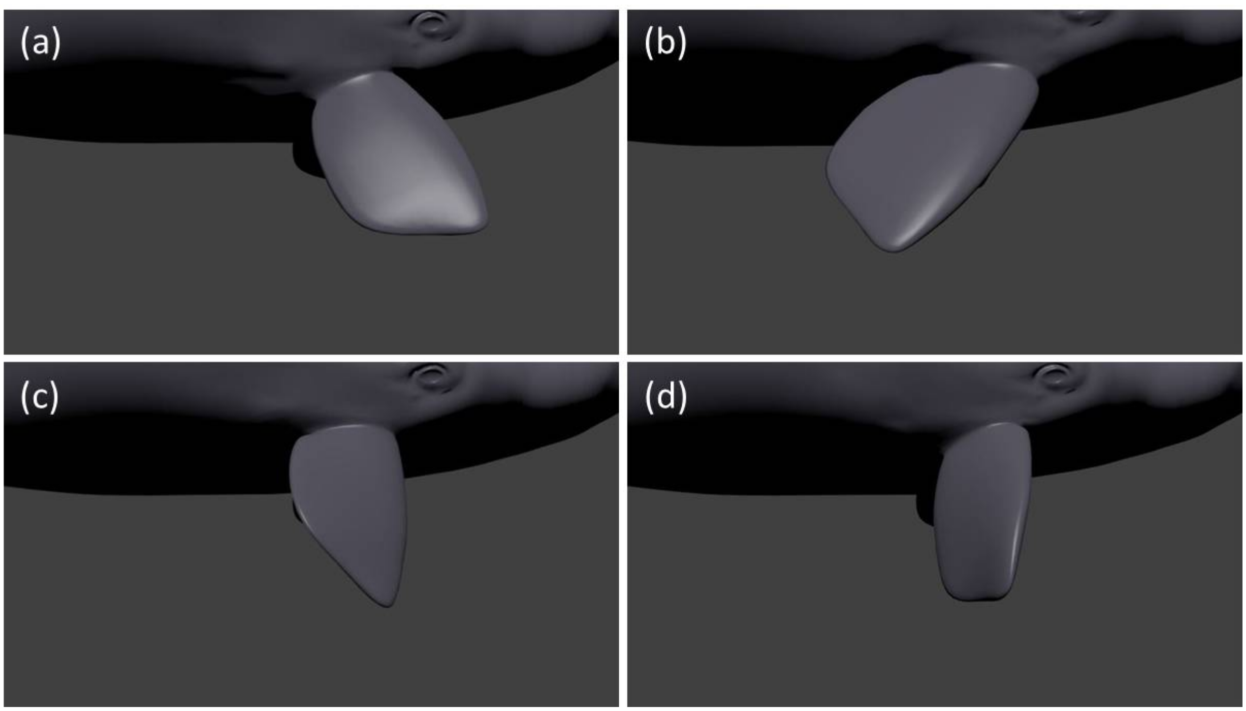
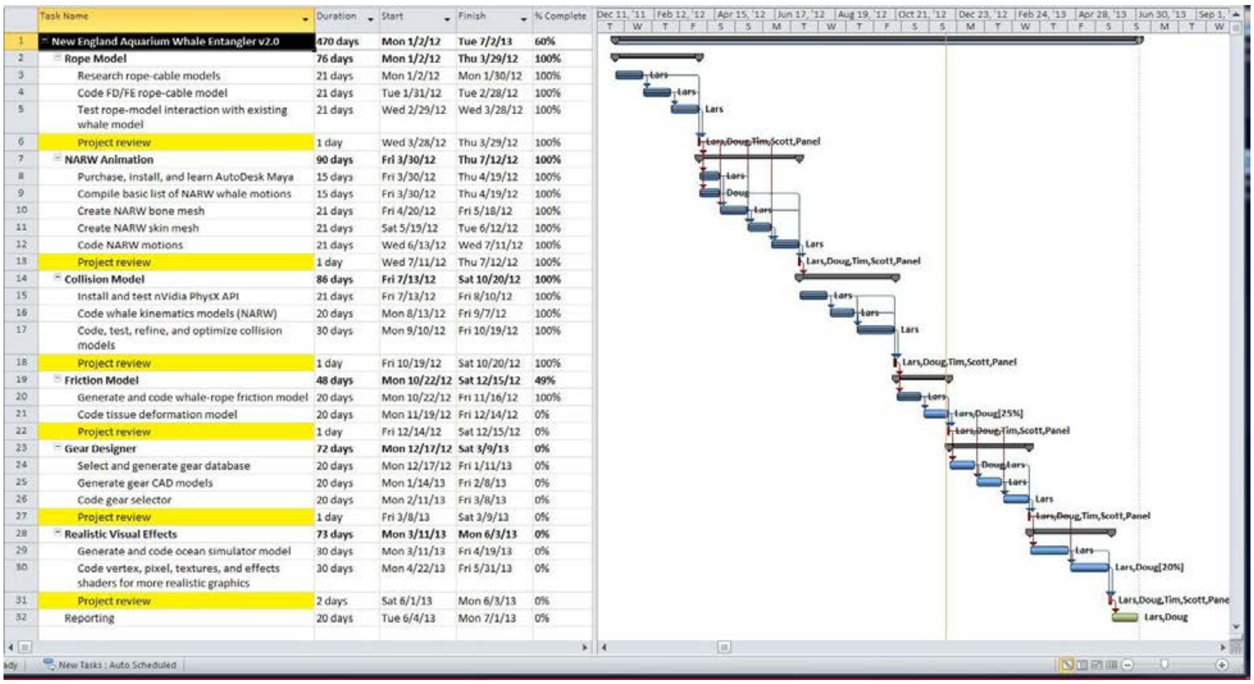


Figure 3-7. Images showing the range of flipper motions, including: (a) abduction, (b) adduction, (c) pronation, (d) supination.

Project Timeline
The original project timeline, updated for the current state of the project, is shown in Figure 3-8. Note that tasks 3, 4, 5, 8, 10, 11, 12, 15, 16, 17, and 20 are 100% complete. Major task groups (2) Rope Model,

(7) NARW Animation, (14) Collision Model, are 100% complete. Major task group (19) Friction Model, is 49% complete. Therefore, the entire project remains on schedule and is 60% complete.

One of the goals of this project is to determine the gear types that pose the greatest risk to NARWs of entanglement. In order to accomplish this task we must first accomplish the major task group (23) Gear Designer, which consists of three subtasks (24) select and generate gear database, (25) generate gear CAD models, and (26) code gear selector. Please note from Figure 3-8 that this major task group is not scheduled to be completed until 11 February, 2013, using separate funding. Therefore, we have not yet completed this importance study of determining which gear types pose the greatest risk of entanglement.



	Task Name	Duration	Start	Finish	% Complete
1	New England Aquarium Whale Entangler v2.0	470 days	Mon 1/2/12	Tue 7/2/13	60%
2	Rope Model	76 days	Mon 1/2/12	Thu 3/29/12	100%
3	Research rope-cable models	21 days	Mon 1/2/12	Mon 1/30/12	100%
4	Code FD/FE rope-cable model	21 days	Tue 1/31/12	Tue 2/28/12	100%
5	Test rope-model interaction with existing whale model	21 days	Wed 2/29/12	Wed 3/28/12	100%
6	Project review	1 day	Wed 3/28/12	Thu 3/29/12	100%
7	NARW Animation	90 days	Fri 3/30/12	Thu 7/12/12	100%
8	Purchase, install, and learn AutoDesk Maya	15 days	Fri 3/30/12	Thu 4/19/12	100%
9	Compile basic list of NARW whale motions	15 days	Fri 3/30/12	Thu 4/19/12	100%
10	Create NARW bone mesh	21 days	Fri 4/20/12	Fri 5/18/12	100%
11	Create NARW skin mesh	21 days	Sat 5/19/12	Tue 6/12/12	100%
12	Code NARW motions	21 days	Wed 6/13/12	Wed 7/11/12	100%
13	Project review	1 day	Wed 7/11/12	Thu 7/12/12	100%
14	Collision Model	86 days	Fri 7/13/12	Sat 10/20/12	100%
15	Install and test nVidia PhysX API	21 days	Fri 7/13/12	Fri 8/10/12	100%
16	Code whale kinematics models (NARW)	20 days	Mon 8/13/12	Fri 9/7/12	100%
17	Code, test, refine, and optimize collision models	30 days	Mon 9/10/12	Fri 10/19/12	100%
18	Project review	1 day	Fri 10/19/12	Sat 10/20/12	100%
19	Friction Model	48 days	Mon 10/22/12	Sat 12/15/12	49%
20	Generate and code whale-rope friction model	20 days	Mon 10/22/12	Fri 11/16/12	100%
21	Code tissue deformation model	20 days	Mon 11/19/12	Fri 12/14/12	0%
22	Project review	1 day	Fri 12/14/12	Sat 12/15/12	0%
23	Gear Designer	72 days	Mon 12/17/12	Sat 3/9/13	0%
24	Select and generate gear database	20 days	Mon 12/17/12	Fri 1/11/13	0%
25	Generate gear CAD models	20 days	Mon 1/14/13	Fri 2/8/13	0%
26	Code gear selector	20 days	Mon 2/11/13	Fri 3/8/13	0%
27	Project review	1 day	Fri 3/8/13	Sat 3/9/13	0%
28	Realistic Visual Effects	73 days	Mon 3/11/13	Mon 6/3/13	0%
29	Generate and code ocean simulator model	30 days	Mon 3/11/13	Fri 4/19/13	0%
30	Code vertex, pixel, textures, and effects shaders for more realistic graphics	30 days	Mon 4/22/13	Fri 5/31/13	0%
31	Project review	2 days	Sat 6/1/13	Mon 6/3/13	0%
32	Reporting	20 days	Tue 6/4/13	Mon 7/1/13	0%

Figure 3-8. Our current progress (as of 12/14/2012) on the WVES project Gantt chart shows us in schedule. Tasks 3, 4, 5, 8, 10, 11, 12, 15, 16, 17, and 20 are 100% complete.

Case Studies

In this section, we investigate three entanglements reported at a recent reverse entanglement workshop held at Woods Hole Oceanographic Institution. The first case study is NMFS E7-99 which is a typical mouth wrap. This whale (Eg 2753) is a female born in 1997, was entangled between 1 and 289 days, was disentangled on 05 June, 1999, and was last sighted in 2009. This whale had two prior entanglement interactions. A drawing of this entanglement is shown in Figure 3-10.

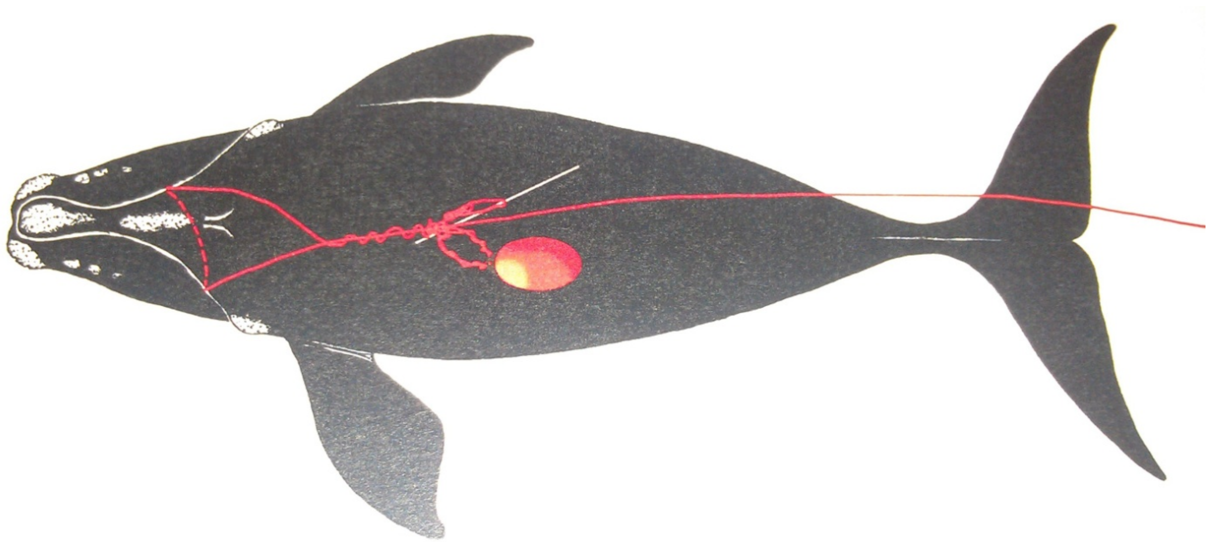


Figure 3-10. NARW entanglement NMFS E7-99. This entanglement is a typical mouth wrap.

In re-creating this entanglement using our VWES, we found that this entanglement type is most easily generated when there is a horizontal line section in the water column. Horizontal line sections can occur at slack tide when a marker line has a sinking line portion attached to the buoy and a floating line portion attached to the trap. On the other hand, when the tide is running, the trap lines tend to be taught and do not have the horizontal portion. In this case, mouth wraps are most easily generated when the whale is foraging in a sideways orientation. We show a re-creation of this entanglement type in Figure 3-12. In this re-creation, the rope becomes entangled in the baleen at first encounter. Subsequent whale motions after first encounter cause the rope to become tangled.

Although our current whale models only include open mouth and closed mouth configurations, we would like to create an additional whale model that allows the whale to open and close its mouth. Our hypothesis is that when a whale first encounters a rope while foraging, it closes its mouth, which then drives the rope up into the baleen plates were the rope becomes firmly wedged. Thus, adding mouth articulation will be an important feature to add to our VWES.

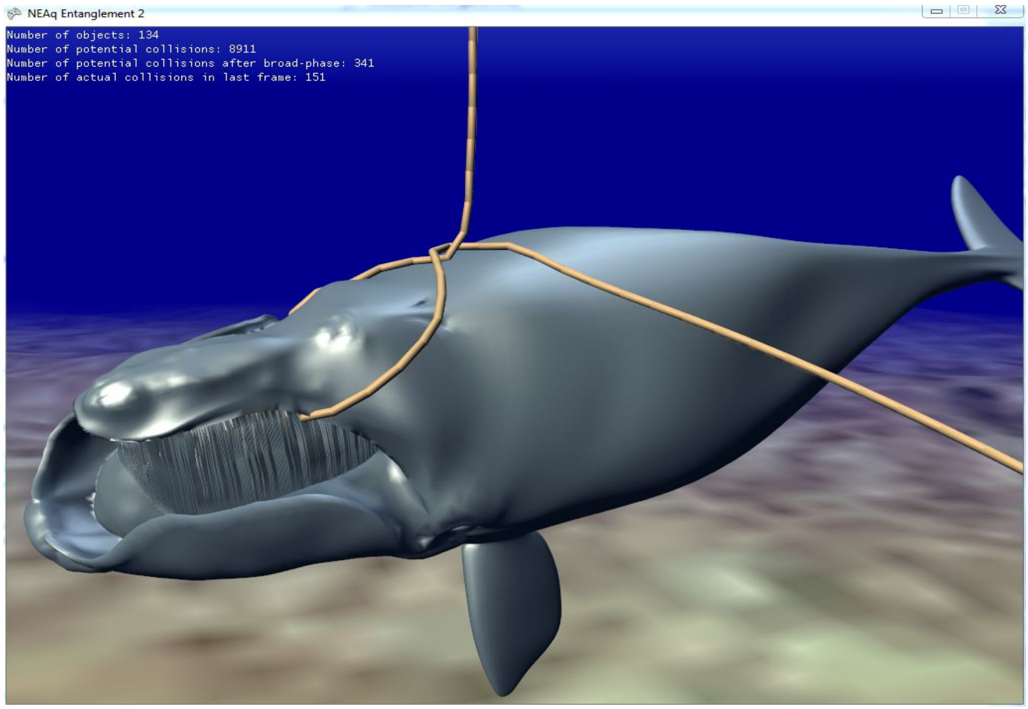


Figure 3-12. Mouth wrap re-created with the VWES. The entanglement of the rope in the baleen occurs on first encounter. The subsequent rope twisting results from the whale's movements after the first encounter.

The next case study we consider is a typical flipper wrap. This entanglement (NMFS E25-05) involved a female NARW (Eg 3445) born in 2004. The whale was entangled between 9 and 296 days. The line wrapped the body near the area of the flippers and was twisted under the whale's ventral side and trailed 400ft aft. The gear included 3/8 polypropylene vertical line, 5/17 and 7/16 polysteel vertical lines and included three hard buoys. This whale was partially disentangled on 13 December, 2005 and was last sighted in 2006. An image of the entanglement is shown in Figure 3-14.

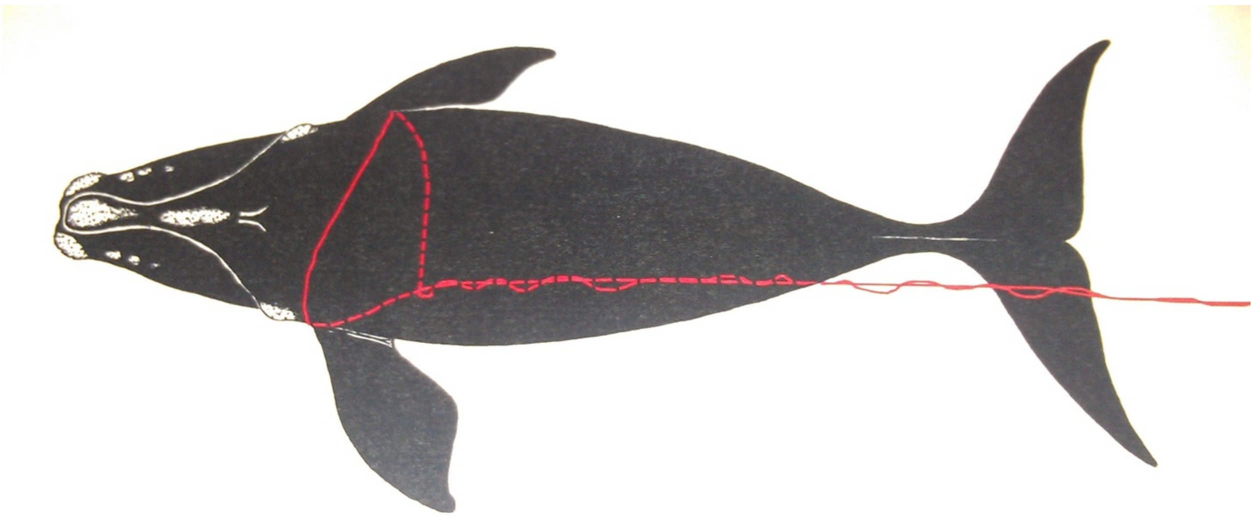


Figure 3-14. NARW entanglement E25-05. This image shows a wrap involving a flipper, one of the common locations for entanglement initiation.

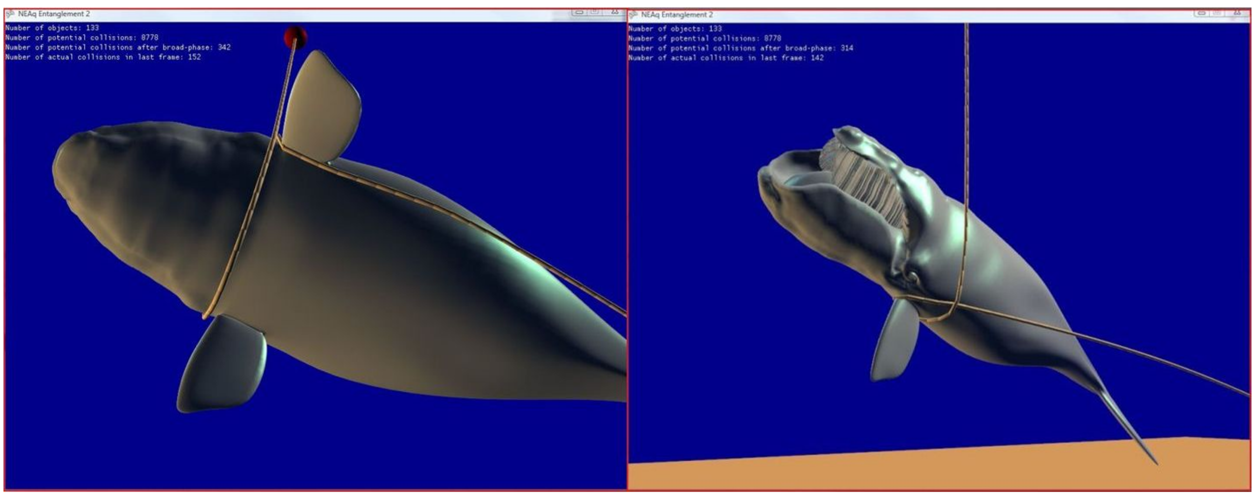


Figure 3-15. Flipper-initiated entanglements generated with the VWES. The left image shows the results of an initial encounter with the left flipper followed by a roll. This results in a flipper and body wrap. The right image shows the result of an initial flipper encounter followed by flipper “thrashing”.

Figure 3-15 shows two different re-created flipper wraps. The left image shows the result of a first encounter at the leading edge of the left flipper followed by a roll. The role created the body wrap after first encounter. The right image shows how trap line can become circumferentially wrapped around the flipper. We generated this entanglement by a first encounter at the leading edge of the flipper followed by flipper thrashing motions.

In re-creating various flipper wraps several observations can be reported. First, the roll direction matters after first encounter. For example, if the whale strikes a trap line with the flipper and rolls toward the line, we found it easier to create a body wrap. Additionally, swimming up or down current was also important. For the whale swimming down current the line remains in tension after the first encounter. On the other hand, for the whale swimming up current, the line can become slack as the whale drags the line against the current. In this case, the slack line has a greater probability of wrapping the whale. An additional observation is that flipper motion at first encounter is likely very important in the entanglement. For example, if the whale is swimming with the flippers swept aft, as would be common in cruising, and then it encounters a line, it will sweep its flippers forward in order to use these control surfaces to turn away from the line. With the flippers swept forward it was easier for us to generate entanglements since the rope was not shed from the flipper is easily.

The final entanglement case study that we report here involves another common entanglement type; the wrap at the caudal peduncle. In Figure 3-16, we show a typical peduncle wrap. This entanglement (NMFS E15-02) involved a female NARW born in 2001 (Eg 3107) that had been entangled between 57 and 226 days. This whale was disentangled on 01 September, 2002 and was dead on 13 October 2002. This whale had one prior entanglement interaction.

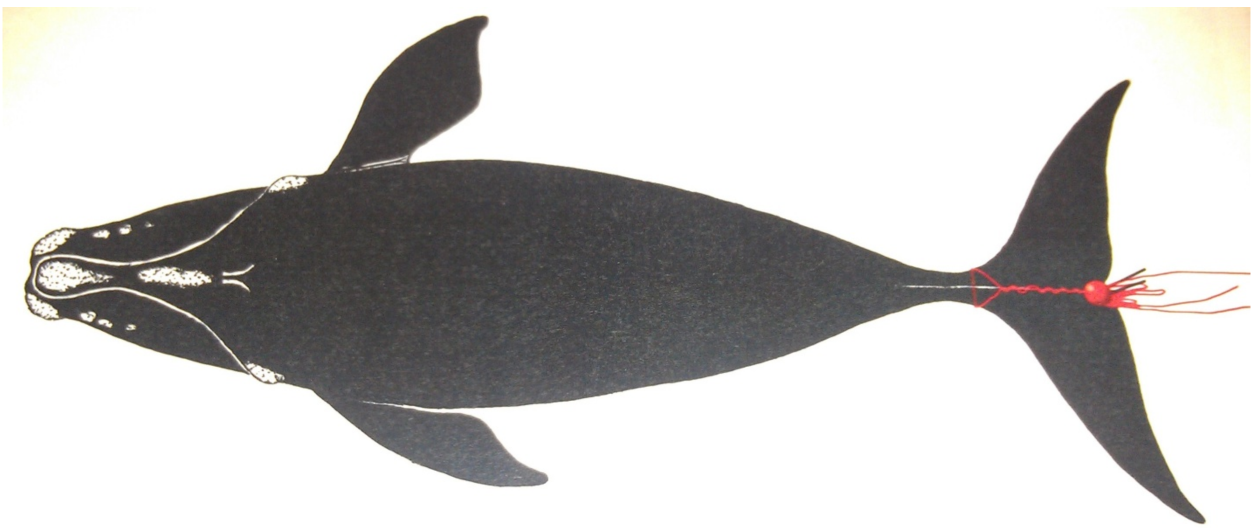


Figure 3-16. NARW entanglement E15-02. This case study shows a typical caudal peduncle wrap.

A re-creation of this entanglement type is shown in Figure 3-17. We found that we could re-create this entanglement type most reliably with a vertical trap line. That is, with a line under tension as it would be when the tide is running. To generate this entanglement type, we swam the whale toward the rope. Then, just before striking the line, we turned the whale using a roll maneuver to avoid the rope. After the roll maneuver, the trailing edge of the tail is nearly vertical. Following this, as the whale swims past the rope, it strikes the line near the peduncle region. If there is sufficient amplitude left in the tail stroke, then the line can strike the peduncle and move to the opposite side of the flukes on either side of the peduncle. As the whale continues to swim, the line becomes tightly wrapped around the peduncle. The twist in the line shown in the re-creation was created by having the whale execute a barrel roll maneuver after wrapping the peduncle.

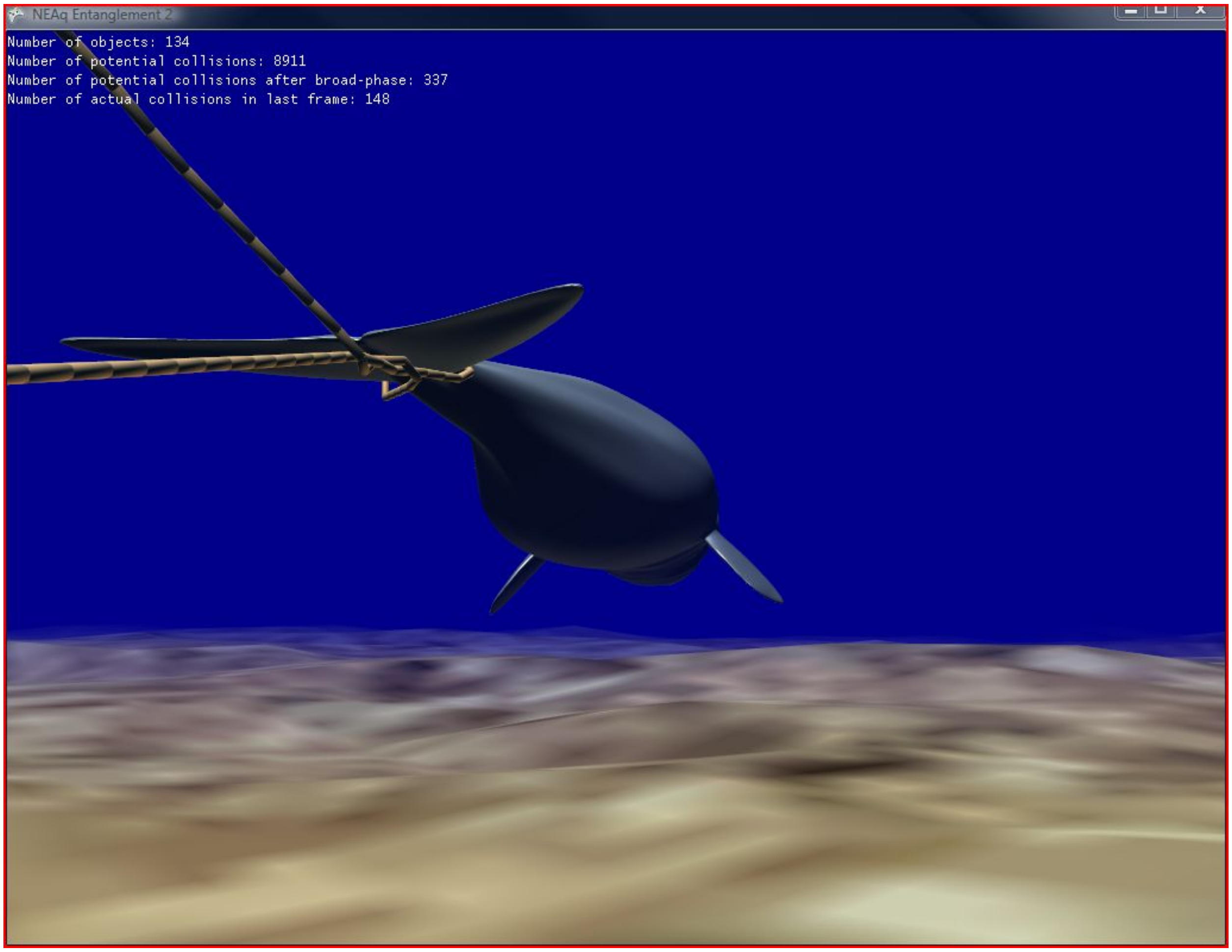


Figure 3-17. Peduncle wrap re-created with the VEWS.

Conclusion

In developing our VWES, one area of the project that consumed a large amount of effort was dynamic collision detection between the whale and the trap line. Collision between a segment of the trap line and a thin whale feature, such as the pectoral flipper leading/trailing edge or tail fluke leading/trailing edge, was the most problematic collision detection problem. Additionally, accurate simulation of rope dynamics under varying loading including tension from the buoy and trap, friction with the animal, drag, and buoyancy were also areas where we had to devote substantial efforts.

Although still under development, the virtual whale entanglement simulator developed under this project will assist marine mammal scientists, fisheries experts, fishing gear designers, and bycatch reduction scientists in understanding what gear types and what whale behaviors lead to entanglements. Additionally, through the virtual testing of different - perhaps new or untested - gear types, this VWES will help to identify promising new gear techniques to avoid baleen whale entanglements.

Acknowledgments

We would like to thank Dr. Anna E. Nousek McGregor for providing the whale model and models of some of the fishing gear used in this study. This investigation is supported by the Consortium for Bycatch Reduction, by the U.S. DOC-NOAA Grant# NA09NMF4520413 and by the New England Aquarium.

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<u>Project 4 – Marine Mammal Color Vision and Fishing Tackle Avoidance</u> (Kean University)

Project Goal and Objectives

The goals of this project are threefold:

1. Sequence the rod and cone visual pigment coding regions using genomic DNA from the most susceptible and threatened species, identify the spectral tuning amino acid substitutions, incorporate these substitutions into the visual pigment model, express the visual pigment and examine the resulting absorption spectra.
2. Obtain fresh tissue yielding quality mRNA from the most susceptible and threatened species (or closely related species) to develop a second visual pigment model.
3. Identify the wavelength(s) of light that will give each particular species the highest level of contrast to their visual perception.

Project 4 Final Report (J. Fasick)

Abstract

Fishing equipment, including lines and nets, have been involved with relatively high numbers of incidental captures and deaths of cetaceans. This suggests that these marine mammals may be unable to visually detect the presence of these underwater obstacles. This research focuses on marine mammal vision, specifically, determining the wavelengths of light (color) to which the eye is most sensitive. Once these wavelengths are determined, it would allow fishing tackle to be constructed or appended with a color that a particular species would be able to detect visually and possibly avoid. To approach this problem, genomic DNA from high incidental capture species will be used to identify the amino acids at key positions in the rod and cone opsin protein components of the visual pigments. These residues will then be incorporated into a spectral tuning model to determine the absorbance maximum of the resulting visual pigment. Alternatively, if fresh eyes are available, total RNA will be used as a template to express the visual pigments and identify the absorbance maxima. This research may be of particular value in easing the incidental captures and deaths of *Eubalana glacialis* (North Atlantic right whale) by fishing tackle used in the Western North Atlantic lobster fisheries.

Goals

The goals of this project were 3-fold:

1) Sequence the rod and cone visual pigment coding regions using genomic DNA from the most susceptible and threatened species, identify the spectral tuning amino acid substitutions, incorporate these substitutions into the visual pigment model, express the visual pigment and examine the resulting absorption spectra.
2) Obtain fresh tissue yielding quality mRNA from the most susceptible and threatened species (or closely related species) to develop a new visual pigment model specific for the mysticete whales.
3) Identify the wavelength(s) of light that will give each particular species the highest level of contrast to their visual perception.

Collaborations/Tissue & DNA Sources

To accomplish these goals, genomic DNA samples from 11 species of mysticete whales were acquired from NOAA NMFS, SWFSC. These samples are listed in Table 1 with the NMFS numbers listed.

We received an eye (NARW *E. glacialis* calf # CALO 0901) from William McLellan, University of North Carolina-Wilmington which has allowed us to directly clone and sequence the rod opsin coding region. We received a second eye from McClellan (NARW *E. glacialis* adult #EgNEFL1103) which was code 3 and may be used at a future date for anatomical analysis with Michael Moore at WHOI.

Dr. Thomas Cronin (Department of Biological Sciences, University of Maryland Baltimore County) and Dr. Mark Baumgartner (Biology Department, Woods Hole Oceanographic Institute) have assisted us in a project involving examining predator/prey relationships associated with vision with the right whale and its primary prey species, the calanoid copepod *Calanus finmarchicus*.

Dr. Benjamin Nickel (Department of Biochemistry, Brandeis University) is our most recent collaborator and has had great success in the expression and biochemical analysis of the right whale rod visual pigment.

Detailed Summary of Completed Work:

1) Estimated Absorbance Maxima of E. glacialis Rod and MWS Cone Visual Pigments

From DNA sequence alignments, we designed a set of degenerate and non-degenerate oligonucleotide primers for amplifying specific regions of the cetacean rod and long-wavelength sensitive (LWS) cone opsins. PCR reactions were first done on bottlenose dolphin genomic DNA to determine correct size and quality of the products. Subsequent PCR products from right whale gDNA (NOAA lab ID numbers 15112, 28311 and 13086) were cloned by ligation into a cloning vector and transformation into bacteria. Colonies containing inserts were picked, cultures grown overnight and PCR amplified again to confirm the presence of inserts. Clones positive for inserts were sequenced. The results from this work were successful with the sequencing of all three amino acid positions in the rod opsin (83, 292 and 299) and a single amino acid position in the LWS cone opsin (292). During this process we identified NOAA sample 15112 as being Tursiops in its origin with mislabeling of this sample most likely occurring at the NOAA labs. Regardless, results from the animal samples 28311 and 13086 provided us with amino acid identity at the important spectral tuning positions mentioned above. We have identified the following amino acid substitutions in the right whale rod visual pigment gene: N83, A292 and S299 with an estimated absorbance maximum of 499 nm. The right whale LWS cone visual pigment possesses the amino acid substitution S292 with a predicted absorption maximum of 524 nm. This work was recently published in the peer-reviewed journal *Marine Mammal Science* [MARINE MAMMAL SCIENCE, 27(4): E321–E331 (October 2011); see Appendix 5].

We had the good luck of receiving a fresh right whale eye (NARW *E. glacialis* calf # CALO 0901) from which we were successful in extracting quality total RNA. We have been able to clone the full length rod opsin, confirm its sequence against genomic DNA, and have successfully expressed this pigment in tissue culture. We have determined that the right whale rod visual pigment has a dark adapted absorbance maximum of 493 nm when compared to that from bovine (496 nm). When the difference spectra absorbance maxima are normalized to bovine rhodopsin reported absorbance maxima of 500 nm we see that the expressed right whale rod visual pigment has an absorbance maxima of 498 nm, nearly identical to the value predicted in our manuscript of 499 nm described above.

We have had limited success in PCR amplifying the middle-wavelength sensitive (green) cone opsin sequence from CALO 0901. To date we have sequenced the regions spanning exons 2-5 from a gene that consists of 6 exons. Our analyses of three different PCR products show inversions, deletions and duplication events in exon 4 of the mRNA. These are very unusual mutations resulting from improper splicing events and would not allow for a functional pigment to be expressed. Without the expression of a functional MWS cone pigment, the photoreceptor cells atrophy and are lost. If this is the case, the animal would be a rod monochromate and possess little or no photopic (day-time) vision. Presently, we are not prepared to state that this species, nor this individual, is lacking a functional MWS cone class. Rather, we have not been able to identify a wildtype like MWS cone opsin sequence from this individual. We are currently examining the genomic DNA from this individual to compare it to other genomic samples that we have acquired through NMFS SWFSC. However, the quickest and most efficient way of answering this question would be to repeat our analysis of the retinal mRNA with another individual, preferably an adult.

2) Spectral Placement of the North Atlantic Right Whale (Eubalaena glacialis) Visual Pigments and Their Potential Role in Detecting Concentrations of the Calanoid Copepod Calanus finmarchicus.

To assess the role that vision may play in the ability of the right whale to detect its primary prey species, the calanoid copepod *Calanus finmarchicus*, we have directly determined the absorbance spectrum of the *E. glacialis* rod visual pigment as well as the transmission spectra of the *C. finmarchicus* carotenoid pigments. We determined that the *E. glacialis* rod visual pigment absorbs light maximally at 493 nm while a previous study positions the absorbance maximum of the *E. glacialis* cone visual pigment at 524 nm. Microspectrophotometric measurements of the *C. finmarchicus* carotenoid pigments result in transmission spectra with minima that match very well with the *E. glacialis* rod and cone visual pigment absorbance maxima, suggesting that these carotenoids would effectively block visible sidewelling or downwelling light. We conclude that the *E. glacialis* visual pigments are ideal for detecting concentrations of copepods in silhouette against natural lighting.

After opsin expression, reconstitution with 11-*cis* retinal and purification, the right whale rod visual pigment, rhodopsin, was shown to have a λ_{max} = 493 nm (Figure 1). In side-by-side purification experiments, the spectrum of right whale rhodopsin was shown to be slightly blue-shifted (3 nm) from that of the more commonly studied bovine rhodopsin (λ_{max} = 496 nm, see Figure 3) and confirmed the previous λ_{max} estimate of right whale rhodopsin. Full length right whale MWS cone opsin cDNA was not successfully PCR amplified from first strand cDNA samples. However, the right whale MWS visual pigment has previously been estimated to have a λ_{max} value of 524 nm and is plotted in Figure 1.

Microspectrophotometric scans of freshly mounted individuals of *C. finmarchicus* (Fig. 2) produced peak optical densities that commonly exceeded 2.0, even though regions selected for scanning were relatively clear compared to unscanned regions. All scans showed strongest absorbance in the wavelength region from 450 to 500 nm. When plotted as transmission spectra, as shown in Figure 1, transmission is greatest at wavelengths longer than 600 nm with transmission minima occurring between approximately 450 and 550 nm. The decreases in the transmission minima shown in Figure 1 are associated with increases in carotenoid pigment density, as the densest pigments produce the lowest transmission spectra (e.g., the maximum OD is 1.98 @ ~497 nm in the bottom curve; 1.56 @ ~ 478 nm in the middle curve; and 1.06 @ ~467 nm in the upper curve).

Our results show that the right whale rod and cone visual pigments are tuned to a region of the spectrum to detect underwater background light but would not be sensitive to wavelengths greater than 650 nm, the very region of the spectrum where the transmission maxima for the *C. finmarchicus* carotenoid pigments are positioned. In this situation, *C. finmarchicus* would produce a perfect high-contrast dark silhouette against the bright background space-light in either the horizontal or upward visual axes. Previous investigations of the feeding behaviors of the right whale suggest that they are capable of detecting variations in prey density in both the horizontal and vertical directions, adjusting their foraging behavior to remain in areas of maximum copepod density. We can speculate that the spectral placement of the right whale visual pigments allow the whale to visually perceive prey concentrations with high spatial and temporal resolution, allowing for the effective adjustment of foraging behavior.

3) Expression and Direct Determination of E. glacialis Rod Visual Pigment Absorbance Spectrum

To better understand the spectral tuning properties of the cetacean rhodopsins, we analyzed expressed rhodopsins from the right whale, bottlenose dolphin, Sowerby's beaked whale and the domestic cow. Here we cloned, expressed, reconstituted expressed opsins with the chromophore 11-*cis* retinal, and purified the resulting visual pigments for analysis by spectrophotometry. The absorbance spectra of these visual pigments are seen in Figure 3 which clearly shows two groupings of pigments based on absorbance maxima. Both the cow and right whale rhodopsin spectra are grouped near each other with absorbance maximum (λ_{max}) values of 496 and 493 nm, respectively. Likewise, both the bottlenose dolphin and beaked whale rhodopsins are grouped near each other with λ_{max} values of 484 and 479 nm, respectively. The placement of these four spectra clearly demonstrates the differences between the right whale from the odontocetes in terms of the spectral sensitivity of the rod visual pigment, with the placement of the right whale rhodospin λ_{max} nearer to that of a terrestrial mammal than to that of the odontocetes. This is most likely due to adaptations resulting in the amino acid substitutions N83, A292, and S299 in the right whale rhodopsin that benefit foraging in a relatively shallow foraging photic environment. Thus, the right whale rhodopsin can be defined as being intermediate in its spectral sensitivity to the terrestrial and deep-sea rhodopsins.

4) Estimated Absorbance Maxima for Eleven Mysticete Whale Rhodopsins

As shown in Table 1 and Figure 4, we have identified the amino acid substitutions occurring in the rod opsin gene at amino acid positions 83, 292 and 299 for 11 extant baleen whales as well as those found in the sperm whale (*Physter macrocephalus*) used for comparison. Based on these amino acid substitutions, we were able to reconstruct the evolution of these substitutions (Figure 5) and estimate the absorbance maximum for each pigment as shown in Table 1. Estimating the absorbance maxima for these visual pigments was accomplished by sequence analysis of exons 1 and 4 of the rod opsin genes from 22 individuals representing 11 species from each of the four mysticete families (Fig. 4). DNA samples used for this analysis were supplied by NMFS SWFSC. Amino acid substitution, estimated absorbance maxima as well as the evolution of the opsin genes is described below. Interestingly, all but one of the mysticete rod visual pigment λ_{max} values described below can be described by the amino acid substitutions and resulting spectra shown in Figure 3.

4) Evolution of the Mysticete Whale Rhodopsins

As seen in Figure 5, the ancient cetacean rhodopsin included the amino acid substitutions N, S, A at positions 83, 292 and 299, respectively and had an absorbance maximum (λ_{max}) of 479 nm. All cetacean studied to date retain the amino acid substitution N83, except for the humpback whale which possesses D83. As the mysticete whales emerged, the Balaenidae acquired two amino acid substitutions (A292 and S299) resulting in a rhodopsin with λ_{max}=493 nm, a red-shifted value when compared to the odontocetes and most likely associated with foraging in relatively shallow waters. Interestingly, the pygmy right whale (*C. marginata*) retains the ancient amino acid substitutions found in odontocetes (λ_{max}=479 nm) associated with deep-sea foraging. Little is known of the foraging patterns of the pygmy right whale, but it is not currently believed to be a deep-diving forager. As the Balaenopteridae and Eschrichtiidae emerged, the majority of the clades acquired the two amino acid substitutions S292 and S299 with λ_{max}=484 nm, a significantly blue-shifted rhodopsin when compared to Balaenidae, first identified and associated with delphinidae. Two exceptions are found with the gray whale (*E. robustus*) which incorporates the amino acid substitutions NAS (λ_{max}=493 nm) like the Balaenidae, and the humpback whale (*M. novaeangliae*) which incorporates the novel amino acid substitutions DSS (λ_{max}=492 nm). We found it very interesting that the Balaenopteridae and Eschrichtiidae rhodopsins were significantly blue-shifted. λ_{max} values of 484 nm have previously only been identified in the delphinidae, animals that dive routinely to several hundred meters to forage. It is not clear why these baleen whales would retain such a blue-shifted visual pigment other than the fact that the placement of the pigment serves well in the photic environment where they forage. The gray whale is a coastal species and the red-shift associated with its rhodopsin, when compared to the Balaenopteridae, makes sense considering the relatively shallow, coastal photic environment in which they forage. Likewise with the humpback whale foraging in relatively shallow photic environments when compared to the delphinidae.

5) Identification of wavelength(s) of light that will provide the right whale with the highest level of contrast in their visual perception.

All cetaceans lack a functional short-wavelength sensitive cone photoreceptor class relying solely on a single MWS cone photoreceptor for day-time photopic vision. Utilizing only a single cone photoreceptor class leaves these animals color blind in bright light conditions. Likewise, the single rod photoreceptor class does not provide color information under dim-light scotopic conditions. Generally speaking, the underwater photic environment to a cetacean does not appear blue, green or red as it may to the human eye. Rather, the cetaceans have adapted to this underwater photic environment with associated blue-shifts in the spectral sensitivities of both their rod and cone visual pigments. Depending on the depth at which individual species forage, the rod visual pigments may be only slightly blue-shifted in its spectral sensitivity as seen in the right, gray and humpback whales (λ_{max} values ≈495 nm) or extremely blue-shifted in their sensitivity as seen in the Balaenopteridae, Eschrichtiidae and Delphinidae (λ_{max} values ≈484 nm) and the Neobaelinidae, sperm and beaked whales (λ_{max} values ≈479 nm).

What does this blue-shift in spectral sensitivity mean in terms of vision and foraging? As the wavelength of maximum sensitivity decreases in cetacean rhodopsins, there is a strong correlation with an increase in depth of foraging. In essence, the deeper an individual species dives to forage, the more blue-shifted the rod visual pigment spectral sensitivity has become. This adaptation has been influenced by the filtering properties of oceanic waters with the removal of long-wavelength light with increasing depth. At several hundred meters depth, the available solar light is very narrow in terms of the visible spectrum and can be place around 480 nm, very near to the spectral sensitivities of the pelagic rods of the odontocetes as well as some mysticetes. At these depths the water color and all objects in the water column that reflect and transmit solar light appear blue to the human eye due to our ability to discriminate spectral hues utilizing our trichromatic cone sensitivities. To the cetacean eye, this same photic environment would appear bright due to the absorbance of the background light by the rods, but would be lacking in what we would describe as color. To the cetacean, objects within this photic environment that reflect/transmit the narrow blue wavelength band at depth would essentially be indiscernible from the background light. However, objects that absorb this blue background light would appear to the cetacean eye as a dark object against a bright background.

With this in mind objects that absorb light in the blue and green region of the spectrum and reflect or transmit light in the yellow, orange or red regions of the spectrum would provide the cetacean eye with the greatest amount of contrast to the background light. This is quite evident with the data that we provide in this report on the prey species *C. finmarchicus* and its red carotenoid pigments. If one were forced to pick a single spectral hue that would provide cetaceans with the greatest contrast underwater that color would be "red" (λ_{max}>700 nm). But essentially any wavelength longer than the wavelengths associated with each animals rod and cone spectra would offer good contrast depending on light conditions (photopic vs. scotopic). These values would be wavelengths longer than 625 nm under scotopic conditions and wavelengths longer than 650 nm under photopic conditions for most cetaceans. The human eye would describe wavelengths of 625 nm as "orange" and 650 nm as "orange" or "red", with λ_{max}>700 nm being described as "red".

Work has been initiated by the New England Aquarium to test these colors in the ocean to determine if right whales are able to detect and/or avoid them (see Scott Kraus, Project 5). Interestingly, when colored objects were videotaped at a depth of several meters, the object painted “red” provided the greatest contrast at distance more so than objects of different colors including white and black.

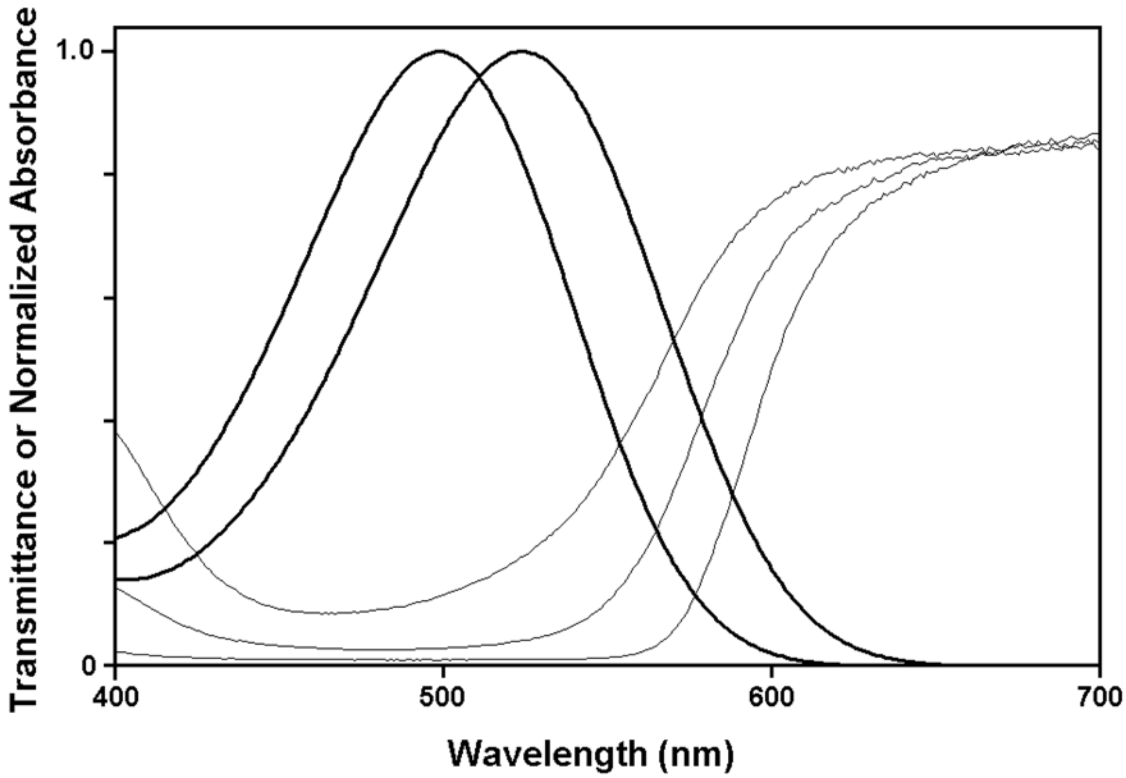

Figure 4-1. Normalized absorbance spectra of the rod and middle-wavelength sensitive (MWS) cone visual pigments of *Eubalaena glacialis* and transmission spectra of carotenoid pigments from *Calanus finmarchicus*. The absorbance spectra for the rod (λ_{max}=493 nm) and MWS cone (λ_{max}=524 nm) visual pigments are shown as dark traces. Normalized transmission spectra of typical carotenoid pigments from *C. finmarchicus* are shown as light traces.

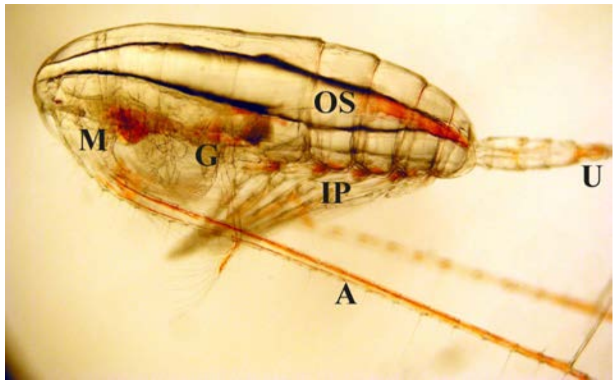

Figure 4-2. Calanoid copepod *Calanus finmarchicus*. Carotenoid pigments are associated with the posterior tip of the oil sac (OS), antennae (A), urosome (U), mouth (M), gut (G) and insertion points of the legs (IP).

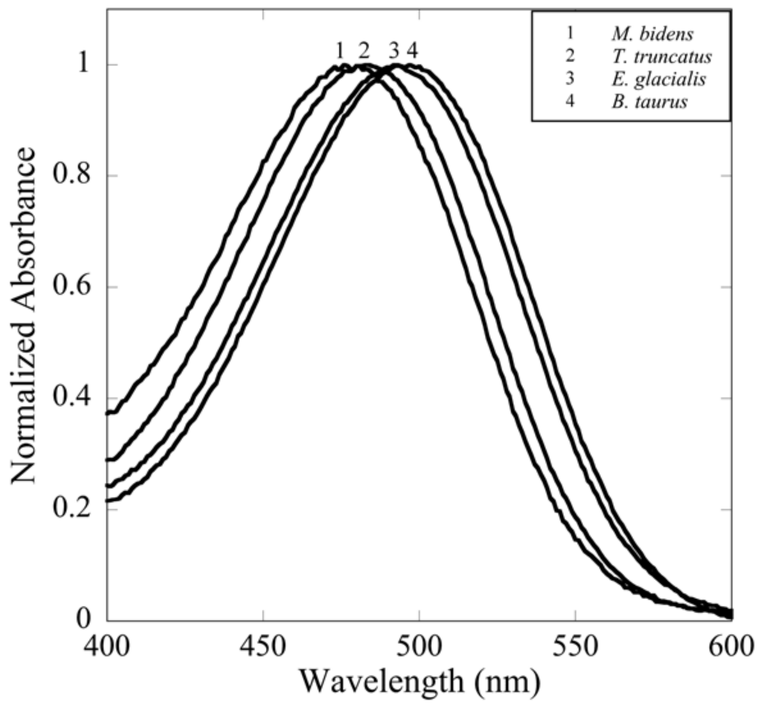

Figure 4-3. Absorbance spectra of dark adapted cetacean rhodopsins. Absorbance maxima are as follows: 1, *Mesoplodon bidens* 479 nm; 2, *Tursiops truncatus* 484 nm, 3, *Eubalaena glacialis* 493 nm; 4, *Bos taurus* 496 nm.

Table 4-1. Estimated Mysticete Rhodopsin Absorbance Maxima and Associated Amino Acid Substitutions.

Mysticete Rho Positions					
Animal	**Number**	**lmax**	**83**	**292**	**299**
Balaenidae					
B. mysticetus	44685	493	N (asparagine)	A (alanine)	S (serine)
B. mysticetus	50787	493	N (asparagine)	A (alanine)	S (serine)
E. australis	18928	493	N (asparagine)	A (alanine)	S (serine)
E. glacialis	CALO 0901	493	N (asparagine)	A (alanine)	S (serine)
Neobalaenidae					
C. marginata	5988	479	N (asparagine)	S (serine)	A (alanine)
C. marginata	5989	479	N (asparagine)	S (serine)	A (alanine)
Balaenopteridae					
B. musculus	43575	493	N (asparagine)	S (serine)	S (serine)
B. musculus	43758	484	N (asparagine)	S (serine)	S (serine)
B. physalus	43617	484	N (asparagine)	S (serine)	S (serine)
B. physalus	43963	484	N (asparagine)	S (serine)	S (serine)
B. borealis	30493	484	N (asparagine)	S (serine)	S (serine)
B. borealis	25386	484	N (asparagine)	S (serine)	S (serine)
B. edeni	30430	484	N (asparagine)	S (serine)	S (serine)
B. edeni	15911	484	N (asparagine)	S (serine)	S (serine)
B. edeni	30451	484	N (asparagine)	S (serine)	S (serine)
B. acutorostrata	23182	484	N (asparagine)	S (serine)	S (serine)
B. acutorostrata	5318	484	N (asparagine)	S (serine)	S (serine)
M. novaeangliae	11201	492	D (aspartic acid)	S (serine)	S (serine)
Eschritidae					
E. robustus	52434	493	N (asparagine)	A (alanine)	S (serine)
E. robustus	52435	493	N (asparagine)	A (alanine)	S (serine)
Delphinidae					
P. electra	cDNA	484	N (asparagine)	S (serine)	S (serine)
Physeteridae					
P. macrocephalus	cDNA	479	N (asparagine)	S (serine)	A (alanine)

Exon 1

	83
Eubalaena glacialis	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA
Tursiops truncatus	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA
Mesoplodon bidens	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVLGGFTTTLYTSMHA
Bos taurus	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**D**LFMVFGGFTTTLYTSLHG
Physeter macrocephalus	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA
Balaenoptera borealis	SFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA
Balaena mysticetus	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA
Balaenoptera physalus	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVLGGFTTTLYTSLHA
Eschrichtius robustus	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA
Balaenoptera edeni	SFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA
Caperea marginata	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA
Megaptera novaeangliae	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**D**LFMVFGGFTTTLYTSLHA
Balaenoptera acutorostrata	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA
Eubalaena australis	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA
Balaenoptera musculus	GFPINFLTLYVTVQHKKLRTPLNYILLNLAVA**N**LFMVFGGFTTTLYTSLHA

Exon 4

	292 299
Eubalaena glacialis	VTRMVIIMVVAFLICWLPYASVAFYIFIHQGSDFGPIFMTIP**A**FFAKSS**S**I
Tursiops truncatus	VTRMVIIMVVAFLICWVPYASVAFYIFTHQGSDFGPIFMTIP**S**FFAKSS**S**I
Mesoplodon bidens	VTRMVVIMVVAFLICWVPYASVAFYIFTHQGSNFGPIFMTIP**S**FFAKSS**A**I
Bos taurus	VTRMVIIMVIAFLICWLPYAGVAFYIFTHQGSDFGPIFMTIP**A**FFAKTS**A**V

Physeter macrocephalus
VTRMVIIMVVAFLICWVPYASVAFYIFTHQGSNFGPIFMTVP**S**FFAKSS**A**I

Balaenoptera borealis	VTRMVIIMVVAFLICWVPYASMAFYIFTHQGSNFGPIFMTIP**S**XFAKSS**S**I
Balaena mysticetus	VTRMVVIMVVAFLICWLPYASVAFYIFIHQGSDFGPIFMTIP**A**FFAKSS**S**I
Balaenoptera physalus	VTRMVIIMVVAFLICWVPYASVAFYIFTHQGSNFGPIFMTIP**S**FFAKSS**S**I
Eschrichtius robustus	VTRMVIIMVVAFLICWVPYASVAFYIFTHQGSNFGPIFMTIP**A**FFAKSS**S**I
Balaenoptera edeni	VTRMVIIMVVAFLICWVPYASMAFYIFTHQGSNFGPIFMTIP**S**FFAKSS**S**I
Caperea marginata	VTRMVIIMVVAFLICWVPYASVAFYIFTHQGSNFGPIFMTIP**S**FFAKSS**A**I
Megaptera novaeangliae	VTRMVIIMVVAFLICWVPYASVAFYIFTHQGSNFGPIFMTIP**S**FFAKSS**S**I
Balaenoptera acutorostrata	VTRMVIIMVVAFLICWVPYASVAFYIFTHQGSNFGPIFMTIP**S**XFAKSS**S**I
Eubalaena australis	VTRMVIIMVVAFLICWLPYASVAFYIFIHQGSDFGPIFMTIP**A**XFAKSX**S**I
Balaenoptera musculus	VTRMVIIMVVAFLICWVPYASVAFYIFTHQGSNFGPIFMTIP**S**FFAKSS**S**I

Figure 4-4. Alignment of amino acid sequences deduced from cetacean rod opsin exons 1 and 4 and MWS cone opsin exons 3 and 5. Amino acid substitutions associated with significant wavelength modulation are in bold and numbered. Underlined regions indicate transmembrane (TM) helices.

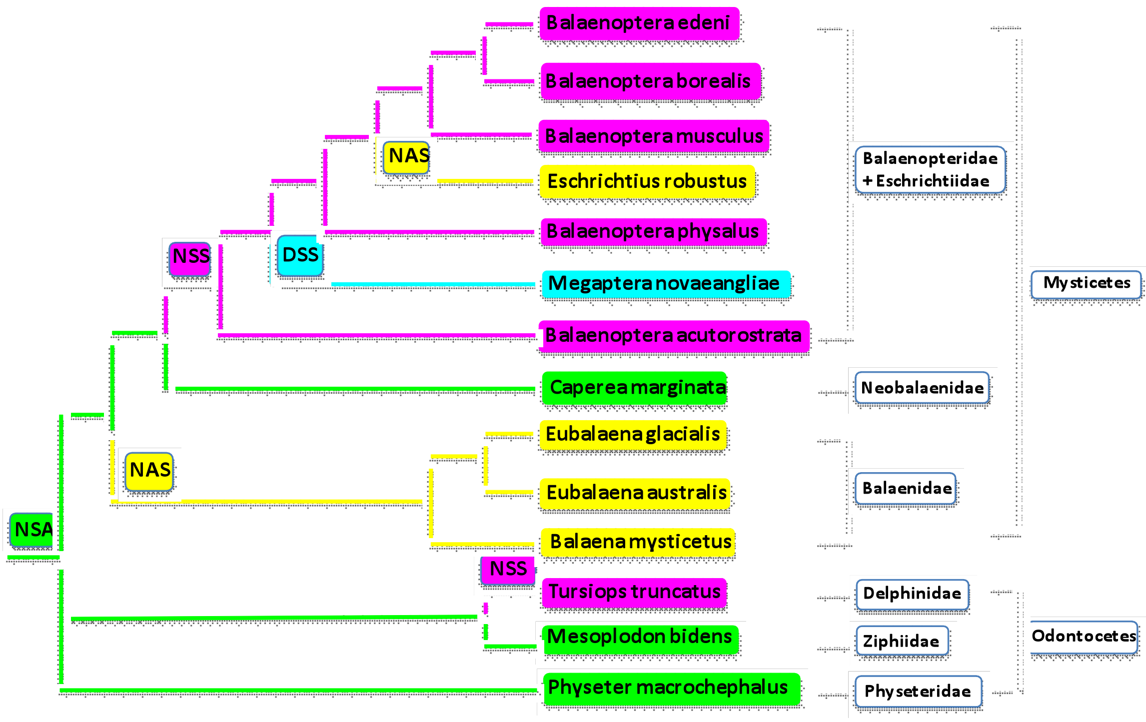

Figure 4-5. Phylogeny of the mysticete whales and the emergence of the amino acid substitutions at positions 83, 292 and 299. Associated absorbance maxima are as follows: NSA, 479 nm, NSS, 484 nm, NAS, 493 nm, DSS, 492 nm. (Note: Terrestrial rhodopsins commonly possess the amino acid substitutions DAA with an absorbance maximum of 500 nm).

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Appendix:

Fasick, JI, N Bischoff, S Brennan, S Velasquez, and G Andrade. 2011. Estimated absorbance spectra of the visual pigments of the North Atlantic right whale (*Eubalaena glacialis*). Marine Mammal Science 27(4): E321-331

<u>Project 5 – Field Studies to Assess the Potential for Using Vision to Reduce Right Whale Entanglements in Fishing Gear</u> (NEAq)

Project Goals and Objectives
The primary goal of this work was to determine right whale responses to rope mimics of various colors and levels of illumination. Our objectives were as follows:

- Develop rope-mimics using those colors that maximize the spectral sensitivity in right whales (from Dr. Fasick's work under Project 4).
- Evaluate the effects of colored and illuminated rope mimics on the behavior of right whales.
- Review literature for information about the effects on sea turtles of the colors most sensitive to right whales, to evaluate potential broader effects.

Project 5 Final Report

Assessments of Vision to Reduce Right Whale Entanglements

Scott D. Kraus and Marianna Hagbloom
New England Aquarium

Introduction

The North Atlantic right whale (*Eubalaena glacialis*) is the most endangered large whale in the north Atlantic, with less than 500 alive today. Population growth is impaired by high levels of human-caused mortalities (Kraus and Rolland, 2007). At least 50% of all deaths in this population are caused by human activities, primarily ship collisions and entanglements in fisheries gear (Cassoff et al, 2011; Moore et al., 2004). Despite management efforts, entanglement rates remain high, and may claim at least one North Atlantic right whale annually along the east coast of North America (Knowlton and Kraus, 2001). Approximately 82% of the animals in the Right Whale Catalog carry scars caused by ropes or nets (Knowlton et al., 2012). Fixed fishing gear is distributed very broadly along the coast of North America, and all types of fixed fishing gear have been recovered from entangled right whales (Johnson et al., 2005; 2007).

As the right whale-gear entanglement problem continues, the failure to solve it jeopardizes the viability of several fixed gear fisheries, especially the lobster fishery (Van der hoop et al., 2012). This work was to determine if the color or visible features of ropes could provide whales a visual deterrent, thereby averting entanglements. It sought to identify those visual characteristics which might be used in rope construction to help whales avoid entanglements.

Methods

The purpose of this experiment was to determine whether changing the visual characteristics of rope mimics in the path of skim-feeding right whales alters the distance at which whales respond by exhibiting a change in behavior. Researchers studying right whales suspect that vision is a critical mode of sensory perception for prey detection and navigation. Cetaceans have adapted well to the spectral properties of a variety of aquatic photic environments, with light-gathering and enhancement mechanisms, high levels of resolution acuity, and special pupillary and retinal mechanisms to adjust to different light levels allowing for vision both above and below the water surface. Fasick et al (2011) estimated the spectral sensitivities of the right whale rod and cone visual pigments (493 nm and 524 nm, respectively) and found that these estimates would allow the rod and cone photoreceptors to be tuned in a way that optimizes photon capture in an extremely light-limited environment. While the photoreceptors are tuned to a region of the spectrum to detect underwater background light, they are insensitive to wavelengths greater than 650 nm, or the red region of the visible spectrum. In this situation, red objects in the water column produce a perfect high-contrast dark silhouette against the bright background light in either the horizontal or upward visual axes.

Although a wide variety of colors are used in fishing ropes, there is a strong preponderance of greens and blacks in fixed gear lines. Based on the early work by Fasick et al (2011) and Kot et al (2012), this experimental work is designed to determine if changing color or the visual characteristics of rope elicits changes in behavior that might be employed to enhance a whale’s ability to avoid entanglements by detecting and maneuvering around such ropes.

We constructed 20-foot rope mimics from two 10 ft sections of rigid PVC pipe approximately the same diameter as 1” rope. The two sections were connected with quick release snap clips, and the entire length was mechanically scored every 2 to 3 inches so that they would shatter if a whale touched them. Ropes were weighted at one end, and attached to a lobster buoy at the other, so that during deployment, whales were presented with the equivalent of a vertical rope in the water column. Each rope mimic lobster buoy was fitted with a 30.5 cm disk oriented horizontally in order to have a fixed measurement reference in any still or video images collected by the observers. We originally planned to try 3 rope colors and one illuminated rope. However, based upon information on whale vision and the fixed gear fishery, additional colors were built. Ropes were painted with a variety of colors, including two that are common in most fisheries (black and green), two types of white rope (one white paint, and one glow in the dark white/green paint), and two colors that appear to occur in the spectral sensitivity for right whales (orange and red) that results in extremely high contrast (Figure 5-1). In 2012, we also developed and tested ropes with flashing or steadily illuminated LED’s, although the LED failure rate was so high that this avenue of work was abandoned.

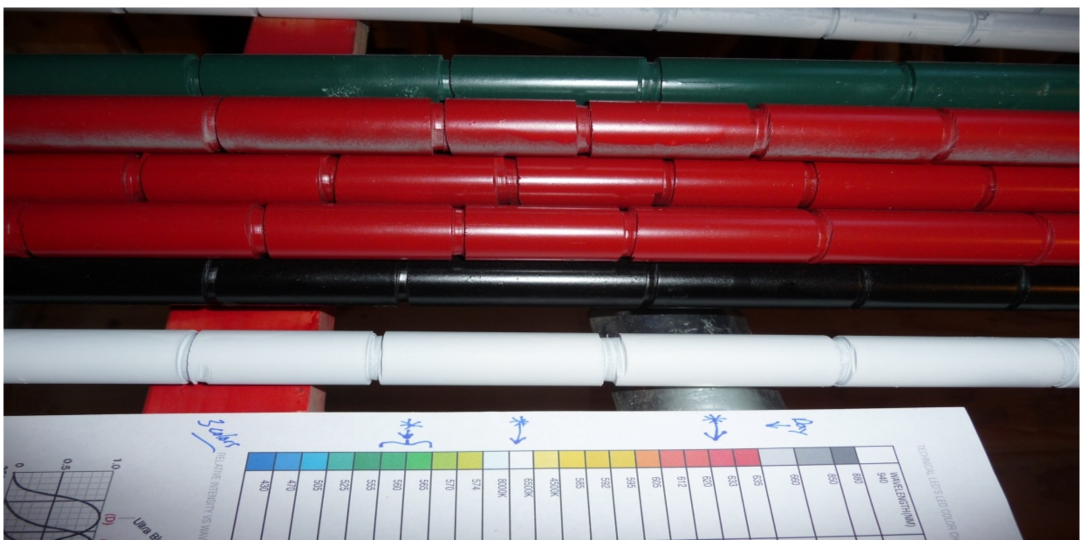

Figure 5-1. Selection of ropes constructed for the experiment (not all colors shown).

The tests occurred in Cape Cod Bay, where multiple right whales sometimes skim-feed along the depth contour lines off of Herring Cove. Surface-feeding whales were chosen because their behavior was continuously visible and it was possible to estimate their trajectories in advance to facilitate placement of the rope mimics. In addition, because the whales were presumably distracted (or focused on) by feeding, this is a robust test to determine responses. In other words, for visual stimuli to be effective, they must be detectable (and the whale must respond) when the whale is busy doing something else.

In both years, as whales encountered the rope mimics (defined as an approach by a whale to a “rope” within 10 m, the limits of underwater visibility), a variety of behaviors occurred. Initially, we believed that the measurement of significance would be changes in swimming direction, and we planned to conduct paired trials of each “rope” color. However, the challenges of working in brief suitable weather conditions, as well as the variability and unpredictability of whale behavior, caused us to change the experimental design by deploying multiple ropes in a row to maximize the probability of encounters. In addition, since all encounters were recorded with HD video, we were able to evaluate all response behaviors, including directional changes, respiration rate changes, submergence events and durations, swimming cessation/change in fluke beat, and tail flicks, for each whale that approached a rope-mimic. In the analysis, any change in behavior as the whale approached the rope mimic indicated that it had seen the rope and was responding. We measured the distance between the "rope" and the whale as it approached, as well as the distance between the two as the whale exhibited its first response using repeated readings taken from a laser range finder, still images of the whale approaching each rope mimic buoy with the reference disk, and the HD video recordings. All analyses were applied to the distance between the whale and the rope mimic at the first change in visible behavior.

We used the M/V Junet, a 42 (12.9m) foot motor yacht with an inboard diesel and a flybridge for this experiment. In 2011, rope "mimics" were deployed from the stern of the M/V Junet as the vessel crossed right whale feeding paths perpendicular to their trajectory, well in advance of the whales passage (ca 75 – 150 m). The M/V Junet then stopped and shut down, so the observers were off to the side of the feeding path (Figure 2), and observations were made of all encounters between the rope mimics and right whales. After the whales passed by, ropes were retrieved and re-deployed as conditions allowed. Deployment of the "ropes" in this fashion led to a straight line of rope mimics with 30 m to 40 m intervals between each rope (Figure 5-3). Since underwater visibility was measured at 10 m or less, this ensured that whales encountering a rope mimic would be confronted with only a single visual stimulus. However, it also meant that a right whale travelling through the exact middle of an inter-rope interval would be unlikely to see either rope.

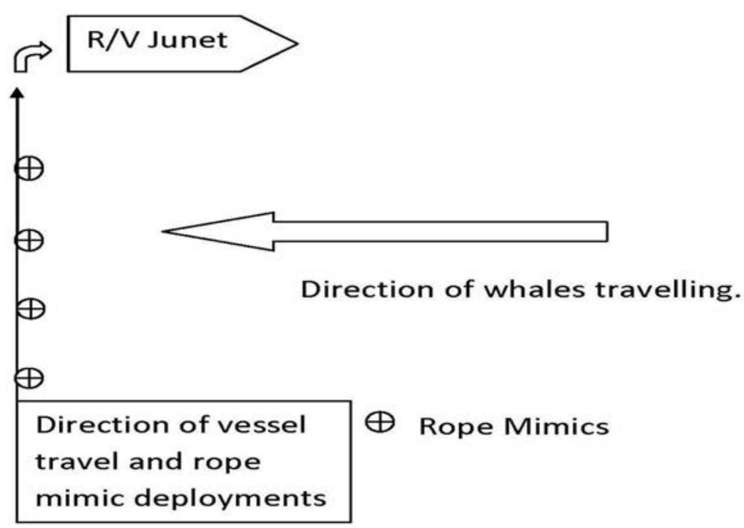

Figure 5-2. Diagram of 2011 experimental design for testing whale responses to rope mimics.

Figure 5-3. An experimental linear deployment of fake ropes in 2011. The right whale in the background (heading left) swam outside the furthest rope mimic.

In 2012 we changed the method of rope mimic deployment. Because the 2011 deployment strategy required the vessel to cross in front of the whales at large distances (ca 100 m), we had no ability to control the probability of an encounter once the ropes were deployed, as approaching whales could swim through the array, or turn around, or change swimming directions long before reaching the experimental area. In addition, there was a small (albeit unlikely) chance that the passage of the M/VJunet could disrupt the aggregations of plankton that the whales were feeding on, possibly leading to changes in behavior related to the change in plankton density, and not to the rope mimics. To eliminate this possibility, and to better control both the deployment locations and the probability of encounters, we used a modified 40” radio controlled electric catamaran to tow the rope mimics into place. This eliminated potentially confounding variables, including ship noise and movements that might have affected whale behavior, as the M/V Junet could stay silent during the entire trial period. This strategy was highly successful, enabling precise deployments with a greatly reduced risk of disturbance.

The primary consideration of “rope” color selection was the experimental power in testing different rope color/types. For example, in 2011, rope mimic colors (red, white, black, and green) were deployed randomly on each set (see Figures 5-1 and 5-2). Unfortunately, because of the relatively few encounters and the variability of the whale movements around the deployments, no encounters between whales and red “ropes” occurred in 2011. In addition, we discovered using underwater cameras that the white “ropes”, (both the glow in the dark white and the straight white paint) became invisible at relatively close distances. For these reasons, the work in 2012 focused on collecting data on encounters between whales and red or orange “ropes”, with limited (and unsuccessful) attempts to use the LED “ropes”.

In 2011 we used night vision equipment to determine the effects of rope mimics on right whale behavior at night on two nights. We used a FLIR Thermosight ATWS Block Infrared imaging system and a U.S. Military night-vision light-intensifying scope to track and film whales. During both nights, as the sun set, skim feeding behavior ceased, and no skim-feeding was subsequently observed despite tracking for several hours. Since skim feeding behavior was essential to track whale responses to rope-mimics, the change in whale behavior meant the no rope mimics were deployed around whales at night. No further efforts were made to follow whales at night.

This research was conducted under NMFS Permit (No 15415), issued to Scott D. Kraus for this specific research activity, valid through March 31, 2014.

In addition to this fieldwork, a literature review of sea turtle vision was conducted to ensure that colored or illuminated ropes would not have a negative effect on sea turtles (Appendix 6). The visual spectrum sensitivity range of the right whale appears to overlap with those of several sea turtle species. No studies have shown any particular color to be attractive or repulsive to sea turtles. Lights have been shown to attract juvenile loggerhead turtles, while experiments to reduce green turtle bycatch in gillnets have used LED lights and chemical light sticks to successfully prevent entanglements.

Results

The M/V Junet launched out of Plymouth, MA, and most work was done between Chatham and Herring Cove (west of Provincetown) along the eastern side of Cape Cod Bay, although in 2012, we worked a few skimfeeding whales on the northeastern side of the Cape. In both years, weather hindered operations, as any wind above 12 knots would move the observation vessel too rapidly downwind to remain stationary relative to the rope mimic deployments. Nevertheless, we managed to work 5 days in 2011 and 6 days in 2012. Not all of these days involved working around whales, because right whales sometime feed in linear patterns (which provided good experimental conditions), but sometimes were observed feeding in random, or circular and unpredictable patterns. In the latter case, no deployments were made, because we could never be certain whether a whale's turn was related to a rope mimic or a change in copepod patch distribution. At the conclusion of both years, we had three days with whale/rope encounters in 2011 and 2 days with whale rope encounters in 2012 (Table 5-1).

Table 5-1. A summary of the deployments, encounters, conditions, and rope color.

Date	Start Time	End Time	Position	Sea State	Cloud Cover	Wall Orienta -tion	Order of Rope Colors	Total # Egs Passed Through
4/7/2011	1802	1826	42 0.1, 70 7.6	2	0%	NE-SW	B, R, W, G	1
4/7/2011	1839	1900	42 0.4, 70 8.4	2	0%	NE-SW	B, W, G	2
4/8/2011	1334	1417	42 2.3, 70 8.1	2	75%	E-W	R, G, W, B	4
4/8/2011	1524	1547	42 1.8, 70 7.9	1	100%	E-W	R, G, W, B	3
4/14/2011	1611	1633	42 1.9, 70 13.0	1	50%	NE-SW	B, G, B, G	17
4/14/2011	1633	1655	42 1.7, 70 13.0	1	50%	NE-SW	W, W	2
4/14/2011	1704	1730	42 1.2, 70 12.3	1	50%	N-S	W, W, G/B, G	1
4/14/2011	1740	1758	42 1.5, 70 12.6	1	50%	NE-SW	W, W, B, B	1
4/14/2011	1813	1835	42 1.2, 70 12.2	1	50%	NE-SW	W, W, G/B, G	1
4/14/2011	1924	1933	42 3.0, 70 14.0	1	50%	NE-SW	W, W, B	3
3/20/2012	1605	1615	42 2.8, 70 14.2	1	0%	n/a	R	3
3/20/2012	1636	1644	42 2.8, 70 14.1	2	0%	n/a	R	1
3/21/2012	959	1005	42 1.76, 70 13.0	2	30%, fog	n/a	R	1
3/21/2012	1009	1020	42 1.76, 70 13.0	2	30%, fog	n/a	R	2
3/21/2012	1038	1055	42 2.0, 70 12.8	2	30%, fog	n/a	R	1
3/21/2012	1130	1200	42 2.15, 70 13.15	1	30%, fog	n/a	O	1
3/21/2012	1206	1235	42 2.36, 70 13.31	1	30%, fog	n/a	O	4
3/21/2012	1332	1422	42 2.5, 70 13.58	1	30%, fog	NW-SE	R, G	7

Data analysis focused on the distance at which the first visible change in behavior occurred. Because the data were non-parametric and consisted of small sample sizes, only strong reactions were measured. The identifications of reactions were based upon observations of the whale's antecedent behavior, videotaped and and/or observed for up to 3 minutes before the encounter between the whale and the rope mimic (Figure 4). Reactions included noticeable changes in direction, submergence, closing the mouth, cessation of respiration, and change in fluke beat (Figure 5-5). The preliminary analysis showed a significant difference in the distance of first change of behavior by right whales confronted with black and green ropes (n=8, mean distance = 2.625 m) vs red and orange ropes (n=7, mean distance = 6.21m) (Mann-Whitney U Test=55.5, p = 0.0018) (see Table 5-2).

Figure 5-4. Right whale approaching a rope mimic before any change in behavior.

Figure 5-5. The same whale showing a change in behavior (submergence and slight acceleration from the ripples at the tail) as it passes by the rope mimic.

Table 5-2. Analysis of distances at which the first change in a whale's behavior occurred in response to an encounter with a rope mimic.

Date	Time	Camera Time	Secchi (ft) over Water Depth (ft)	Lighting	Color of rope	Min Est. Distance from Rope (m)	Eye distance from rope at first rxn	Mean	Variance	SD
4/7/2011	1808	2:00	n/a	back lit	B	2	2	2.625	0.76786	0.876275
4/14/2011	1617	1:13	14/14	front lit	G	2.5	2.5			
4/14/2011	1617	1:24	14/14	back lit	B	0	2.5			
4/14/2011	1618	2:42	14/14	back lit	G	2	3			
4/14/2011	1619	3:09	14/14	back lit	G	2.5	3			
4/14/2011	1619	3:42	14/14	front lit	G	1.5	4			
4/14/2011	1624	8:15	14/14	back lit	G	2	3			
4/14/2011	1624	8:16	14/14	back lit	G	0	1			
3/20/2012	1609	6:30	25/25	front/side	R	3	5.5	6.2143	1.65476	1.286375
3/20/2012	1637	9:00	25/25	front/side	R	5	6			
3/21/2012	1048	9:00	20/20	backlit	R	5	6			
3/21/2012	1150	23:53	20/20	backlit	O	3	7			
3/21/2012	1211	28:39:00	20/20	backlit	O	5	7			
3/21/2012	1217 (b)	33:38:00	20/20	backlit	O	3	4			
3/21/2012	1217 (f)	39:29:00	20/20	front	O	6	8			

The underwater visibility was measured with the vertical drop of a Secchi disk, and in all cases the visibility exceeded the distance at which the first changes in behavior were observed. In most of the locations where whale/rope encounters were recorded, the underwater visibility extended to the bottom (Table 5-2). When we did secchi readings in deeper waters, the underwater visibility was approximately 10 m in both years. However, on one occasion, we lowered an underwater camera to collect visibility in the horizontal plane, and that distance appeared to be somewhat less than the traditional vertical Secchi measurement, possibly due to the way in which sunlight illuminated particles in the water near the surface.

We recorded whether the direction of how the rope appeared illuminated (from the front or behind) for each whales' approach (Table 5-2). There was no significant difference in behavioral response distances between illumination characteristics (front or backlit) ($p = 0.28$, t-test with unequal variances), although sample sizes are small.

Night Vision Work

On two nights we attempted to conduct this experiment after sunset under extremely low-light condition (no moon). The night vision equipment worked well, enabling observations of right whales at night. The infrared camera provided relatively low resolution images that made the whales appear white (warm) against a black (cold) background (Figure 5-6a and b). Blows were visible at nearly ½ a mile, but the ability to identify individuals was compromised by the poor resolution. The military light intensifying scope had better resolution, and the green phosphor images were in some cases adequate for individual whale identifications (Figure 5-6c and d).

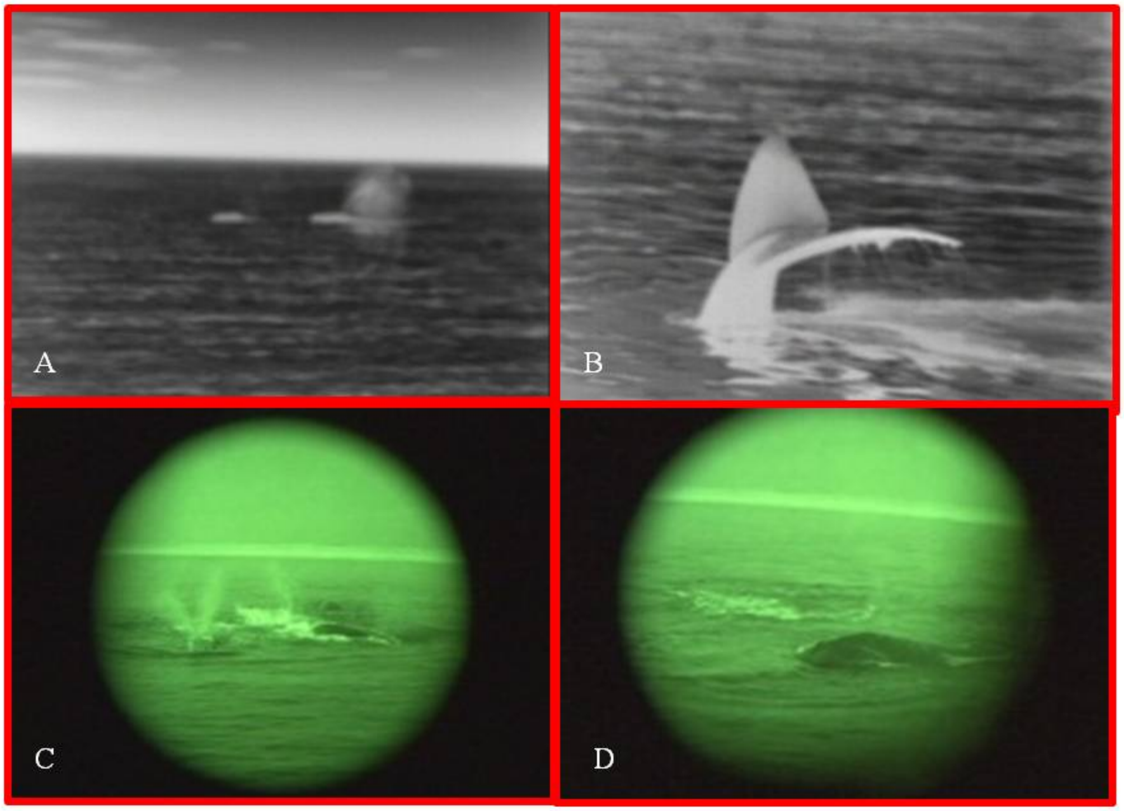

Figure 5-6. Night vision images taken on April 14th 2011 between 2000 and 2100 hours (sunset was at approx 1840). A) Infrared image of distant blow. B) Infrared image of right whales flukes. C) Light intensifying image of right whales courtship group. D) Light intensifying image of right whale head.

However, on the two days we attempted to continue the rope mimic tests into the evening, right whale behavior changed as the sun set. Skim feeding at the surface ceased, making it impossible to conduct the experimental trials, and the whales initially dispersed. Using the night vision equipment, we followed the whales to determine if skim feeding might occur later in the evening. Instead, no skim feeding was observed, and some right whales started socializing (Figure 5-6C), while others started deeper dives (Figure 5-6B). No skim feeding was observed for the rest of the evening, and observations ceased around midnight. After two nights of observations with similar behavior changes, no further attempts were made to conduct rope-mimic trials at night.

Outreach

The details and results of this work have been presented in public on three occasions. The PI gave talks at the Gulf of Maine Research Institute summer speaker series in Portland Maine, and at the Bigelow Labs Café Scientifique speaker series in Boothbay Harbor, Maine, in August of 2012. In addition, more technical results of this work were presented at the North Atlantic Right Whale Consortium in New Bedford, MA November of 2012.

Discussion

This experimental work proved extremely challenging, with weather, whale behavior, and technical issues all reducing appropriately controlled encounters between whales and rope mimics. Despite 11 days and two nights at sea, sample sizes for different rope color datasets were very small. Nevertheless, despite the small sample sizes, there appears to be a significant difference in the distance of first changes in behavior between whale encounters with black/green ropes and red/orange ropes. Had these differences been slight (e.g. on the order of 20% difference, we would not have had the statistical power to demonstrate any differences. However, the appearance of strong differences in behavior in these circumstances suggests a real phenomenon in right whales visual detection capabilities.

The spectral sensitivity of the right whale rod visual pigment has recently been directly determined (Bischoff et al., 2012), and is shown in Figure 7. The *E. glacialis* rod visual pigment is tuned to a region of the spectrum to detect underwater background light but appears insensitive to wavelengths greater than 600 nm. The primary prey species of the North Atlantic right whale, the calanoid copepod *Calanus finmarchicus*, transmits light in the red region of the visible spectrum. Microspectrophotometric measurements of the *C. finmarchicus* carotenoid pigments show light transmission profiles that are nearly the inverse of the spectral sensitivities of the *E. glacialis* rod visual pigment, effectively blocking light between 450 and 550 nm while transmitting light maximally at wavelengths greater than 600 nm. Therefore, right whale prey, *C. finmarchicus* would produce a perfect high-contrast dark silhouette against the bright background in either the horizontal or upward visual axes. In this experiment, the red and orange ropes produce reflected light that occurs in the red portion of the spectrum, and may have created a higher contrast image than all other colors, thereby allowing right whales to detect those “ropes” at a greater distance.

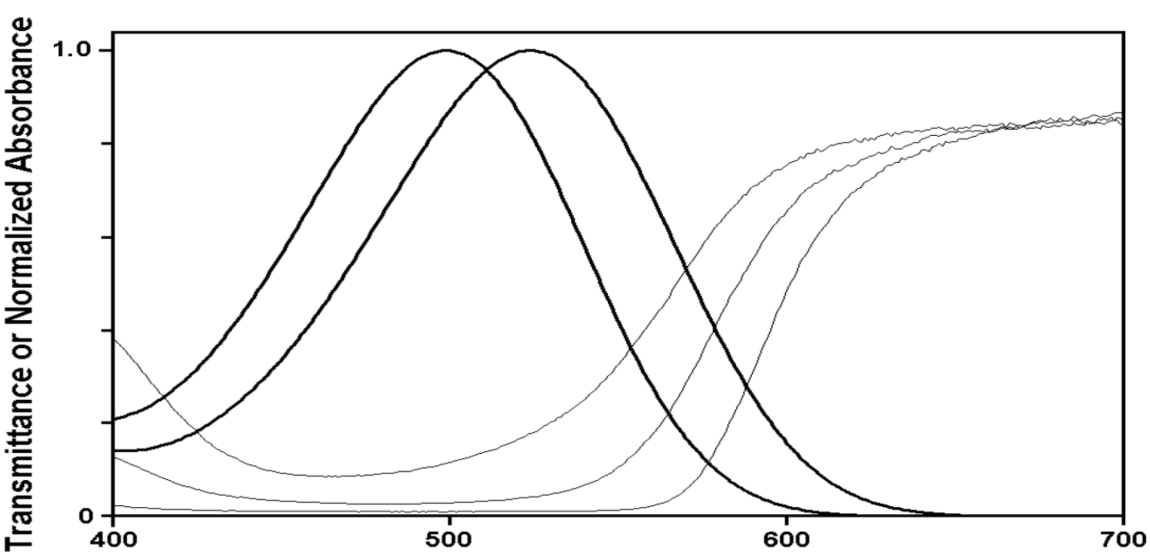

Figure 5-7. Right Whale Visual Pigment Absorbance Spectra & *C. finmarchicus* Oil Pigment Transmission Spectra.

Conclusion and Next Steps

In conclusion, this work provides strong evidence that changing the colors of rope used in fishing gear may improve whales' ability to detect and avoid those ropes under daylight conditions. However, the small sample sizes used in the comparative analysis call for caution, and further work is needed. This project will continue for at least one more year with funding from NMFS Bycatch Reduction Engineering Program, in an attempt to double the sample sizes, to refine our experimental techniques and methods, and to get robust answers to the question of whale vision and entanglement probabilities.

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<u>Project 6 – Identification of Current Lobster Fishing Practices</u> (MLA, NEAq)

Project Goal and Objectives
This project's aim was to characterize current lobster fishing practices, thus filling a major gap in our understanding of lobster trap gear. This reference guide will provide fisheries managers with a better understanding of the fishery and help them evaluate the relative impacts of potential regulatory changes involving lobster gear. It also serves as a tool for further engaging lobstermen in constructive dialogue about the kinds of gear and fishing methods that may pose the lowest risk to whales from entanglements.

Project 6 Final Report

Documenting the Temporal and Spatial Gear and Vessel Configuration of the Maine Coast Lobster Fishery

Maine Lobstermen's Association

The MLA met with members of the lobster fishing industry to document the full range of fishing gear and deployment methods used in the Gulf of Maine lobster fishery and to discuss practical gear modifications that have potential to reduce the risk of entanglement, or the severity of entanglement, of whales in vertical lines.

Background

In 2009, the Gulf of Maine lobster fishery landed nearly 93.5 million pounds of lobster valued at $298 million. Maine landed 79 million pounds (85%), New Hampshire landed 3 million pounds (3%) and Massachusetts landed 11.5 million pounds (12%). According to the 2009 ASMFC stock assessment report, the American lobster resource has high abundance and recruitment in the entire Gulf of Maine, but not in most of the surrounding New England coastal waters.

Gulf of Maine lobstermen are regulated under the Atlantic Large Whale Take Reduction Plan (NOAA 1997). Since the inception of the whale plan in 1997, lobstermen have complied with measures to help reduce the risk of entanglements with lobster gear such as keeping lines as knotless as possible, prohibiting floating line at the surface, and requiring the use of 600 pound weak links. Until 2008, lobstermen had complied with the Dynamic Area Management (DAM) and Seasonal Area Management (SAM) regulations when they were replaced with broad –based regulations requiring groundlines to be composed of sinking rope. A portion of Maine state waters are exempt from the sinking line regulation. Massachusetts lobstermen had mandated sinking groundlines in all state waters prior to the implementation of the federal regulations.

Lobstermen comply with other regulations to protect whales based on fishing location, such as seasonal measures in the Cape Cod Bay Critical Habitat area. Lobstermen fishing outside the exemption line mark their gear with a four-inch red tracer mid-way down the buoy line and include 600-pound weak links on all floatation devices. Lobstermen in federal waters are allowed only one endline on trawls of five traps or less. Lobstermen are required to haul gear a minimum of once every 30 days and to mark their buoys with their license number. Under federal regulations, Gulf of Maine lobstermen are required to use highflyers in federal waters outside 12 miles for trawls of more than three traps. The law requires lobstermen to deploy a metal radar reflector at least 8 inches high at each end.

The ASMFC lobster management plan requires all lobster dealers to submit monthly reports with daily catch information for each harvester. ASMFC also mandates harvesters to provide trip level reporting which has been fully implemented in Massachusetts and New Hampshire, and at a 10% reporting level in Maine. All three states have implemented surveys to collected data on the number of vertical lines in the fishery.

Gear Configuration Survey

In 2010, the MLA began a survey of gear fished in the Maine lobster fishery. The MLA initiated an in-person, harbor-by-harbor technique to collect data from all areas of the coast in Maine. MLA identified Maine's fishing harbors through the state's zone council system. The Maine coast is divided into seven lobster management zones, named A through G from east to west. Each zone is subdivided into districts that represent the harbors within each zone. The MLA contacted each district representative by mail and phone for their guidance to cluster districts that shared fishing territories so that they could be interviewed together. During these meetings, MLA collected data on gear and vessel configuration, best practices, and additionally documented the temporal and spatial patterns of the fishery for a Woods Hole Oceanographic Institute lead whale/fishery risk modeling project[8].

The meetings were kept small, ranging from two to ten lobstermen, to minimize intimidation and ensure that participants were comfortable speaking about their fishery. This approach allowed lobstermen to describe their gear and vessel configurations on an individual basis and then to characterize the temporal and spatial gear distribution for their common fishing territory collaboratively.

During each meeting, MLA presented information on the severity of right whale entanglements, large whale population statistics, and previous measures employed to reduce severe entanglements. This generated much discussion and helped to educate lobstermen about the complexities of the large whale entanglement issue.

Following the presentation, lobstermen participated in informal interviews to characterize their fishery. Many completed a written survey to depict gear configurations including the surface buoy and trap configurations.

These discussions also provided lobstermen with an outlet to discuss changes in local fishing practices as a result of the industry's conversion from floating to sinking ground line, and to share anecdotal information on whale sightings and numerous other details relevant to the fishing practices of each harbor.

In addition to these harbor meetings held in Maine, regional meetings were held in Maine, New Hampshire and Massachusetts to discuss how gear is deployed and to identify best fishing practices that minimize entanglement risks. In Maine, best practices were discussed with the MLA Board of Directors in February, 2011, with lobstermen during a seminar to discuss lobstermen's experience with sinking

[8] MLA is partnering with Woods Hole Oceanographic Institute, New England Aquarium and Keen State University in a project "Mitigating risk to whales from lobster fishing", funded through the Northeast Regional Sea Grant Programs.

rope held at the Maine Fishermen's Forum in March, 2011 and through individual interviews. In New Hampshire, a small regional meeting was organized with lobstermen in early April, 2011. In Massachusetts, a seminar was organized to discuss best practices during the Massachusetts Lobstermen's Association Annual Meeting in February, 2011. A second meeting was held at the Massachusetts Lobstermen's Association's monthly delegates meeting held in April, 2011.

Maine Gear and Vessel Configuration Summary

The Maine lobster fishery is the most diverse and largest fishery in the Gulf of Maine. In 2009, Maine issued nearly 5,400 commercial lobster licenses. According to the Maine Department of Marine Resources (DMR), approximately one-third of licenses are not actively fished and the number of full- versus part-time lobstermen is unknown. In 2010, Maine landings reached a record high at 93 million pounds, which resulted in a value over $308 million for the state of Maine, with an average ex-vessel price of $3.31 per pound. Maintaining a healthy lobster stock and an operationally feasible and safe fishery is of paramount importance to the state.

Maine has designed a system to control entry into the fishery. In order to obtain a Maine commercial lobster license, one must complete the Apprentice Program. This program requires an individual to be sponsored by a licensed commercial lobsterman and to document a minimum of 1,000 hours over a minimum two-year time period. Once completed, the apprentice is eligible to obtain a lobster license through the limited entry system.

Currently, six of Maine's seven lobster zones have closed their zone to entry and require a certain number of trap tags be retired before a student or apprentice can enter the fishery. Zones B, D, E, F and G have a 5:1 exit-to-entry ratio requiring 4,000 lobster trap tags to be retired before accepting a new entrant (3,200 in Zone E due to 600 trap limit). Zone A has a 3:1 ratio, requiring 2,400 tags to leave the fishery before issuing a new license. Zone C remains open.

The Zone Council system requires lobstermen to declare a home zone on their license and to identify any other zones in which lobster gear will be fished. A lobsterman must fish 51% of his gear in his declared zone and may only shift 49% of his gear into declared adjacent zones. This restricts east/west movement in the fishery in state and federal waters, preventing expansion of fishing effort to adjacent zones.

In 2003, Maine implemented mandatory dealer reporting of lobster landings by trip and in 2008, 10% mandatory trip level reporting by harvesters. These data show that roughly 30% of Maine lobster licenses are not fished. Additionally, Maine DMR has conducted surveys to detail spatial and temporal gear configuration in 2006, 2008 and 2009, an annual recall survey to measure vertical line density in 2009 and a fishery-independent aerial and vessel-based survey to measure vertical line density in 2010 and 2011.

Lobster Pot Gear Configurations in the Gulf of Maine

The MLA successfully completed the gear description report entitled "Lobster Pot Gear Configurations in the Gulf of Maine", which was printed and published in January 2012 by the New England Aquarium (Appendix 7). The MLA fact checked all materials with lobstermen from Maine, New Hampshire and Massachusetts. The report includes professional graphics of how gear is rigged in the Gulf of Maine, which were completed under a subcontract with Andrew Cook, from "Lobstering is an Art".

Of the 1200 copies printed more than 700 copies have been distributed. The report was distributed at various meetings and conferences, including: North Atlantic Take Reduction Team 2012 meeting, the MLA Board of Directors, the 2012 Maine Fishermen's Forum and the Annual Massachusetts Lobstermen's Association weekend, at seven Zone outreach meetings, and the 2012 North Atlantic Right Whale Consortium Annual Meeting. Maine Marine Patrol, Maine colleges, businesses, and other institutions have also requested copies of the report. Friendship Trap is also planning an in-store display based on the report and graphics.

The MLA included a presentation on the gear report during seven outreach meetings along coastal Maine, with a focus on having lobstermen from each zone review the gear description and illustrations. All feedback on gear rigging has been recorded for use if a second edition is printed. Overall the report has been praised as an accurate depiction of the fishery and a valuable tool to people who carry out research on the water.

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<u>**Project 7 – Stable Isotope Analysis of Pilot Whale Diet**</u> (Duke)

Project Goal and Objectives

The goal of this project was to quantify the relative contribution of local pilot whale depredation on tuna off North Carolina, and to quantify better the proportion of the population that engages in depredation. The objective of this project was to determine the relative importance of tuna in the diet of pilot whales in the Cape Hatteras Special Research Area (CHSRA) using stable isotope analysis. Using stable isotope analyses of pilot whale tissues, tuna, and squid Duke researchers will determine the relative contribution of tuna to the diet of pilot whales, and thus estimate the ecological importance of depredation to pilot whales. This analysis will also help determine whether depredation is exhibited by all pilot whales or only selected individuals by comparing $\delta^{15}N$ signatures among individual animals.

Project 7 Final Report

Reducing Conflicts Between Fisheries and Protected Species in North Carolina: Stable Isotope Analysis of the Diet of Pilot Whales

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Project Background

The most acute conservation problem currently facing marine mammals is bycatch, the unintended capture of animals in fishing gear (Read et al. 2006). The problem of bycatch is particularly challenging when marine mammals remove captured fish from fishing gear, a process known as depredation. Depredation and bycatch are common features of many pelagic and demersal longline fisheries throughout the world (Gilman et al. 2006). Depredation results in increased cost and lost revenue for the fishery due to a reduction in the quantity and value of catch ad damage to fishing gear. In addition, marine mammals may become entangled and die in fishing gear while engaging in depredation.

The Pelagic Longline Take Reduction Team (PLTRT) was convened by the National Marine Fisheries Service in 2005 to address the bycatch of pilot whales (*Globicephala spp.*) in the Atlantic pelagic longline fishery. This fishery primarily targets bigeye (*Thunnus obesus*) and yellowfin (*Thunnus albacores*) tuna. The diet of short-finned pilot whales (*G. macrohynchus*) is believed to be comprised mostly of squid (Mintzer et al. 2008), but pilot whales are known to take advantage of foraging opportunities presented by fishing gear (e.g. Gannon et al. 1997) including pelagic longline catches. At the present time we do not understand the prevalence of this behavior at a population level or whether certain sex or age classes, social groups, or individuals preferentially engage in depredation in this fishery.

Stable carbon and nitrogen isotope analysis is a powerful technique that can be used to address many questions concerning foraging ecology, habitat use, diet composition, and tropic ecology (see reviews by Hobson 1999; Kelly 2000; Newsome et al. 2010). The stable isotopic composition of the tissues of animal reflects the average isotopic composition of its assimilated diet, although isotope enrichment occurs between an animal and its food (DeNiro and Epstein 1978). ^{13}C enrichment is estimated to be 1-2‰ per trophic level due to carbon isotopic fractionation during assimilation or respiration (DeNiro and Epstein 1978; Peterson and Fry 1987). ^{15}N enrichment between trophic levels is 3-4‰ per trophic level, mainly due to the preferential excretion of ^{14}N in urine (DeNiro and Epstein 1981; Minagawa and Wada 1984; Peterson and Fry 1987).

As the enrichment in ^{15}N is relatively large and predictable between predator and prey, it can serve to identify an animal's trophic position within a community (Minagawa and Wada 1984; Fry 1988; Hobson and Welch 1992; Rau et al 1992; Lesage et al. 2001). ^{13}C enrichment along the food chain is relatively small and more variable but, instead, it reflects sources of primary production (Rau et al. 1992; Lesage et al. 2001). Carbon isotopes can provide information about the type of foraging habitat, from inferences regarding the sources of carbon (Ramsay and Hobson 1991; France 1995; Smith et al. 1996; Clementz and Koch 2001).

Isotope ratios are expressed in delta (δ) notation as parts per mil (‰) where δ is the isotope ratio of the sample relative to a standard using the following equation:

$$\delta^{h}X = [(R_{sample}/R_{standard})-1] \times 1000$$

where X is the element, h is the mass of the heavy isotope and R_{sample} and $R_{standard}$ are the heavy and light isotope ratios ($^{13}C/^{12}C$) or $^{15}N/^{14}N$) of the sample and standard, respectively (Newsome et al. 2010). The accepted standards are carbonates from Vienna Pee Dee Belemnite limestone for δ^{13}N (Newsome et al. 2010).

Objectives

The main objective for our project was to investigate the prevalence of depredation in pilot whales found in the Cape Hatteras Special Research Area (CHSRA), North Carolina. Pilot whales typically feed on squid (Mintzer et al. 2008), but if they regularly supplement their diet with tuna from longlines, we should observe elevated $\delta^{15}N$ signatures in their tissues. To address this question, we sampled pilot whales over several years and from multiple pods to determine the general prevalence of depredation in this population. Preliminary analysis of photo-identification images indicate that some of the pilot whales have been observed over multiple seasons during several years, and thus may be resident in the CHSRA.

Methods

Sample Collection
We collected skin samples of short-finned pilot whales during research cruises in the CHSRA from 2006 to 2010. We used a remote biopsy sampling system to obtain a small skin sample, using a projectile dart equipped with a specialized stainless-steel sampling tip launched from a modified crossbow with a 150-lb pull strength (Figure 7-1). Our sampling efforts focused on distinctive adult individuals, avoiding mature females with small dependent calves, to avoid double sampling any individual pilot whale; a photographer documented each biopsy attempt to identify the individual sampled.

The biopsy samples were initially collected to determine species identification (long-finned or short-finned pilot whale) and were stored in vials containing dimethyl sulfoxide (DMSO) saturated with NaCl, which is used for preserving tissue samples for generic analysis. Beginning in 2008 we sub-sampled each biopsy sample, with half of the sample stored in DMSO and the other half of the sample frozen at -20°C for stable isotope analysis. During a research cruise in 2010 in the CHSRA we also biopsied offshore bottlenose dolphins (*Tursiops truncatus*) to examine population structure in these dolphins. All of these samples were frozen at -20°C.

We also collected skin samples from stranded pilot whales. A mass stranding of 33 short-finned pilot whales occurred along the Outer Banks of North Carolina in January, 2005. Necropsies and sample collection were performed on 27 of these animals (Hohn et al. 2006). We obtained skin samples from 24 of these animals and three other short-finned pilot whales that stranded individually along the northern portion of the Outer Banks from 2005-2010. All samples from stranded animals were frozen at -20°C.

We obtained samples of bigeye and yellowfin tuna at Etheridge Seafood, Wanchese, North Carolina from pelagic longline vessels returning from fishing trips in the CHSRA in October 2006 and May 2007. Each fish was weighed and a hollow metal probe was inserted behind the pectoral fin, removing a core of sin and muscle used to judge the quality of the fish. We collected 69 samples from bigeye tuna and 77 samples from yellowfin tuna; all samples were placed in individual vials and frozen at -20°C. During October, 2007 we also obtained a 25 lb box of squid from a seafood distributor in Wanchese, North Carolina. These are local squid that the longline fishermen use as bait and are likely long-finned squid (*Loligo pealeii*) commonly referred to as *Loligo*.

Sample Preparation and Analysis
There is considerable variability in how cetacean tissues are prepared for stable isotope analysis, particularly in terms of sample preservation and whether or not lipid is extracted from the samples prior to analysis (Table 7-1). Lipids are known to be depleted in ^{13}C compared to proteins and carbohydrates

and typically have more negative $\delta^{13}C$ values than proteins or carbohydrates (DeNiro and Epstein 1977; Post et al. 2007). Many, but not all, cetacean researchers extract lipid prior to analysis of stable isotopes (Table 1). In addition, several publications have suggested that it is possible to correct for the effects of DMSO preservation on isotopic signatures via lipid extraction on preservation effects of $\delta^{13}C$ and $\delta^{15}N$ values of pilot whales, we designed a matched sample experiment using skin samples from 10 pilot whales from the mass stranding in 2005. We chose these animals because of the relatively large skin samples available, because multiple sub-samples were required from each specimen for this experiment. Each piece of skin was sub-sampled, which one portion preserved in DMSO and the other portion frozen. Barrow et al. (2008) found that samples stored in DMSO for one to 30 days had different preservation effects than those stored for 60 days. All of our archived samples had been stored in DMSO for more than three years, so we allowed the samples to remain in DMSO for a minimum of 60 days.

The samples were then rinsed with de-ionized water, freeze-dried and further sub-sampled, with half of each sample receiving no further treatment and the other half subjected to lipid extraction. Each of these latter sub-samples was triple rinsed in de-ionized water and then lipids were extracted using a chloroform and methanol solvent (2:1 v/v), following the protocol of Lesage et al. (2010). We placed skin tissues in glass tubes with 8-10ml of the solvent, shook them for 10 minutes and stored them overnight. The solvent was removed the next day via pipette and a fresh 10ml of solvent was added. We repeated this procedure three times. Following lipid extraction, all 40 samples (20 lipid extracted, 20 with no lipid extracted) were homogenized either by use of a ball mill or mechanical chopping. We then weighed the samples and sealed them in tin capsules and sent them to the Duke Environmental Isotope Laboratory (DEVIL), in Durham, North Carolina, to be analyzed by isotope mass spectrometry.

After examining the results of the matched sample experiment (see below) we decided to extract lipids from all remaining samples. Following lipid extraction, a sub-sample (n=20) of the samples was run through a nitrogen evaporator to confirm that all lipids had been successfully extracted. The samples were homogenized and then weighed and sealed in tin capsules and analyzed by isotope mass spectrometry at DEVIL, Durham, North Carolina.

We divided the tuna samples into two seasonal categories (fall and spring) and three size class categories (small, medium, and large) and randomly selected five samples from each group, resulting in 30 samples of bigeye tuna and 30 samples of yellowfin tuna. We also randomly selected 20 squid samples for analysis. The selected samples were thawed and dried in a drying oven at 60°C for a minimum of five days to a stable weight. We then homogenized samples with mortar and pestle, extracted the lipids, weighed and sealed them in tin capsules. These samples were also analyzed by isotope mass spectrometry at DEVIL, Durham, North Carolina. To confirm that the tuna were correctly identified to species at the time the samples were collected we performed genetic analyses on a subsample of the tuna samples (19 bigeye and 23 yellowfin tuna). We sequenced a portion of the mitochondrial cytochrome b gene using methods described in Bartlett and Davidson (1991). The genetic tests confirmed morphological species identifications for all samples.

We analyzed the results of the matched sample experiment with a two-way crossed ANOVA. Potential differences in stable isotope signatures caused by gender, age class, and indications of past fishery interactions were examined using a non-parametric Wilcoxon test. Inter-species differences in stable isotope value were also tested with Wilcoxon tests. We performed all statistical tests using JMP 8.0 statistical software.

Results

We obtained skin samples from 96 short-finned pilot whales, including 69 biopsies and 27 samples from stranded animals (Figure 7-2 and Table 7-2). We confirmed the identity of all specimens as short-finned pilot whales by molecular analysis in the laboratory of Dr. Patricia Rosel (NMFS/SEFSC). This genetic analysis also indicated that our sample included three sets of duplicate samples, with two samples obtained from three separate whales; we average isotope values for these individuals, resulting in a total of 93 samples. Eleven pilot whale biopsy samples collected during May 2008 were processed without lipid extraction and were excluded from further analysis.

Effects of Sample Preservation and Lipid Extraction
The results from our matched sample experiment demonstrated that preservation method did not have an effect on either $\delta^{13}C$ ($p = 0.672$) or $\delta^{15}N$ values ($p = 0.129$). Lipid extracted samples, however, had significantly enriched $\delta^{13}C$ ($p = 0.0001$) compared to non-lipid extracted samples but lipid extraction did not significantly affect $\delta^{15}N$ values ($p = 0.841$; Table 3). There was no interaction between preservation and lipid extraction for $\delta^{13}C$ ($p = 0.236$) or $\delta^{15}N$ ($p = 0.547$).

P*ilot Whales and Potential Prey*
There were significant differences in $\delta^{13}C$ values ($p < 0.0001$) and $\delta^{15}N$ values ($p < 0.0001$) between pilot whales and their potential prey (Figure 7-3). Short-finned pilot whales had the highest $\delta^{13}C$ signatures but a similar $\delta^{15}N$ signature as that of bigeye tuna. *Loligo* had the lowest $\delta^{13}C$ value and a $\delta^{15}N$ value intermediate between the two tuna species. Yellowfin tuna had a slightly more enriched $\delta^{13}C$ value than *Loligo* but the lowest $\delta^{15}N$ value. Bigeye tuna had the most enriched $\delta^{13}C$ signature and the highest $\delta^{15}N$ signature of the three potential prey species (Table 7-4).

Effects of Gender in Pilot Whales
We confirmed the sex of 41 female and 41 male short-finned pilot whales using genetic analysis (P. Rosel, pers. comm.). There was a significant difference in $\delta^{15}N$ values ($p = 0.011$) but not in $\delta^{13}C$ values ($p = 0.137$) between the sexes. Male short-finned pilot whales had significantly higher $\delta^{15}N$ values (12.2 ± 0.8) than female short-finned pilot whales (11.7 ± 0.8).

Effects of Age Class in Pilot Whales
We examined differences in isotopic values among adults, subadults and calves in 26 stranded pilot whales. We assigned age class using the criteria provided in Hohn et al. (2006). We excluded one sample (RT22) because of inconsistencies in the source data concerning length. We found no significant differences in either $\delta^{13}C$ ($p = 0.382$) or $\delta^{15}N$ values ($p = 0.547$) among age classes (Table 5).

Effects of Past Fishery Interactions in Pilot Whales
We also investigated the effect of past fishery interactions on the isotopic signatures of the 27 stranded pilot whales. Ten of these whales (37%) had physical evidence of past fishery interactions, including broken teeth and healed line scars on their mandibles, bodies, or other appendages (Hohn et al. 2006; Figure 7-4). Seventeen animals had no evidence of previous fishery interactions. Pilot whales of all age classes showed evidence of past fishery interactions (Table 7-6). We found no significant differences in either $\delta^{13}C$ ($p = 0.978$) or $\delta^{15}N$ values ($p = 0.513$) between pilot whales with evidence of previous fishery interactions and those with no evidence of past interactions.

Comparisons with Bottlenose Dolphins
There were significant differences in both $\delta^{13}C$ ($p < 0.0001$) and $\delta^{15}N$ (p = 0.0.17) between the offshore bottlenose dolphins and short-finned pilot whales (Figure 7-5). Pilot whales had significantly enriched $\delta^{13}C$ values compared to bottlenose dolphins and significantly higher $\delta^{15}N$ values.

Discussion

The short-finned pilot whales and bigeye tuna we sampled exhibited similar $\delta^{15}N$ values, suggesting that depredation of bigeye tuna (the primary target species of the pelagic longline fishery) is not a widespread behavior in this population. This finding supports reports of the intermittent occurrence of depredation by participants in this fishery (Captain D. Hemilright, pers. comm.). Interestingly, we found no significant differences in $\delta^{15}N$ values between whales with evidence of past fishery interactions and those that did not. These results are similar to those found by Abend and Smith (1997) who compared stable isotope signatures between long-finned pilot whales caught in fishing gear versus stranded animals and found no difference in $\delta^{13}C$ or $\delta^{15}N$ values between the two groups. Cetacean skin has a tissue turnover rate of approximately two to three months (Hicks et al. 1985) and isotopic values reflect diet assimilated during that period. None of the stranded animals we sampled had fresh wounds from fishery interactions, so perhaps it is not surprising that these individuals did not have $\delta^{15}N$ values indicative of recent depredation. Nevertheless, this finding suggests that the occurrence of depredation is intermittent, even amongst individuals that engage in this behavior.

Nevertheless, more than one-third of the stranded animals had evidence of previous interactions with fishing gear, including individuals of all age classes. This suggests that interactions with fishing gear are relatively common and that many animals survive these entanglements and hooking. Of course it is impossible to determine what proportion of entangled and hooked individuals succumb to their injuries. In addition to the pelagic longline fishery, several other fisheries operate in the CHSRA, including a commercial greenstick fishery, a charter fishery and a recreational troll fishery, all targeting tuna. During our research cruises we observed many pilot whale groups in close proximity to these fishing vessels (Figure 7-6) and observed pilot whales trailing monofilament fishing line on several occasions (Figure 7-7).

Male short-finned pilot whales had significantly higher $\delta^{15}N$ values, but similar $\delta^{13}C$ values, when compared to female whales. de Stephanis et al. (2008) found no significant difference in $\delta^{13}C$ or $\delta^{15}N$ values between male and female long-finned pilot whales in the Strait of Gibraltar. Kiszka et al. (2010) found no statistically significant differences between males and female short-finned pilot whale in the central South Pacific, but males had higher $\delta^{13}C$ and $\delta^{15}N$ signatures than females. Our results do not indicate that male and female pilot whales feed at different trophic levels, because the mean difference in $\delta^{15}N$ between males and females was less than 1‰ and the increase in $\delta^{15}N$ between trophic levels is typically 3-4‰. Our findings do, however, indicate that the diets of the two sexes differ. We plan to explore differences in the foraging behavior or male and female whales using data collected with digital acoustic tags (DTags) that record depth, sound and orientation (Johnson and Tyack 2003).

We found no significant differences in isotopic signatures amongst three age classes of stranded pilot whales. This result is somewhat surprising because other studies have found that nursing marine mammals have lower $\delta^{13}C$ and higher $\delta^{15}N$ values than adults (Hobson and Sease 1998; Knoff et al. 2008; Fernández et al. 2011). It is possible that the stranded animals identified as calves were no longer nursing. Lactation was not recorded for any of the stranded whales (Hohn et al. 2006), nor was milk reported in the stomachs of the calves. One calf had no hard parts in its stomach, one had seagrass and the other two had prey parts representative of the diet of mature pilot whales (Mintzer et al. 2008). We acknowledge that our designations of age classes is relatively crude and limited by small sample sizes; a more sophisticated analysis would require age estimates from these individuals, but such estimates are not yet available.

We observed significant differences in isotopic signatures between short-finned pilot whales and bottlenose dolphins in the CHSRA. The pilot whales had significantly enriched $\delta^{13}C$ compared to the bottlenose dolphins. Both species co-occur in the same environment, so this difference may be due to pilot whales foraging deeper in the water column than bottlenose dolphins. $\delta^{13}C$ values increase with depth and proximity to organic matter sources near the sea floor (France 1995; Hobson 1999; Kiszka et al. 2010). Short-finned pilot whales are known to forage at depths exceeding 1000m (Aguilar Soto et al. 2008) and pilot whales we equipped with DTags in this area have foraged at depths up to 1044m (A.J. Read, unpublished data). We do not have dive records for the bottlenose dolphins in our study area, but Corkeron and Martin (2004) tagged two offshore bottlenose dolphins off eastern Australia and found that the dolphins spent two-thirds of their time in water less than 5m deep and dove to a maximum of 155m. If bottlenose dolphins in the CHSRA exhibit similar behavior, differences in foraging depth may explain the higher $\delta^{13}C$ values found in pilot whales.

The pilot whales also had significantly higher $\delta^{15}N$ values than the bottlenose dolphins, but the mean difference in $\delta^{15}N$ was only 0.5‰. Offshore bottlenose dolphins exhibit a relatively catholic diet; prey items include pelagic fish, especially in the family Myctophidae, and cephalopods, including *Ornithoteuthis antillarum*, *Illex* spp., *Histioteuthis* spp. and *Octopus* spp. (Barros and Stolen 2001; Hoelzel et al. 1998). Minzter et al. (2008) examine the stomach contents of the short-finned pilot whales that mass stranded in North Carolina in 2005 and found that the stomachs contained prey remains from nine cephalopod families and one fish species; the largest prey item was a *Taonius pavo* squid with a mantle length of 393mm. Aguilar Soto et al. (2008) suggested that short-finned pilot whales may employ foraging sprints at depth to capture relatively large, high caloric squid prey. The ability of pilot whales to capture prey that are larger and have higher nutritional quality perhaps explains their higher $\delta^{15}N$ signatures relative to offshore bottlenose dolphins.

Unfortunately, we did not have access to any of the cephalopod species found commonly in the stomachs of stranded pilot whales in North Carolina, as none of these species are harvested commercially. Mintzer et al. (2008) found *Loligo* prey remains in the stomachs of stranded whales, but with a relatively low frequency of occurrence, and concluded that *Loligo* does not constitute a substantial portion of the diet of short-finned pilot whales in this area. This is in contrast to the Pacific, where *Loligo* comprise a large portion of the prey items in the stomachs of stranded animals (Sinclair 1992).

Our stable isotope results indicate that neither bigeye nor yellowfin tuna are important components of the diet of short-finned pilot whales. The pilot whales and bigeye tuna were feeding at the same trophic level, as evidenced by their similar $\delta^{15}N$ signatures. Both of these predators had a mean $\delta^{15}N$ value 1.8‰ greater than the yellowfin tuna, likely due to differences in their prey. The bigeye tuna we sampled were substantially larger than yellowfin tuna; the average weight of the bigeye tuna was 33kg compared to 19kg for the yellowfin. This difference in size may result in resource partitioning with the larger bigeye tuna foraging at greater depths and consuming larger prey than the smaller yellowfin (Menard et al. 2007) which, in turn, would be reflected in their isotopic signatures. This hypothesis is supported by observations from other areas; Potier et al. (2004) found that epipelagic fish comprised the majority of fish prey of yellowfin tuna in the Indian Ocean, while mesopelagic fish dominated the diet of bigeye tuna.

Conclusion

The results of our research indicate that preserving short-finned pilot whale skin samples in DMSO for relatively short periods (60 days) did not have an effect on δ13C or δ15N values. These findings are in contrast with other studies that have found effects of DMSO preservation on δ13C and δ15N values in a variety of cetacean species including beluga whales (*Delphinapterus leucas*), harbor porpoise (*Phocoena phocoena*), minke whales (*Balaenoptera acutorostrata*), fin whales (*Balaenoptera physalus*) (Lesage et al. 2010), and humpback whales (*Megaptera novaeangliae*) (Todd et al. 1997). Our finding that lipid extracted samples were enriched in δ13C relative to non-extracted samples is consistent with other research (Post et al. 2007; Lesage et al. 2010). We conclude that the effects of preservation in DMSO are variable and perhaps complex, but recommend extracting lipid from samples used for stable isotope analysis of cetacean tissues.

In conclusion, we found no evidence that tuna are an important component of the diet of short-finned pilot whales in the CHSRA. Nor did we find any indication that individual pilot whales consistently engaged in depredation, even including those with evidence of past fishery interactions. This is despite our success in sampling animals from many different pods, from both sexes and several age classes. The indications of past fishery interactions on many of the stranded pilot whales supports the idea that depredation, perhaps on a variety of commercial and recreational fishing gears, may be a *widespread* behavior throughout this population. However, the lack of any stable isotope signature reflecting recent depredation in any of the whales we sampled leads us to conclude that individual whales engage in this behavior only *infrequently*.

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Waples, D., K. Zelnio, H. Koopman and A. Read. 2011. The effects of DMSO preservation on stable isotope signatures of short-finned pilot whales (*Globicephala macrorhynchus*). Nineteenth Biennial Conference on the Biology of Marine Mammals, Tampa Bay, Florida. Poster Presentation.

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Figure 7-1. Collecting a skin sample from a short-finned pilot whale in the Cape Hatteras Special Research Area using remote biopsy sampling.

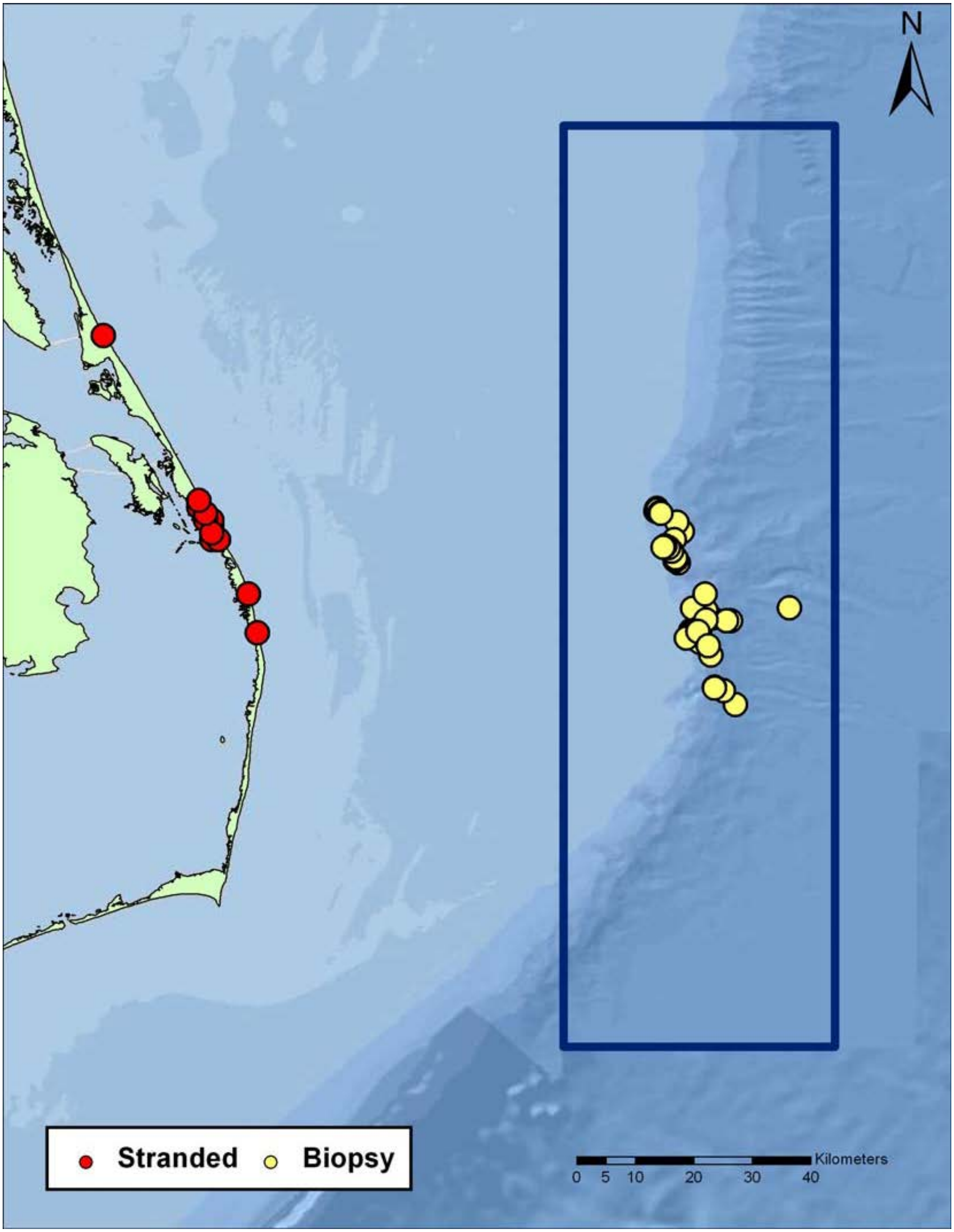

Figure 7-2. Locations of skin samples of short-finned pilot whales. The borders of the Cape Hatteras Special Research Area are outlined in the blue rectangle.

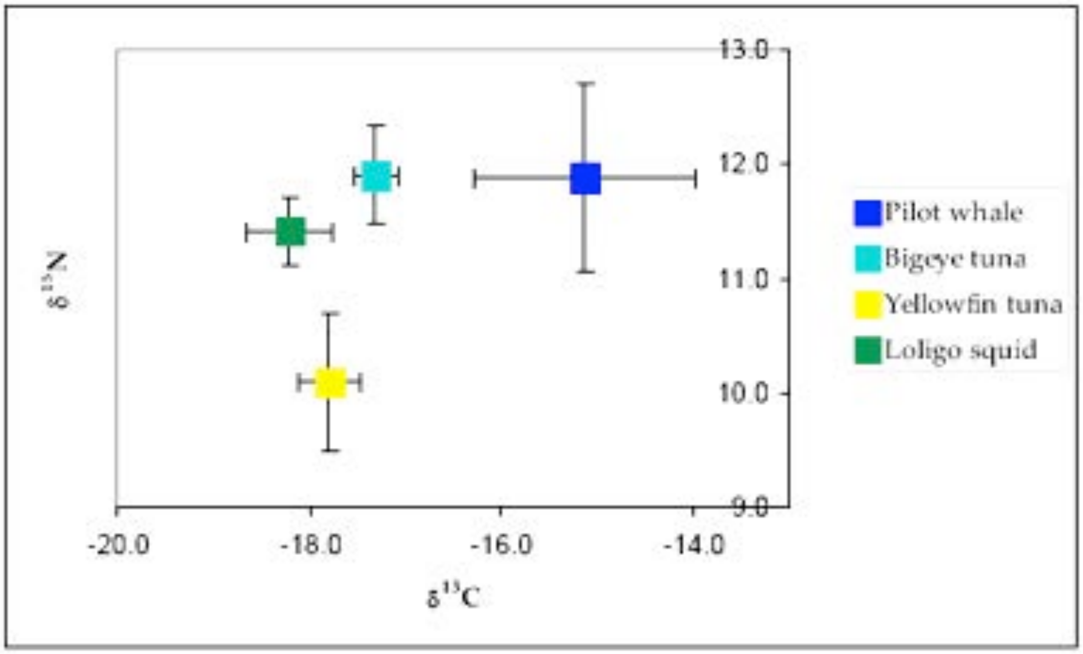

Figure 7-3. Stable isotope ($\delta^{13}C$ and $\delta^{15}N$) mean (± SD) values for short-finned pilot whales (n = 83), bigeye tuna (n = 30), yellowfin tuna (n = 30) and Loligo squid (n = 20). Isotope values are expressed in ‰.

Figure 7-4. Healed scars of past fishery interaction on a short-finned pilot whale stranded on the Outer Banks, NC in January 2005.

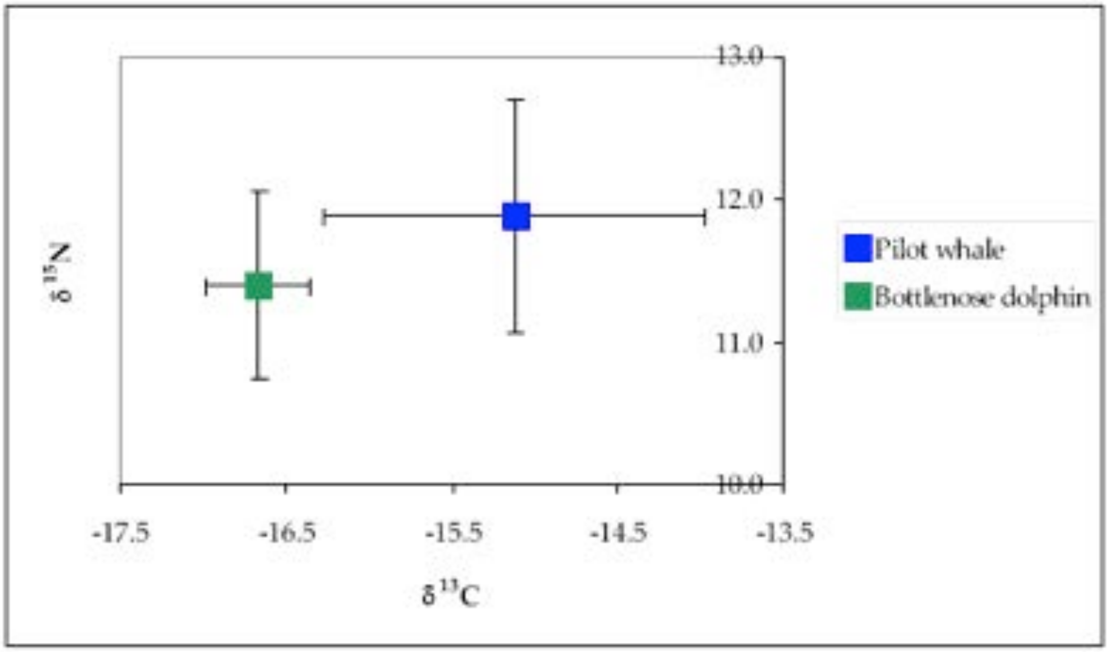

Figure 7-5. Stable isotope ($\delta^{13}C$ and $\delta^{15}N$) mean (± SD) values for short-finned pilot whales (n = 83) and offshore bottlenose dolphins (n = 14). Isotope values are expressed in ‰.


Figure 7-6. Pilot whales in close association with a commercial charter vessel in the Cape Hatteras Special Research Area.

Figure 7-7. Short-finned pilot whale in the Cape Hatteras Special Research Area with monofilament line trailing from its dorsal fin.

Table 7-1. Cetacean stable isotope studies including species studied, sample preservation method and whether lipid extraction was performed on samples.

Authors	Year	Species	Preservation Method	Lipid Extraction
Abend and Smith	1995	Long-finned pilot whale	Not reported	No
Abend and Smith	1997	Long-finned pilot whale	Frozen	No
Todd et al.	1997	Humpback whale	DMSO or frozen	Yes
Das et al.	2000	Striped dolphin, common dolphin	Frozen	Yes
Ruiz-Cooley et al.	2004	Sperm whale	DMSO	Yes
Lusseau and Wing	2006	Bottlenose dolphin	Frozen	No
Marcoux et al.	2007	Sperm whale	DMSO	Yes
de Stephanis et al.	2008	Long-fined pilot whale	Frozen	Yes
Witteveen et al.	2009	Humpback whale	DMSO or ethanol or frozen	Yes
Kiszka et al.	2010	Spinner dolphin, rough-toothed dolphin, short-finned pilot whale, melon-headed whale	Ethanol then frozen	Yes
Ohizumi and Miyazaki	2010	Dall's porpoise	Frozen	No
Fernández et al.	2011	Bottlenose dolphin	Frozen	Yes

Table 7-2. Sample source and preservation method for all pilot whale skin samples used in this research.

Date	Source	Number of samples	Preservation
January 2005	Stranding	24	Frozen
May 2005	Stranding	1	Frozen
September 2006	CHSRA research cruise	6	DMSO
May 2007	CHSRA research cruise	27	DMSO
August 2007	CHSRA research cruise	16	DMSO
May 2008	CHSRA research cruise	11	Frozen and DMSO
July 2008	Stranding	1	Frozen
February 2010	Stranding	1	Frozen
July 2010	CHSRA research cruise	6	Frozen
September 2010	CHSRA research cruise	1	Frozen
Total		**94**	

Table 7-3. Mean (± SD) stable isotope values for the four treatments in the matched sample experiment examining effects of preservation method and lipid extraction on stable isotope values. Isotope values are expressed in ‰.

Treatment	$\delta^{13}C$	$\delta^{15}N$
DMSO not lipid extracted	-17.1 ± 0.7	12.4 ± 0.5
Frozen not lipid extracted	-16.6 ± 0.5	12.3 ± 0.5
DMSO lipid extracted	-16.6 ± 0.9	12.5 ± 0.4
Frozen lipid extracted	-15.9 ± 1.0	12.1 ± 0.3

Table 7-4. Mean (± SD) stable isotope values for short-finned pilot whales and their potential prey. Isotope values are expressed in ‰.

Species	Number of animals	Mean $\delta^{13}C$ (± SD)	Mean $\delta^{15}N$ (± SD)
Short-finned pilot whale	83	-15.1 ± 1.1	11.9 ± 0.8
Bigeye tuna	30	-17.3 ± 0.2	11.9 ± 0.4
Yellowfin tuna	30	-17.8 ± 0.3	10.1 ± 0.6
Loligo squid	20	-18.2 ± 0.4	11.4 ± 0.3

Table 7-5. Mean $\delta^{13}C$ and $\delta^{15}N$ values for 26 stranded short-finned pilot whales classified by age class. Isotopic values are expressed in ‰.

Age class	Number of animals	Mean $\delta^{13}C$ (± SD)	Mean $\delta^{15}N$ (± SD)
Adult	16	-15.7 ± 1.0	11.3 ± 1.0
Subadult	6	-16.3 ± 0.5	11.7 ± 1.2
Calf	4	-15.4 ± 1.0	11.3 ± 0.6

Table 7-6. Age class and fishery interaction status for the 27 stranded short-finned pilot whales.

Age class	Number of animals	Number with fishery interactions	Percent with fishery interactions
Adult	17	7	41
Subadult	6	2	33
Calf	4	1	25
Total	**27**	**10**	**37**

Project 8 – Testing "Whale-safe" Hooks in the Cape Hatteras Special Research Area (Nova Southeastern University)

Project Goal and Objectives

Preliminary work in 2007 and 2008 (Bayse and Kerstetter 2010) suggested that fishing hooks designed to straighten when hooked on a pilot whale might be a feasible means for reducing fisheries interactions. The goal of this project was to determine whether a whale-safe circle hook could be used as a gear modification to reduce pilot whale bycatch while retaining target catch. A field trial was carried out to compare target and non-target catches by longline fishermen operating in the Cape Hatteras Special Research Area using standard circle hooks and a "whale-safe" hook produced under this project.

Project 8 Final Report

Evaluation of Variable Strength Hooks to Reduce Serious Injury Pilot Whale Interactions with the North Carolina-Based Pelagic Longline Fishery

Dave Kerstetter
Nova Southeastern University

Abstract

The number of interactions between shortfin and longfin pilot whales *Globicephala melaena* and *G. macrorhynchus* (hereafter collectively "pilot whales") with commercial pelagic longline fishing gear has apparently increased in recent years, especially around the southern portion of the Mid-Atlantic Bight (MAB) statistical area off North Carolina's Outer Banks that was designated as the "Special Research Area" in 2006 by the Atlantic Pelagic Longline Take Reduction Team. This southern MAB area is also the primary fishing grounds for a local pelagic longline fleet operating throughout the year out of Wanchese, North Carolina, as well as seasonal fishing effort from the rest of the U.S. Atlantic fleet. If the current rates of pilot whale interactions continue, the entire U.S. Atlantic pelagic longline fishery may face more restrictive regulatory measures in these traditionally productive fishing grounds, resulting in serious economic cost to the industry. Preliminary work in 2007 and 2008 (Bayse and Kerstetter 2010) suggested that fishing hooks designed to straighten when hooked on a pilot whale might be a feasible means for reducing fisheries interactions. During 2010 and 2011, eight trips were taken aboard cooperating pelagic longline fishing vessels in the North Carolina-South Carolina offshore areas of high historical rates of interactions with pilot whales, testing two weaker (thinner wire gauge) versions of the industry-standard size 16/0 and 18/0 circle hooks. No significant reduction of target catch, target catch weight, or bycatch was observed during these trials. However, the recent imposition of a weak hook regulation in the Gulf of Mexico by the NOAA Fisheries Service for bluefin tuna bycatch reduction has resulted in an unwillingness of the local fleet to continue even limited field trials, based on the premise that similar regulations would be imposed upon the North Carolina-South Carolina offshore yellowfin tuna/swordfish pelagic longline fishery.

Introduction

The U.S. pelagic longline fishery in the western Atlantic Ocean has historically had a high frequency of bycatch interactions with istiophorid billfish, marine turtles, sharks, and some marine mammals (Yeung 1999; Baum et al. 2003; Cramer 2003; ICCAT 2006). Several approaches have been used to reduce the frequency of bycatch and bycatch mortality in this fishery, including time/area closures, a mandatory switch in terminal gear from J-style hooks to circle hooks, minimum gangion line lengths relative to buoy line lengths, and federal safe handling and release training requirements (Watson et al. 2005). Within the National Marine Fisheries Service (NMFS or NOAA Fisheries Service) statistical area of the western

Atlantic Ocean known as the "Mid-Atlantic Bight" (MAB[1])[9]there is concern about apparently increasing interaction rates between the pelagic longline fishery and pilot whales.

In the western Atlantic, there are two species of pilot whales: long-finned pilot whales (*Globicephala melas*) and short-finned pilot whales (*G. macrorhynchus*). Both of these species are known to interact with pelagic longline gear, but their physical characteristics are very similar, making them difficult to distinguish while in the water from both boat-side perspectives and aerial surveys. Both species also have wide geographic ranges, and their populations are believed to overlap within the MAB statistical area between 35° and 39° North latitude (Payne and Heinemann 1993; Bernard and Reilly 1999).

Pilot whales primarily interact with pelagic longline gear from their depredation of caught animals and are often seen feeding on hooked fish, especially bigeye tuna (NMFS, unpubl. data; D. Kerstetter, pers. obs.). Tuna and swordfish are not a regular part of the pilot whale diet, however, which primarily consists of deep-water squid (Gannon et al. 1997a, b; Mintzer et al. 2008), and such depredation appears to be a learned behavior (DAPLTRT 2006). Pilot whales also occasionally become entangled in the mainline (Garrison 2003, 2005), with anecdotal reports of individuals "scratching" themselves on the mainline to remove ectoparasites (Captain G. O'Neill, F/V *Carol Ann* and Captain A. Mercier, F/V *Kristen Lee*, pers. comms.).

Between 1992 and 2005, there were 113 reported pilot whale interactions in the western North Atlantic U.S. pelagic longline fishery (including the Gulf of Mexico), including 61 determined as serious injuries and four observed dead (Johnson et al. 1999; Yeung 2001; Garrison 2003, 2005; Garrison and Richards 2004; Fairfield-Walsh and Garrison 2006). "Serious injury" is defined as an injury sustained by a marine mammal that will likely result in death, one definition in a set of distinct injury definitions regarding interactions with fisheries gear that was developed by a NOAA Fisheries team of veterinarians and marine mammal scientists. Injuries to individual marine mammals are determined to fall within a particular definition based upon fishery observer data and focus on whether the animal was internally hooked (or hooked in a non-visible location), how much fishing gear was still attached to the animal at release, any other apparent injuries, and the manner in which the animal swam away from the vessel (Angliss and DeMaster 1998). Of the 61 serious injuries, five were mouth hooked, 20 released with entangled gear, and 36 a combination of the two (DAPLTRT 2006). More specifically, there were 46 observed interactions with pilot whales from 2001 to 2005, of which 43 occurred within the MAB (DAPLTRT 2006). There were an estimated (i.e., extrapolated) 86 serious injuries to pilot whales from 2001 to 2005 (Waring et al. 2007). The serious injury estimates for pilot whales are extrapolated for management purposes and considered at a five year average to minimize the effect of a single "bad" year (Barlow et al. 1995). The number of serious injuries is below the potential biological removal (PBR), determined for the western Atlantic Ocean to be 249 (Wade and Angliss 1997). The status of the western Atlantic stock is unknown, but the PBR is above the insignificance threshold of 10% and therefore required a formal take reduction plan for the U.S. Atlantic pelagic longline fishery under the Marine Mammal Protection Act (MMPA; Waring et al. 2007). The Atlantic Pelagic Longline Take Reduction Team for Pilot Whales met for the first time in 2005, and the team quickly added Risso's dolphin (*Grampus griseus*) due to the frequency of occurrence along with pilot whales in the fishery. Since finalizing the Take Reduction Plan in 2007, the team continues to receive updates on incidental takes from NOAA on a quarterly basis, with in-person meetings approximately every two years.

[1] Regional and area names signify National Marine Fisheries Service (NMFS or NOAA Fisheries Service) pelagic fishery statistical area boundaries and do not necessarily relate to distinct geographical areas (Richards 1999).

The majority of the current U.S. Atlantic fishery uses one of two types of hooks: the forged "strong" hook, which is oval in cross-section, and the bent-wire "weak" hook, which is made of bending a cylinder of metal and thus circular in cross section. The forged "strong" hook straightens out at a higher pull force than the bent-wire "weak" hook. Pilot whales' weight commonly exceeds 227 kg, and can reach 1300 kg as adults, whereas yellowfin and bigeye tuna are rarely caught above 90 kg (Collette and Nauen 1983; Nakamura 1985; Wynne and Schwartz 1999; Jefferson et al. 2008). Although swordfish can achieve a maximum size of over 450 kg/995 lb, swordfish of that large size are extremely rare in the U.S. fishery; the majority are much smaller, with a pelagic observer-measured average whole weight in 1997 being only 15.4 kg (Cramer and Adams 1999; this minimum size has since increased). Weak hooks would presumably straighten when attached to a large animal such as a pilot whale; this straightening effect could allow the animal to escape more quickly, both reducing the amount of time hooked and decreasing the potential of entanglement in the leader monofilament, which is relatively stronger than the bending strain of the hook (181 kg/400 lb test strength)

In particular, the MAB statistical area – ranging from around Cape Hattaras, North Carolina to a line near Rhode Island – is primarily a mixed yellowfin tuna/swordfish fishery. It is fished throughout the year by a local fleet of small pelagic longline and greenstick[10] gear vessels based out of Wanchese, North Carolina, as well as seasonally by many other larger vessels in the U.S. Atlantic pelagic longline fleet. Anecdotal reports suggest that when the bent-wire hooks were tried in this local fishery, a number of them were retrieved straightened, and despite not knowing what animal had straightened them, fishermen became so concerned about losing potential catch that the fleet went all to the forged "strong" hook (Captain D. Hemilright, F/V *Tar Baby*, pers. comm.). Through a combination of several factors, including this potential loss of target catch, the fishery now primarily uses strong hooks.

Terminal gear changes are not new in the U.S. Atlantic pelagic longline fishery. Research has consistently shown that the change from J-style hooks to circle hooks has shown to decrease bycatch interactions and mortality in pelagic longline fisheries while not significantly changing the catch rate of most target species (Hoey 1996; Falterman and Graves 2002; Watson et al. 2005; Kerstetter and Graves 2006). Despite some ambiguity regarding swordfish catch rates, NOAA Fisheries made the change to circle hooks mandatory for the U.S. pelagic longline fishery in 2004. More specifically for pilot whale interaction research, the fishery is now familiar with hook comparison research and research protocols. Given the difference in hook strength between the forged "strong" and bent-wire "weak" hook types, a terminal gear change could take advantage of the size disparity between pilot whales and target species by using a weaker strength hook that retains the target fish species, yet releases the much larger pilot whales by straightening the hook. Evidence of little or no change in catches could support a precautionary change within the MAB fishery to weaker hooks, thereby decreasing the number of observed interactions involving pilot whales.

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[10] "Greenstick" gear involves the use of a large, carbon-fiber or fiberglass pole (colored green by the original Japanese manufacturer, hence the name) that mounts to the top of the wheelhouse and drags a 25-pound "bird" approximately 300 yards behind the vessel. From this line is a number of drop lines, which each dangle bait at the water surface. It was first used in the United States by the Hawaiian troll fishery. The gear is anecdotally very effective at targeting yellowfin tuna, although catch rates – including bycatch rates – in the U.S. Atlantic fisheries that use it are poorly known. (An on-going study by NOAA Fisheries is working to quantify these catch rates, but these data are not yet available.) Many of the small pelagic longline vessels in the Wanchese-based fleet also use greenstick gear during transits to and from the pelagic longline fishing grounds to maximize ex-vessel revenue, although none of the three vessels during this project did so.

The only published study to date examining the use of weaker hooks for marine mammal interaction reduction is a pilot study by Bayse and Kerstetter (2010).[11] This research conducted 21 pelagic longline sets targeting yellowfin tuna and bigeye tuna in the MAB using alternating forged "strong" and bent-wire "weak" size 16/0 hooks. Nine additional research sets targeting swordfish in the South Atlantic Bight (SAB) NOAA Fisheries statistical area with size 18/0 hooks were also conducted the same alternating hook methodology. Results for the tuna targeting sets showed no significant reduction in total catch ($\alpha < 0.05$) of any target species, although weak hooks exhibited higher catch per unit effort (CPUE) for both tuna and swordfish. The only species to show a significant difference in total catch between "strong" and "weak" 16/0 hooks was the pelagic stingray, with more individuals caught by the "strong" hook. The size 18/0 hook sets had similar catches for all species except the target species swordfish. Swordfish CPUE was non-significantly higher for the "strong" hook, while also having significantly higher total catches. Seven weak hooks were retrieved straightened over the course of all 30 sets, and one of these hooks was observed being straightened by a pilot whale at boatside during the haulback of the gear. While not conclusive, such results do strongly suggest further research into weak hooks for the reduction of marine animal bycatch in the pelagic longline fishery.

The use of weak hook technology for reducing the bycatch of large fishes (e.g., bluefin tuna *T. thynnus*) has long been discussed, and an on-going project by NOAA Fisheries in the northern Gulf of Mexico is examining this very idea. However, the potential reduction of other marine bycatch species has not been thoroughly examined other than the Bayse and Kerstetter (2010) pilot study. This study in the MAB region further compared the catch rates of target and non-target species caught with two different models of strong and weak circle hooks in the North Carolina-based Atlantic pelagic longline fishery to further assess the utility of these hooks for reducing the interaction rate with pilot whales.

Research Goals and Objectives

Goal 1: To identify a means by which the North Carolina-based pelagic longline fleet can continue to operate in its traditional fishing grounds by using a different type of terminal gear (i.e., hook model) that will reduce interactions with pilot whales.

The primary objective of this work was to identify a means by which the U.S. Atlantic pelagic longline fleet (including North Carolina vessels) can continue to fish in its traditional grounds by using a different type of gear that will reduce interactions with pilot whales. This project proposes to further assess the utility of so-called "weak" hooks to bend and thus release from contact with large marine mammals. This would therefore reduce the number of interactions classified as "serious injuries" between pilot whales and commercial pelagic longline fishing gear, particularly in the southern portion of the MAB statistical area where such interactions are an important management concern. The work by Bayse and Kerstetter (2010) supports the previous anecdotal hypothesis that weak hooks may straighten and release large animals over 300 pounds, such as pilot whales and other large marine mammals.

[11] A research project funded jointly by the NOAA Fisheries Service and the New England Aquarium Consortium for Wildlife Bycatch Reduction examined similar weak versus control hooks in the Honolulu-based pelagic longline fishery targeting bigeye tuna in the fall of 2010. This work was subsequently presented at the International Circle Hook Symposium in Miami, Florida in May 2011 and was published in the Bulletin of Marine Science in 2012: Bigelow, K.A., D.W. Kerstetter, M.G. Dancho, and J.A. Marchetti. Catch rates with variable strength circle hooks and the potential to reduce false killer whale injury in the Hawaii-based tuna longline fleet.

Goal 2: To quantify any differences in catch rates between the experimental hook models for the target fishes in this commercial fishery, primarily swordfish and yellowfin tuna, but also the high-value bigeye tuna. Such quantified comparisons will also include non-target (bycatch) species of special recreational or ecological concern.

A secondary goal of this project is to quantify any differences in catch rates for the target fishes in this commercial fishery, primarily swordfish and yellowfin tuna, but also the high-value bigeye tuna. If catch rates for the target fishes show no difference between these two hook types, then the weak hooks may be suggested to management for consideration as an interaction rate reduction method in simply a precautionary manner within the southern MAB area, as such a move would therefore likely have minimal economic effect to the impacted fishery. More importantly, the quantification of these catch rates is important for assessing the impact of proposed management action, as opposed to relying on anecdotal data or extrapolation from other, non-experimentally tested hook models.

Along with this quantification for target species, these same weak hooks may also show catch rate differences for large bycatch species with recreational fishery importance, such as blue marlin *Makaira nigricans*. They may also show differences in catch rates for species with depleted population levels or other ecological importance, including sea turtles. While pilot work by Bayse and Kerstetter (2010) did not find any significant differences in catch rates, that work was hampered by relatively low sample sizes and limited temporal replication. This proposed hook work may therefore show differences in catch rates not apparent in the Bayse and Kerstetter (2010) prior research.

Goal 3: To evaluate the effectiveness of the NOAA Fisheries Service-approved dehooking and disentanglement protocols for pilot whales, as well as document the rates and types of depredation on commercial pelagic longline catches.

Finally, the research was intended to qualitatively evaluate the effectiveness of the NOAA Fisheries Service-approved dehooking and disentanglement protocols for pilot whales. All of the captains to be involved with this research were certified on current dehooking and disentanglement protocols and equipment, and yet the current limited exposure with fisheries observers may have prevented the transmission of some insight or improvement in current procedures. As part of current POP protocols, this research also intended to document the rates and types of depredation on commercial pelagic longline catches within this area of special concern for pilot whale interactions.

Materials and Methods

This study alternated weak hooks (hooks that straighten at *ca.* 200 pounds pull strength) and the status quo "strong" hooks (*ca.* 350 pounds test strength) along the length of the mainline set, similar to the pelagic longline research described in Watson et al. (2005) and Kerstetter and Graves (2006). In comparison with those projects, which gauged fishing efficiency between hook types, the objective of this proposed work was to evaluate the number of pilot whales still attached to the gear at haulback, the standard of whether an interaction is included in the NOAA Protected Resource Division quarterly and annual accounting.[12]

[12] If a pilot whale is hooked during the "soaking" of the gear, but then subsequently straightens the hook and is not present on the gear at haulback, there is technically no documented interaction.

Hook Types
This work tested two different models of "weak" hooks, both manufactured by O. Mustad & Son A.S. (Gjövik, Norway): 1) the experimental size 16/0 Mustad 39988D (the same hook being tested in the Gulf of Mexico for reduction in bluefin bycatch), which straightens out at ~100 lb/45 kg (C. Bergman, NOAA Fisheries, unpubl. data) and 2) the stock size 18/0 Mustad 39960, which straightens out at ~225 lb/102 kg (Bayse and Kerstetter, 2010).[13] The "strong" hook model in both cases was the same size hook (i.e., 16/0 "weak" to 16/0 "strong") forged model LPCIRBL from Lindgren-Pitman, Inc. (Pompano Beach, FL), which has shown itself through the fishery as almost impervious to straightening, even during times that it hooks marine mammals and manta rays *Manta* spp. Technically, the size 16/0 hook straightens ~250 lb/113 kg, while the size 18/0 hook straightens ~350 lb/159 kg (Bayse and Kerstetter, 2010). Both O. Mustad & Son A.S. and Lindgren-Pitman, Inc. hook types are commonly used in the U.S. Atlantic fishery, although the LPCIRBL model is much more frequent within the North Carolina fleet.

Data Collection
Hooks were alternated "strong-weak-strong-weak-strong" for each five-hook "basket" (hooks between floats), with the next basket alternated "weak-strong-weak-strong-weak"; this deployment method guarantees equal hook placement across all positions within the basket (see Kerstetter and Graves 2006). All other gear configurations remained consistent with regulations for the U.S. Atlantic pelagic longline fishery (e.g., leader lengths must be ≥ 100% of buoy floatline length; NMFS 2006). Hook spacing was relatively uniform within each set, and the choices of gangion and buoy line lengths and set locations were typical of the fishery. A mixture of squid (*Illex* spp.) and Atlantic mackerel (*Scomber scombrus*) bait was used during all experimental sets. All vessels had NOAA-required live-release equipment, and the captains and crews were certified on the techniques used to release bycatch species with minimal injury.

Two graduate students were trained as fisheries observers by the NOAA Fisheries Pelagic Observer Program (POP). The observers used standard POP data sheets to record data on all caught animals, including: identification to species, measured length, hook type, location of the hook on the organism, and disposition (alive or dead) at gear retrieval. Fish that did not move while hooked in the water or on deck were conservatively considered "dead" (per Falterman and Graves 2002 and Kerstetter and Graves 2006). Hooking location was recorded per POP protocol and collated into three categories for analysis: mouth hooked, foul hooked, or gut hooked. Also as per POP protocol, the lengths of large bycatch species was estimated, as was the lengths of target species that were damaged from sharks, marine mammals, or other causes (e.g., squid). Dressed weights were recorded for headed-and-gutted fish, but only for species that were weighed individually for sale (only tunas and swordfish).

The completed POP forms and data were shared with the POP in accordance with prior fisheries research, although all confidentiality protocols regarding these data remain in effect regarding preventing public disclosure of identifiable information. These data went through normal POP QA/QC procedures to ensure the accurate documentation of all catches and associated vessel data. In additional to the biological data on all caught fishes, all marine mammal and sea turtle interactions were to be documented with both photographs and standard POP reporting forms for later confirmation of

[13] The project also intended to test an experimental size 18/0 Mustad 39960 model made with the 5.0 mm wire rather than the standard 5.2 mm wire, which should straighten out at a lesser force than the stock 18/0 size hook at between ~150-200 lb/68-91 kg (J. Pierce, O. Mustad & Son A.S. (USA), pers. comm.). However, the minimum size order of 10,000 hooks and at least a six-month lead time for such a custom order precluded the inclusion of this hook model.

species identification and injury location, if applicable. Fisheries observers and captains also engaged in qualitative evaluations of the effectiveness of dehooking and disentanglement equipment and techniques.

Data Analyses
Data analyses were conducted similarly to Bayse and Kerstetter (2010) and Kerstetter and Graves (2006) using paired (i.e., by set) comparisons of Catch-Per-Unit-Effort (CPUE) values, which are generally expressed in the pelagic longline fishery as unit catch per 1000 deployed hooks. T-tests were used to compare between hook types for individual fish lengths and dressed weights. All statistical significance was assessed at the $\alpha < 0.05$ level. All of these methods have been used in previous peer-reviewed literature on similar paired gear comparison research (e.g., Kerstetter and Graves 2006 and Bayse and Kerstetter 2010). All statistical analyses were conducted using SAS (v.9.1; Cary, NC).

Vessels
The vessels participating in this project were subject to a lengthy set of requirements (detailed in Appendix I of the original proposal; not included here) that was similar to other cooperative pelagic longline research, including standardized gear configurations and practices that are in accordance with those operating parameters of the fleet in this geographic area. The vessels were also required to have scientific personnel (i.e., student observers) aboard during each set to record data on POP-standard forms, as well as agree to collect biological samples when possible. Regardless of home port locations, any participating captains and vessels had all traditionally fished in the study area on at least a seasonal basis.

Results

Trip Details
Eight trips were conducted, six in 2010 and two in 2011 (Tables 8-1A and 8-1B) testing both size 16/0 and 18/0 hooks aboard a total of three vessels. The gear summary details for the trips based on hook size are found in Tables 2A and 2B. A total of 747 fishes were caught by the gear, although primarily yellowfin tuna and swordfish – both target species in this fishery.

Catch rates and characteristics
The catch rates (as catch-per-unit-effort or CPUE; expressed as catch per 1000 hooks) are listed in Tables 8-3A and 8-3B. The CPUEs for the target species – yellowfin tuna for size 16/0 hooks and swordfish for size 18/0 hooks – are the highest among the catches (see Figures 8-1A and 8-1B for size 16/0 hooks and Figure 8-2 for size 18/0 hooks). For the size 16/0 hooks, no significant differences in CPUEs were seen for “All swordfish” ($p>0.21$), “All yellowfin tuna” ($p>0.70$), “Retained tunas” ($p>0.87$), or “Retained swordfish” ($p>0.67$). For the size 18/0 hooks, there was no significant difference in CPUE for swordfish ($p>0.38$). Figures 8-3A and 8-3B detail the length and weight comparisons between the “weak” and “strong” hook types for size 16/0 hooks, although there were no significant differences between the hook types in either comparison.

Hook deformation
Of all the 747 fishes caught, only five hooks came to the vessel with visible deformation and all were size 16/0 (see Table 8-4 and Figure 8-4); no deformed 18/0 hooks were seen in this study.

Discussion

Catch and Catch Composition
The catch rates and catch composition were as expected for this fishery and these target species. Although higher numbers of individuals would have increased the statistical power of the results, the statistical analyses suggest that even an increase in power would have resulted in very similar findings.

Research Goals and Objectives

Goal 1: To identify a means by which the North Carolina-based pelagic longline fleet can continue to operate in its traditional fishing grounds by using a different type of terminal gear (i.e., hook model) that will reduce interactions with pilot whales.

Although these research sets did not catch any pilot whales, these results continue to suggest that so-called "whale safe" hooks may have utility for reducing pilot whale bycatch in this fishery. However, as detailed below, it is unlikely that the fleet operating off North Carolina will adopt these weaker hooks voluntarily.

Goal 2: To quantify any differences in catch rates between the experimental hook models for the target fishes in this commercial fishery, primarily swordfish and yellowfin tuna, but also the high-value bigeye tuna.

The low catch rates of bigeye tuna precluded meaningful statistical analyses, but the results for swordfish and yellowfin tuna in the size 16/0 hooks, and swordfish in the size 18/0 hooks, suggest no difference in catch rates or other characteristics (i.e., weight and length) between the weak and strong hooks.

Goal 3: To evaluate the effectiveness of the NOAA Fisheries Service-approved dehooking and disentanglement protocols for pilot whales, as well as document the rates and types of depredation on commercial pelagic longline catches.

Although pilot whales were observed around the vessels during some of the trips, none were hooked by the gear, so this goal could not be addressed.

Practical Aspects of Research Proposal
The planned research protocols generally worked as expected. The only substantial problem encountered during this project regarded fishing effort, which was at the sole discretion of vessels within the North Carolina permanent or seasonal fleet. As described during prior reporting periods, there was simply no compensation available under this research project budget to convince vessel captains to take an observer and test this alternative terminal gear if it was likely that pilot whales would be caught and observed (even though such interactions would not be included on later catch extrapolations by the NOAA Fisheries Service). We ended up trying all sorts of alternative arrangements to induce participation in the project, including adding observer per diem and the occasional purchase of small amounts of gear (e.g., a 50# spool of monofilament mainline), some of which worked, but never consistently enough to provide a rationale for continuation. The other factor that hindered fishing efforts was the unusually active storm season during 2011 (see Table 8-5), which particularly affected the small-vessel fleet out of Wanchese, North Carolina. Much more recently (and ironically), the fleet

has been encountering very high interaction rates with pilot whales in their traditional fishing grounds, forcing many vessels to participate in other fisheries (e.g., bottom longline for tilefish).

Submission of Final Data

Finally, all data associated with the project are currently being compiled into an electronic format for submission as an accompanying data CD with a hard-copy version of the final report to the Consortium. This compilation will include: a) preliminary and final versions of the field datasheets, and b) scanned (.pdf-format file) deck-level datasheets from each completed fishing night. If there are any other raw data your office would request from this project, please let us know as soon as possible.

Impacts and Benefits

This work likely was hampered by the similar research on weaker-strength hooks being conducted by the NOAA Fisheries Service Pascagoula Laboratory in the northern Gulf of Mexico pelagic longline fishery for yellowfin tuna; early word got out to the U.S. Atlantic fleet that catches of larger fish were less, and several captains indicated that they were unwilling to participate in a project where they absolutely believed they would catch less fish in North Carolina as well. Additionally, several captains wished to avoid being the ones who participated in the research that resulted in management regulations decreasing the catch of the whole fleet (especially in a close-knit community like Wanchese). The impact of the results in this project will be presented at the upcoming fall conference call meeting of the Atlantic Pelagic Longline Take Reduction Team ("Team"), although it is unclear what the Team – especially the environmental NGOs and the NOAA Fisheries Service representatives – will do regarding the apparent unwillingness of the fishery to participate in funded collaborative research like this program.

Extension of Results

The North Atlantic swordfish and yellowfin tuna stocks remain very important sources of revenue for the U.S. domestic pelagic fishery, despite the pelagic longline gear type being currently excluded from several of the historically productive fishing grounds in the Florida Straits for this species as well as the gear restrictions currently in place off the North Carolina coast in the Special Research Area. The extension of the results will likely be minimal, however, given the current antagonism within the U.S. Atlantic pelagic longline fleet regarding the mandatory use via NOAA Fisheries Service regulations of weaker-strength circle hooks for the reduction of pilot whale bycatch.

The final analyses of the project data, particularly regarding the behavior of the gear during the fishing period, are still ongoing and those results may be used within other collaborative work on gear behavior and pilot whale interactions within the North Carolina-based pelagic longline fishery and researchers at Duke University. We expect these results to be converted into a scientific manuscript for submission to a peer-reviewed journal within the next 12 months.

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Tables 8-1A and 8-1B. Trip summary details for eight pelagic longline "whale safe" gear research sets with size 16/0 (Table 2A, above) and 18/0 (Table 2B, below) circle hooks within the North Carolina-based fishery.

2010

Trip #	Type of Experimental Hook Used	# of Experimental Hooks Depeloyed	Start Date of Trip	Number of Sets	Vessel	Port of Departure
N06003	16/0	270	9/10/10	1	F/V Sea Bound	Cape Hatteras, NC
N06004	16/0	327	9/13/10	1	F/V Sea Bound	Cape Hatteras, NC
N06005	16/0	1050	9/23/10	3	F/V Jamie B	Wanchese, NC
N06006	16/0	1311	10/7/10	4	F/V Jamie B	Wanchese, NC
N06007	16/0	845	10/17/10	3	F/V Jamie B	Wanchese, NC
N06008	16/0	975	10/22/10	3	F/V Jamie B	Wanchese, NC

2011

Trip #	Type of Experimental Hook Used	# of Experimental Hooks Depeloyed	Start Date of Trip	Number of Sets	Vessel	Port of Departure
N06009	16/0	2355	8/17/11	8	F/V Jamie B	Wanchese, NC
Z06003	18/0	2767	4/15/11	7	F/V Shady Lady	Cherry Point, SC

Tables 8-2A and 8-2B. Gear summary details for pelagic longline "whale safe" gear research sets with size 16/0 (Table 2A, above) and 18/0 (Table 2B, below) circle hooks within the North Carolina-based fishery.

Gear Summary for Trips using 16/0		**+/- stddev**
Total Set Weak Hooks (Q hook)	7133	-
Total # of Trips	7	-
Total # of Sets	23	-
# of Individuals Caught	414	-
Total # of Straightened Hooks	19	-
Straightened Hooks with Unknown Catch	14	-
Straightened Hooks with Kept Catch	5	-
Straightened hook rate per 1000 hooks	0.27%	-
Straightened hook rate without catch	0.20%	-
Bait	100% Illex	-
Average Set Duration	1.94	0.34
Average Haul Duration	4.53	0.58
Hooks per set	620	101
Hooks between floats	5	-
Weighted Average of Gangion+Leader Length(ft)	40.08	5.713142743
Weighted Average of Dropline length(ft)	43.62	2.89

Gear Summary for Trips using 18/0		**+/- stddev**
Total Set Weak Hooks (Q hook)	2767	-
Total # of Trips	1	-
Total # of Sets	7	-
# of Individuals Caught	113	-
Total # of Straightened Hooks	0	-
Straightened Hooks with Unknown Catch	0	-
Straightened Hooks with Kept Catch	0	-
Straightened hook rate per 1000 hooks	0	-
Straightened hook rate without catch	0	-
Bait	45% Illex, 55% Mackerel	
Average Set Duration	4.1	0.21
Average Haul Duration	7.4	1.84
Hooks per set	790	19.11
Hooks between floats	5	-
Floatline (m)	30	-
Branchline (m)	34	-

Tables 8-3A and 8-3B. Analyses of catch-per-unit-effort (CPUE; catch per 1000 hooks) for pelagic longline "whale safe" gear research sets within the North Carolina-based fishery. Table 3A (top) shows CPUE for size 16/0 hooks. Table 3B (bottom) shows CPUE for size 18/0 hooks.

16/0 Weak Hook		
Species	**Weak Hook**	**Strong Hook**
Yellowfin Tuna	18.6	17.4
Blackfin Tuna	6.3	5.3
Swordfish	5.9	3.6
Bigeye Tuna	0.7	1.1
Albacore	1.1	0.8
Unknown thunnid	1.4	0.8
Scalloped Hammerhead	1.8	2.4
Pelagic Stingray	1.7	1.3
Unidentified Shark	1.7	1.3
Little Tunny	1.4	1.0
Blue Shark	1.4	0.7
Silky Shark	1.0	0.7
Billfish	1.1	0.6

18/0 Weak Hook		
Species	**Weak CPUE**	**Strong CPUE**
Swordfish	6.87	8.67
Blueshark	2.89	1.81
Dolphin	1.81	2.17
White Marlin/Spearfish	2.17	2.17

Table 8-4. Changes in hook structure with catch. Experimental hooks were size 16/0 circle hooks in the North Carolina-based pelagic longline fishery; no deformed size 18/0 hooks were found during experimental work.

Species Retained	lbs	Bent Hook Gape (cm)	Standard Gape (cm)	Gape Size Increase (%)
YFT	41	4.8	2.5	92%
YFT	45	4.6	2.5	84%
YFT	55	3.7	2.5	48%
SPL	57	4	2.5	60%
SPL	256	4.6	2.5	84%

Table 8-5. List of tropical storms and hurricanes encountered during 2011 field season, with two-week preferred fishing periods around full moon for North Carolina-based pelagic longline fleet indicated in green font. **Bold Dates–** Dates were wave height reached over 7 ft recorded by buoy 150 miles off coast of NC indicating unlikely fishing with participating fleet. GREEN Dates – Indicate 1 week before and 1 week after each full moon for months of fishing activity

4/10/2011-4/24/2011

5/10/2011-5/24/2011

06/19/11

6/8/2011-6/22/2011

06/21/11-06/30/11

07/07/11-07/10/11

7/8/2011-7/22/2011

07/15/11

July 17-22 Tropical Storm Bret

07/26/11

July 20-22 Tropical Storm Cindy

08/04/11-08/08/11

August 1-7 Tropical Storm Emily

8/6/2011-8/20/2011

August 14-16 Tropical Storm Gert

August 20-28 Major Hurricane Irene

08/26/11-08/28/11

August 28-29 Tropical Storm Jose

August 29- September 10 Major Hurricane Katia

09/06/11-09/10/11

9/5/2011-9/19/2011

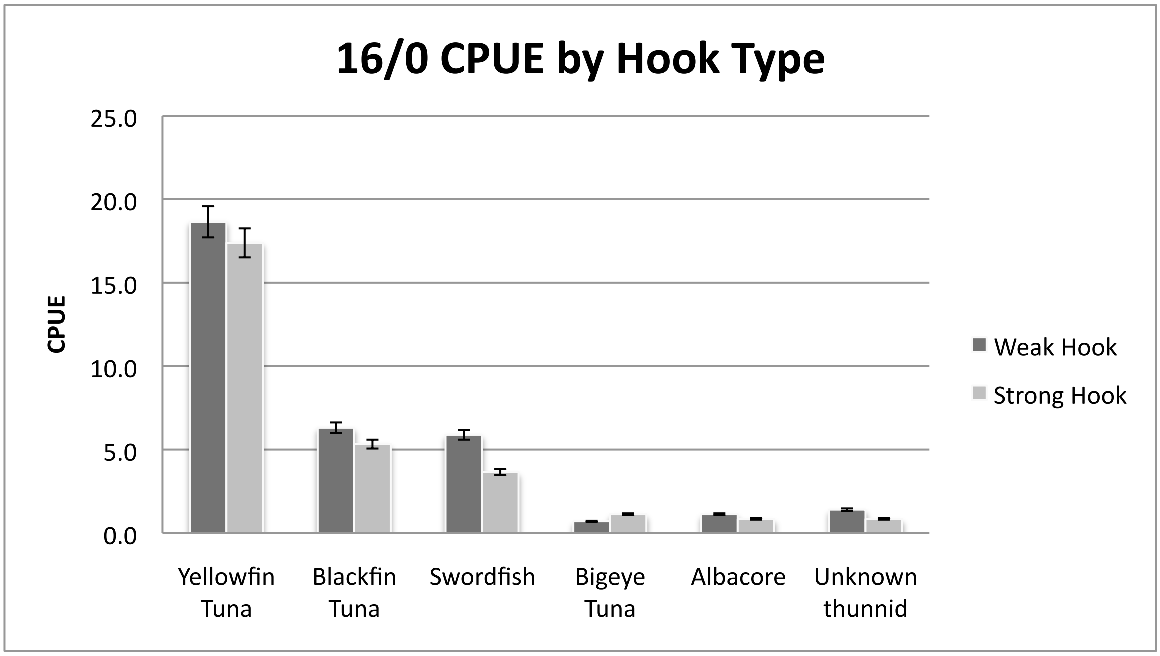
September 6-16 Hurricane Maria

09/16/11-09/19/11

September 21-October 3 Major Hurricane Ophelia

09/25/11

Figures 8-1A and 8-1B. Analyses of catch-per-unit-effort (CPUE; catch per 1000 hooks) for pelagic longline "whale safe" gear research sets with size 16/0 hooks within the North Carolina-based fishery. Figure 1A (top) shows CPUE for target swordfish and tuna species. Figure 1B (bottom) shows CPUE for non-target fish species.



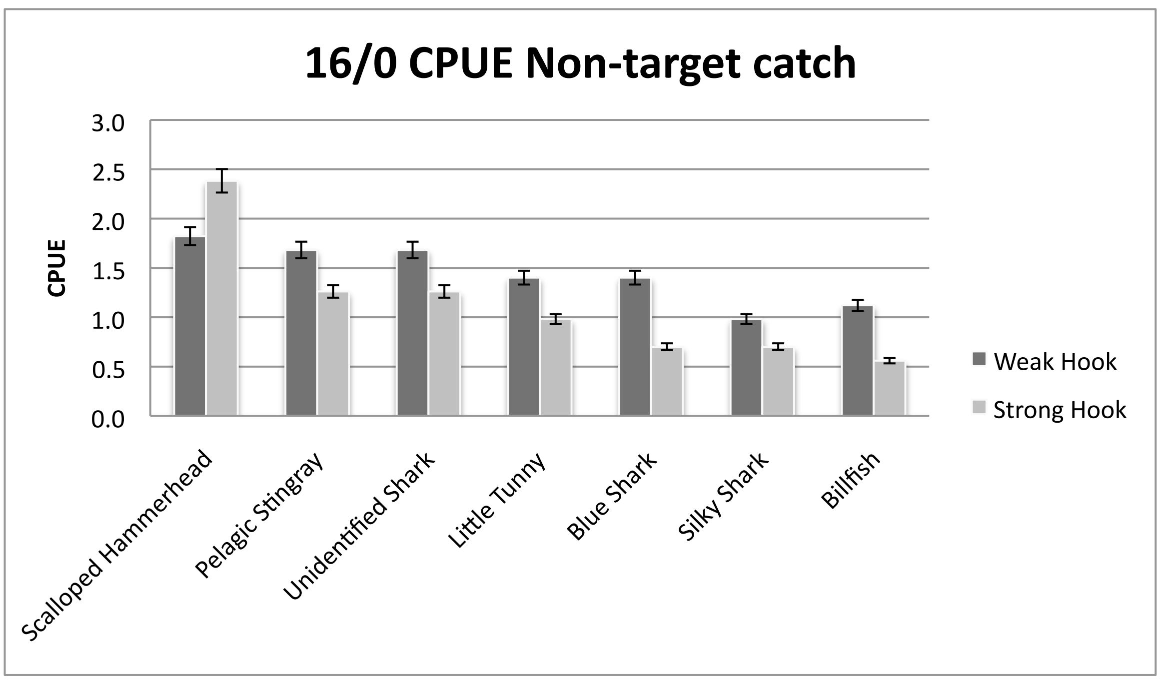
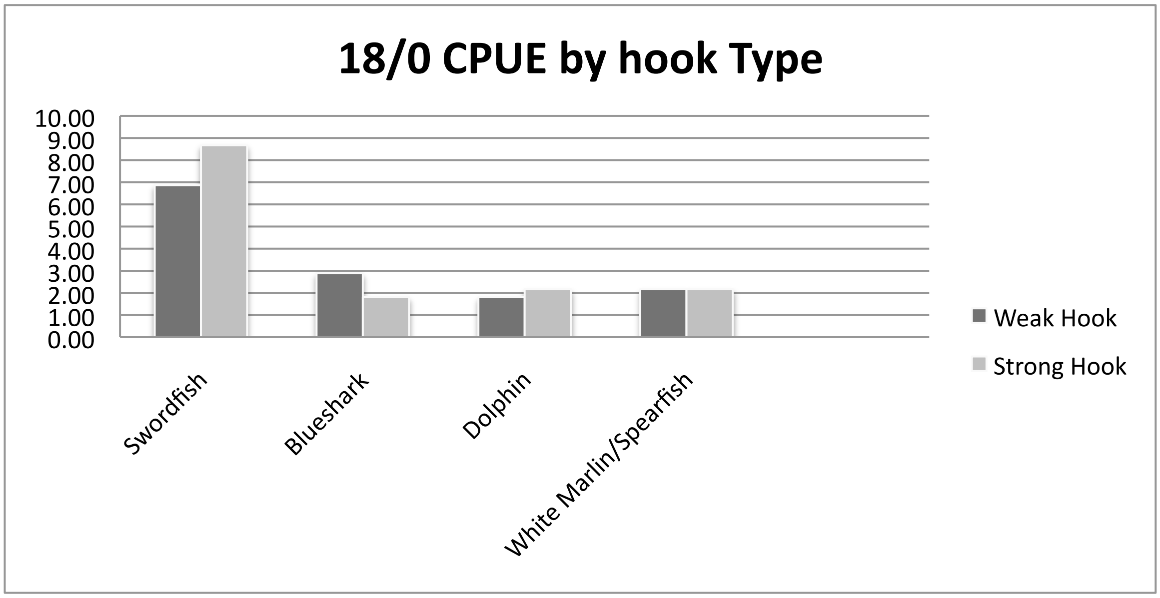
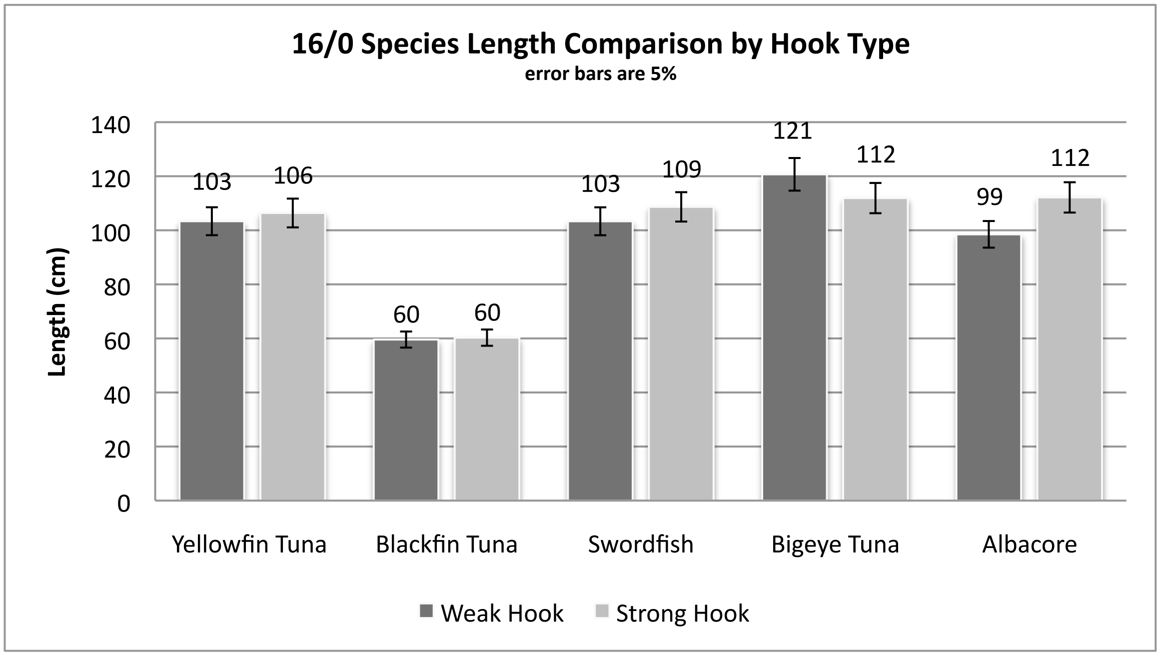


Figure 8-2. Analyses of catch-per-unit-effort (CPUE; catch per 1000 hooks) for pelagic longline "whale safe" gear research sets with size 18/0 hooks within the North Carolina-based fishery.



Figures 8-3A and 8-3B. Analyses of catches by pelagic longline "whale safe" gear research sets with size 16/0 hooks within the North Carolina-based fishery. Figure 1A (top) shows CPUE for target swordfish and tuna species. Figure 1B (bottom) shows CPUE for non-target fish species.



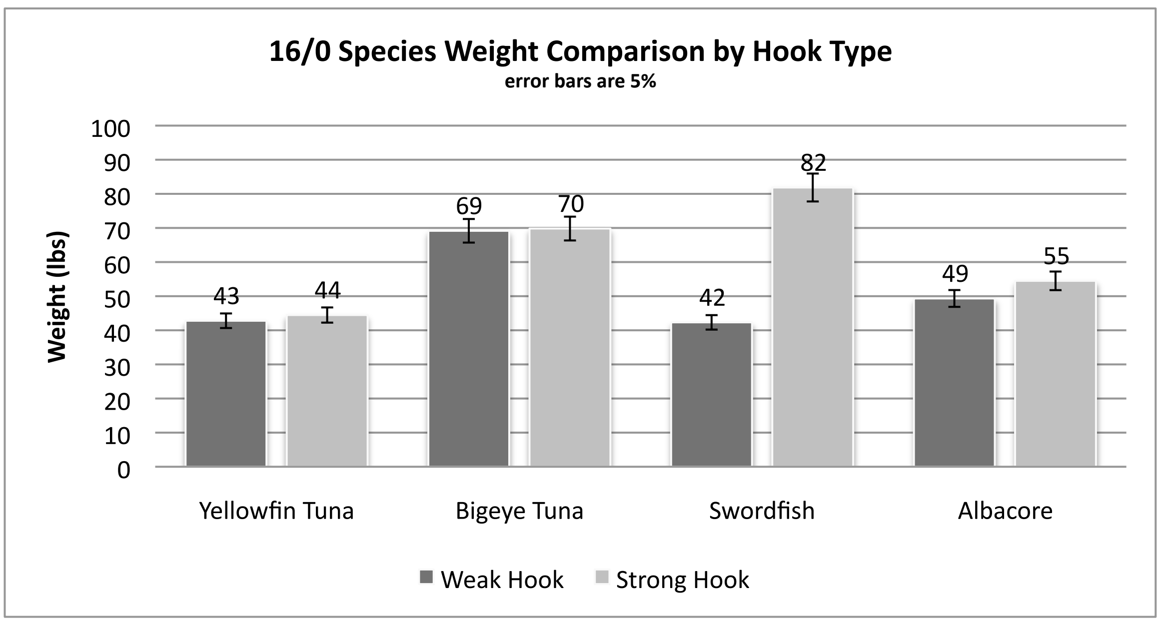
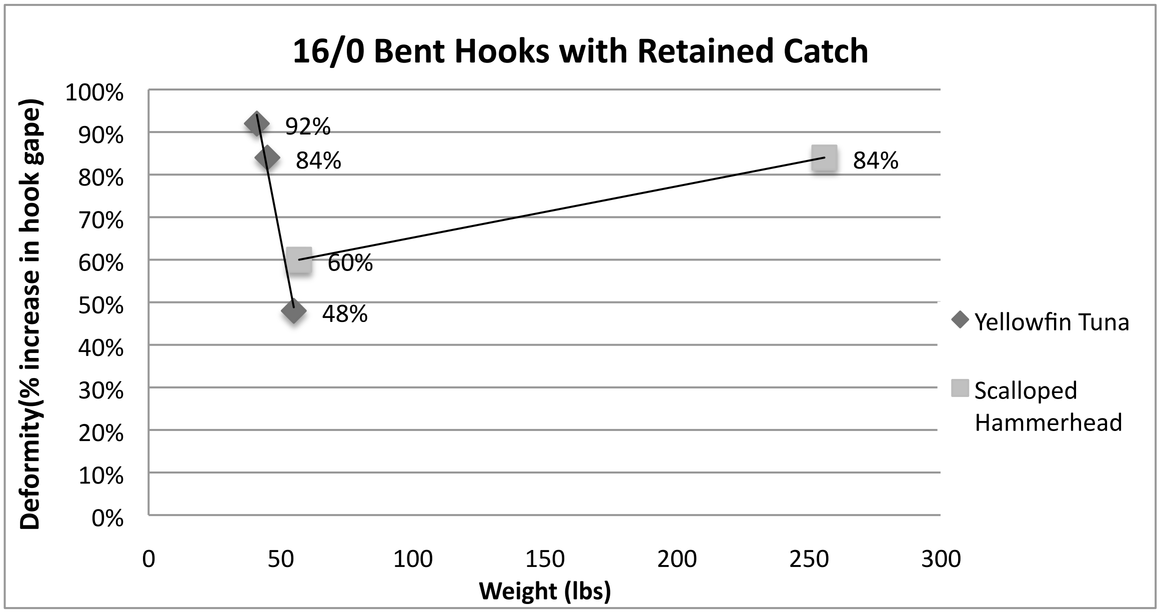


Figure 8-4. Hook deformity of size 16/0 circle hook with weight of individual animal from pelagic longline fleet off North Carolina. This graph shows the measured increase in deformity from standard hook gape of 2.5 cm. Example: YFT (BH1)**:** Standard gape of 39988D 16/0: 2.5 cm, Bent Hook 1 Measured Gape: 4.8cm; therefore: (4.8cm-2.5cm)/ (2.5cm) =.92*100=<u>92%.</u>



<u>Project 9 – Efficacy of Electropositive Metals to Reduce Shark Bycatch in Longline Fisheries</u> (Florida Atlantic University [FAU], NEAq)

Project Goal and Objectives

One potential method to deter sharks from biting longline baits, while not impacting the catch of the target teleost species, is to exploit the sensitivity of the shark electrosensory system. Electropositive elements naturally lose electrons and create a monopole negative charge distribution in seawater. This electric field is well within the range of detection by the shark electroreceptors and has been demonstrated to repel sharks from baits (Brill 2009; Wang et al 2008; Stoner and Kaimmer 2008). This project aimed to test the efficacy of various lanthanide elements and their alloys as potential shark repellents. The work consisted of two components, a behavioral assay and a neurophysiological assay.

Project 9 Final Report

Efficacy of Electropositive Metals to Reduce Shark Bycatch in Longline Fisheries

Stephen Kajiura
Florida Atlantic University

Methods and Results

Before either assay could be initiated, it was first necessary to test the various candidate metals, as well as controls, to determine which was the most suitable to be used for subsequent experiments. Six lanthanide-based electropositive metals (Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), CeLa mischmetal, PrNd mischmetal, and PrNd metal alloy) and two control metals (Lead and stainless steel) were purchased. Local machine shops were identified that could process the metals and all of the metals were machined to a uniform size of 1”x1”x1/4”.

At FAU, electric field measurements were conducted for all of the metals at ambient seawater temperature and salinity. Each metal (n=6 for each of the 8 metals) was dipped into the seawater at 10 distances from the recording electrode (1, 2, 3, 4, 5, 10, 15, 20, 25, and 30cm). The data were analyzed and all of the electropositive metals produced significantly greater electric fields than the control metals at distances ≤ 10cm (Figure 9-1). The electric field magnitude did not differ significant among the six electropositive metals in part because the electropositive metals demonstrated a large amount of variance in their generated electric fields (Figure 9-2).

The metals were also tested using the same assay but at different temperatures and salinities. The metals were tested in full strength seawater at 12 °, 18 °, and 24 °C and were also tested at 24 °C at salinities of 0, 12, 24, and 36ppt. The measured voltage did not vary with temperature (Figure 9-3), but increased dramatically with decreasing salinity (Figure 9-4).

The metals were also tested for dissolution rate in seawater. The mode of action of the metals relies upon oxidative reaction with seawater, which generates an electric field around the metal and results in the release of hydrogen gas and an oxide precipitate. The metal itself is slowly dissolved in the process. Different metals dissolved at different rates and would thus remain effective for greater or lesser periods of time (Figure 9-5).

Based upon output voltage (uVolts/gram), dissolution rate, machinability, and cost, it was decided to conduct subsequent experiments with the lanthanide element Neodymium (Nd) (Figure 6).

Behavioral assays

Behavioral trials were conducted at the Florida Atlantic University marine lab on the lemon shark (*Negaprion brevirostris*) and the bonnethead shark (*Sphyrna tiburo*) which represent two families (Carcharhinidae and Sphyrnidae, respectively) within the Order Carcharhiniformes. Trials were also conducted at the Marine Biological Laboratory in Woods Hole, MA, on the piked dogfish (*Squalus acanthias*) and the smooth dogfish (*Mustelus canis*). Although these are both commonly called dogfish, the piked dogfish is in the Order Squaliformes whereas the smooth dogfish is in the Order Carcharhiniformes, like the species tested from Florida. (For more detailed information on the methods used to conduct the behavioral assays on *S. acanthias* and *M. canis* see Jordan et al 2011, Appendix 8; for methods on *N. brevirostris* and *S. tiburo* see McCutcheon 2012, Appendix 9).

Behavioral assays were performed on several individuals (n=4-13) of each species. Trials consisted of a choice test in which sharks were presented simultaneously with baits affixed to one of four treatments: acrylic, stainless steel, lead, or Neodymium. The treatment samples were in turn affixed to a 1m^2 acrylic plate that enabled the samples to be equidistantly spaced. When the plate was introduced to the tank, it was noted from which treatment the bait was removed. Sharks were tested both individually and in groups of 2-4 conspecifics, because shark density has been observed to influence behavior (Robbins et al 2011). Piked dogfish and lemon sharks were unable to be tested individually. When maintained in isolation, individuals of these species demonstrated stressed swimming behavior and would not feed. Therefore, only group feeding results are available for these two species.

The percentage of bites at each of the treatments for bonnethead and lemon sharks are illustrated in Figure 9-7. For each of the species and treatments, the results of whether the lanthanide metal appears to be effective at reducing bites on bait, are presented in Table 9-1. For the species with large sample sizes (bonnethead n=12, and lemon shark, n=13) the Nd was ineffective at reducing bait removal from the metal. Neodymium appeared to be effective with the smooth dogfish when tested individually only, and the piked dogfish when tested in groups, but for the piked dogfish in particular, the sample size was small with only 4 individuals tested. (For more detailed results on the experiments with Nd see Jordan et al 2011, Appendix 8 and McCutcheon 2012, Appendix 9).

In addition to tests of the efficacy of various metals, experiments were also conducted on the response of the sharks to prey-simulating electric fields. Both the piked dogfish and smooth dogfish demonstrate similar behavioral responses to weak electric fields and their responses are similar to those of other species previously reported in the literature. These experiments confirm the electrosensitive nature of the test species and also confirm that the responses are typical of other shark species (Table 9-2).

Neurophysiological assays

In preparation for these assays, FAU carefully dissected the cranial nerves on representatives of four species, the Atlantic stingray, *Dasyatis sabina*, the bonnethead shark, *Sphyrna tiburo*, the lemon shark, *Negaprion brevirostris*, and the piked dogfish, *Squalus acanthias*. These anatomical familiarization studies were a necessary prerequisite to be able to successfully perform neurosurgery on live animals. FAU has also consulted with a human surgeon and a veterinarian on additional refinements to its techniques.

The neurophysiology experiments became fraught with technical difficulties and satisfactory recordings from the primary afferent neurons or the anterior lateral line nerve (ALLN) were never achieved. Although the principal investigator (SMK) has successfully recorded from the visual, olfactory, and electrosensory systems in the past, the challenging nature of presenting an electrical stimulus to a conductive seawater environment and attempting to record from electrosensory neurons proved to be overwhelming. The principal investigator (SMK) has been granted a sabbatical leave to spend several months starting in March 2013 working with a colleague (Dr Tim Tricas) at the University of Hawaii learning single unit recording techniques. Through this new procedure, we can apply a different neurophysiological recording technique and finally address the efficacy of the lanthanide metals as stimulants of the elasmobranch electrosensory system. This work will be completed at no additional cost to the Consortium and a final report that includes completed neurophysiological assays will be provided by June 2013.

Conclusion

The results of these studies provide additional evidence that sensitivity to electric fields is comparable across elasmobranchs. However, despite that similarity, the behavioral responses to Nd varied between species. Although Nd may be a successful deterrent for some species, other factors were important in determining responses, including hunger level and competition. The results from Jordan et al. (2011) suggest that Nd may be a more successful repellant in fisheries where solitary species are the majority of the bycatch. The results from McCutcheon 2012 were less favorable, suggesting that the sharks were able to detect the voltage produced by the Nd, but they were not deterred by its presence.

Outputs

The results of the behavioral trials with the piked dogfish and smooth dogfish were published in the Journal of Experimental Marine Biology and Ecology. "Behavioral responses to weak electric fields and a lanthanide metal in two shark species", by Laura K. Jordan, John W. Mandelman, Stephen M. Kajiura. These data were also presented as an oral presentation at the joint meeting of the American Society of Ichthyologists and Herpetologists and the American Elasmobranch Society conference in July 2011. All three authors were in attendance and the talk was presented by Laura K. Jordan.

The results of the behavioral trials with the bonnethead and lemon sharks were completed as part of the graduate MS thesis by Sara M. McCutcheon at Florida Atlantic University. The thesis was successfully defended on February 29, 2012 and a draft of the thesis is attached. This work was submitted to the journal Fisheries Research as "Efficacy of lanthanide metals as shark repellents" by Sara McCutcheon and Stephen Kajiura and is currently being revised based on reviewer comments. These data were also presented as an oral presentation by SM McCutcheon at the joint meeting of the American Society of Ichthyologists and Herpetologists and the American Elasmobranch Society conference in August 2012.

Table 9-1. Efficacy of the lanthanide element Neodymium (Nd) at deterring sharks from biting at bait. Sharks were tested either individually or in a group of 2-4. Although the results are mixed, in 4 out of 6 treatments the Nd metal is ineffective at deterring the sharks from removing bait.

Species	**Individual**	**Group**
Lemon shark (n=13)	Not tested	Not effective
Bonnethead shark (n=12)	Not effective	Not effective
Smooth dogfish (n=8)	Effective	Not effective
Piked dogfish (n=4)	Not tested	Effective

Table 9-2. Sensitivity of sharks to prey-simulating, electric stimuli. There was no significant difference in sensitivity between the two species for the median detected e-field, minimum detected e-field, or maximum orientation distance.

Species	**Median detected e-field (nV/cm)**	**Minimum detected e-field (nV/cm)**	**Maximum orientation distance (cm)**
Smooth dogfish (n=8)	28.71	2.78	25.8
Piked dogfish (n=4)	13.61	1.47	30.1

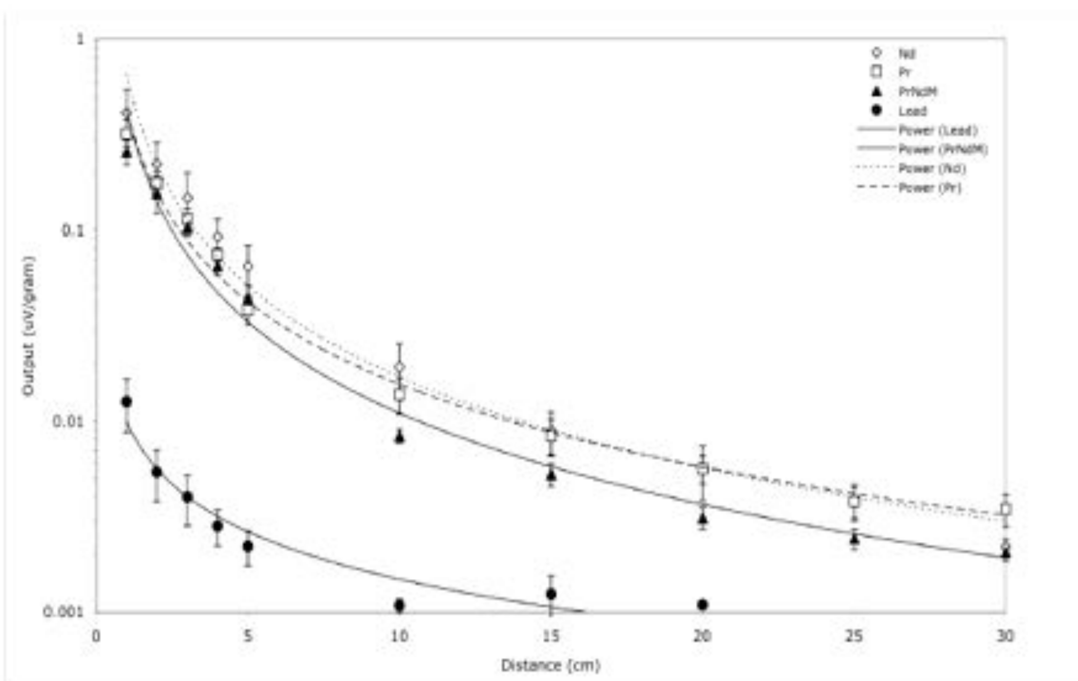


Figure 9-1. Electrical output (uV/gram) decreased with distance from the recording electrode. Similar slopes were obtained for all metals, but the output of the electropositive metals was more than 10x greater than a lead control.

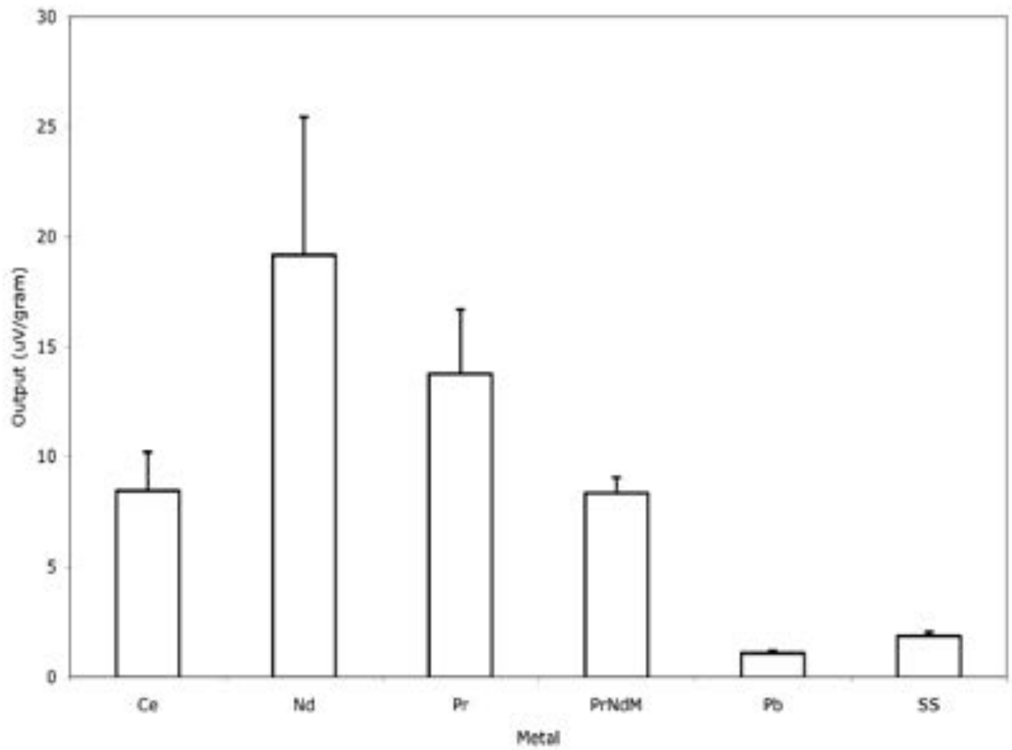


Figure 9-2. Electrical output (uV/gram) compared among electropositive metals and controls at a distance of 10cm from the recording electrode. The electropositive metals all produced a significantly greater electric field than the controls.

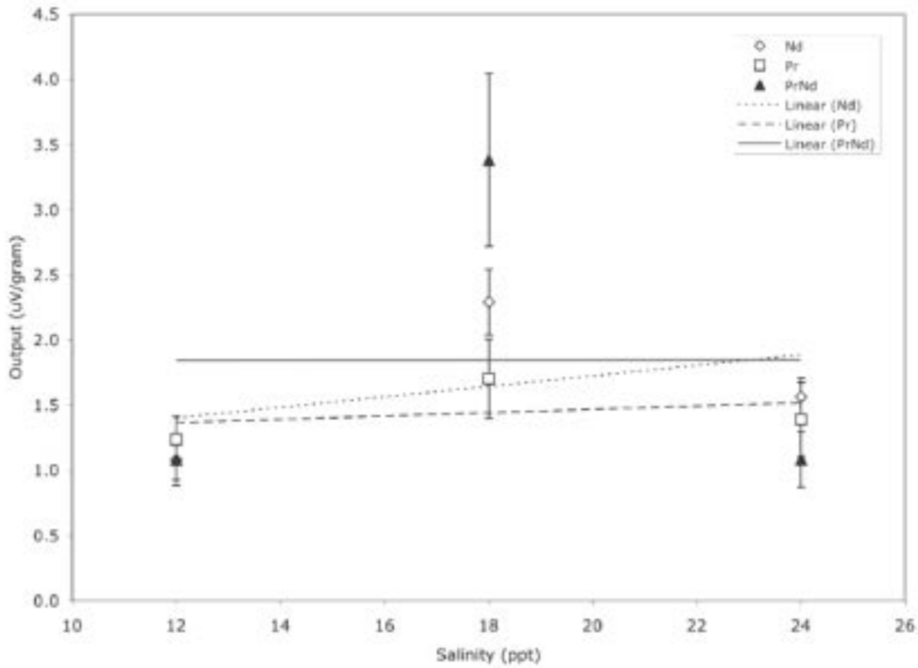


Figure 9-3. Electrical output (uV/gram) did not vary predictably with temperature over the tested range.

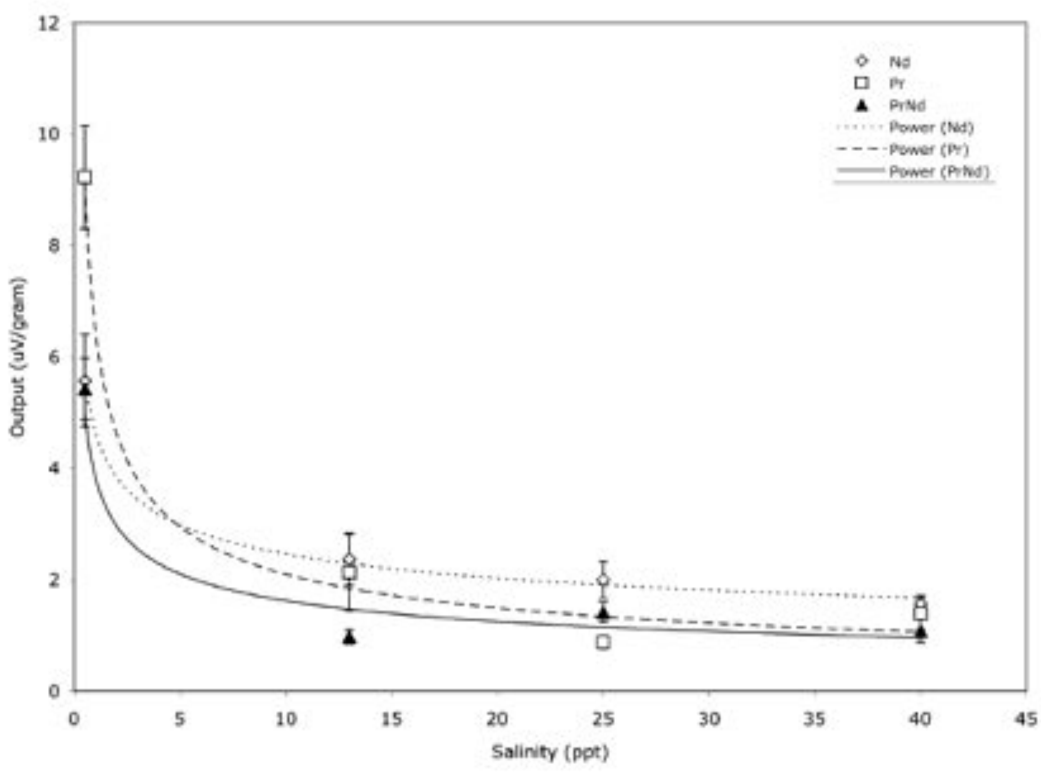


Figure 9-4. Electrical output (uV/gram) decreased with increasing salinity due to the grounding effect of the electrolytic seawater.

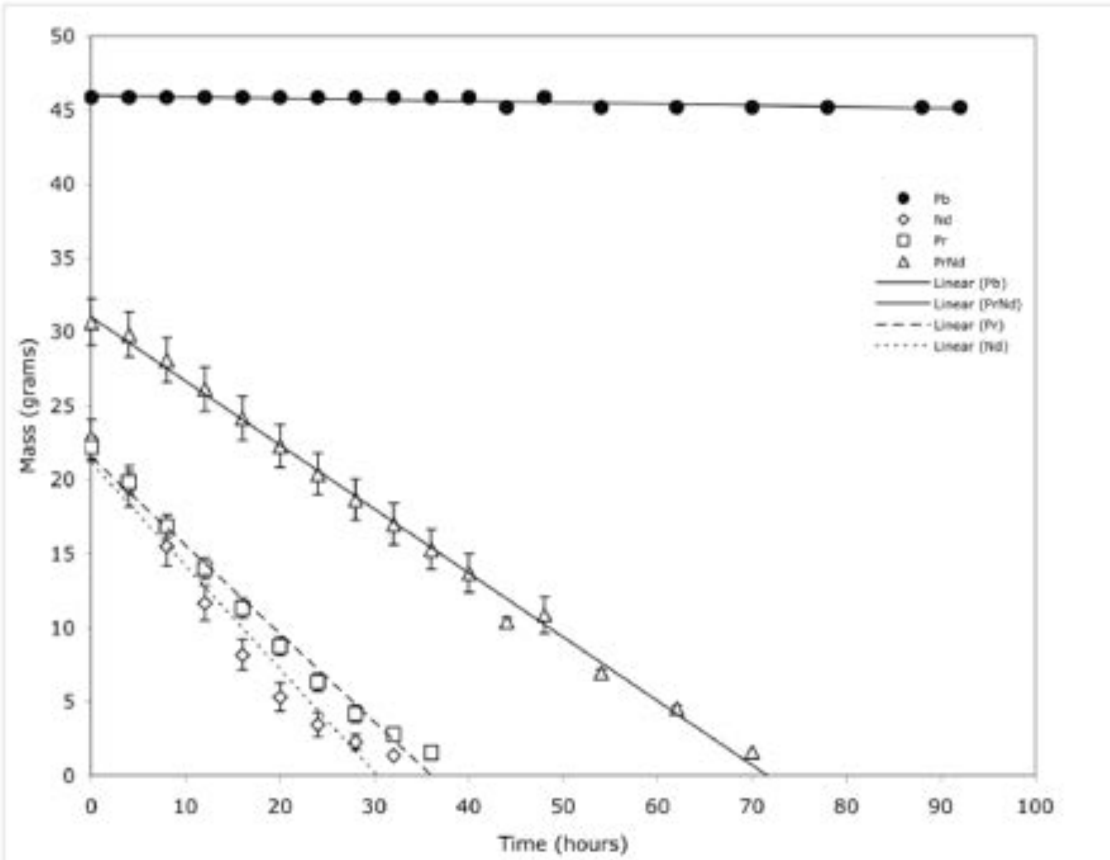


Figure 9-5. Total mass of various electropositive metals decreased with exposure time in seawater as the samples dissolved. In contrast, the control treatment (lead) did not dissolve over that same time period.

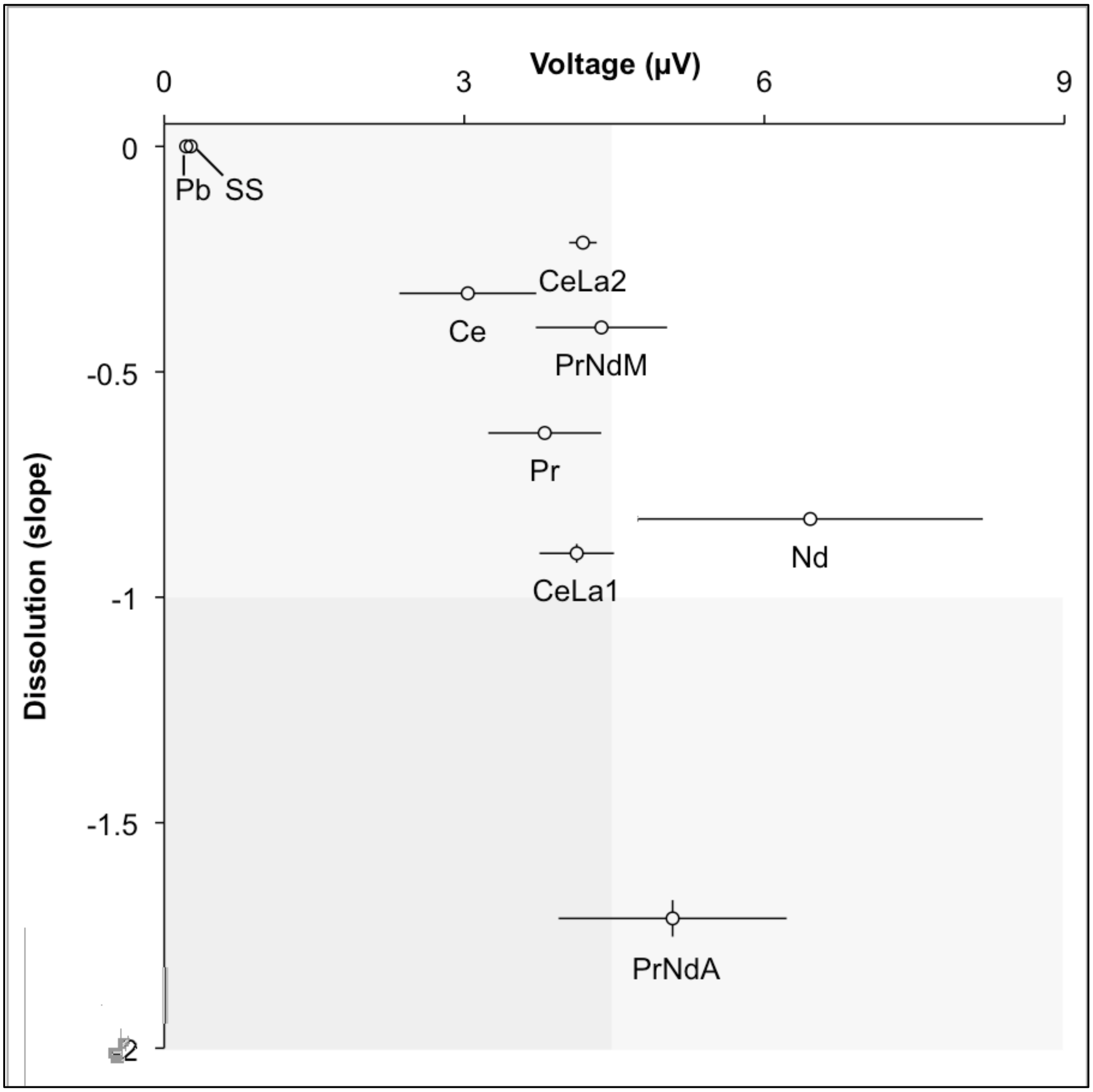


Figure 9-6. To determine the best candidate metal for shark behavioral trials, voltage (mean ± s.e.m.) was plotted against dissolution rate (mean ± s.e.m.) for seven lanthanide metals and two controls. The best metal candidates produce the greatest voltage and possess the slowest dissolution rate (slope close to 0) and occur in the upper right quadrant. Based upon these criteria, Neodymium (Nd) was chosen for the shark behavioral trials.

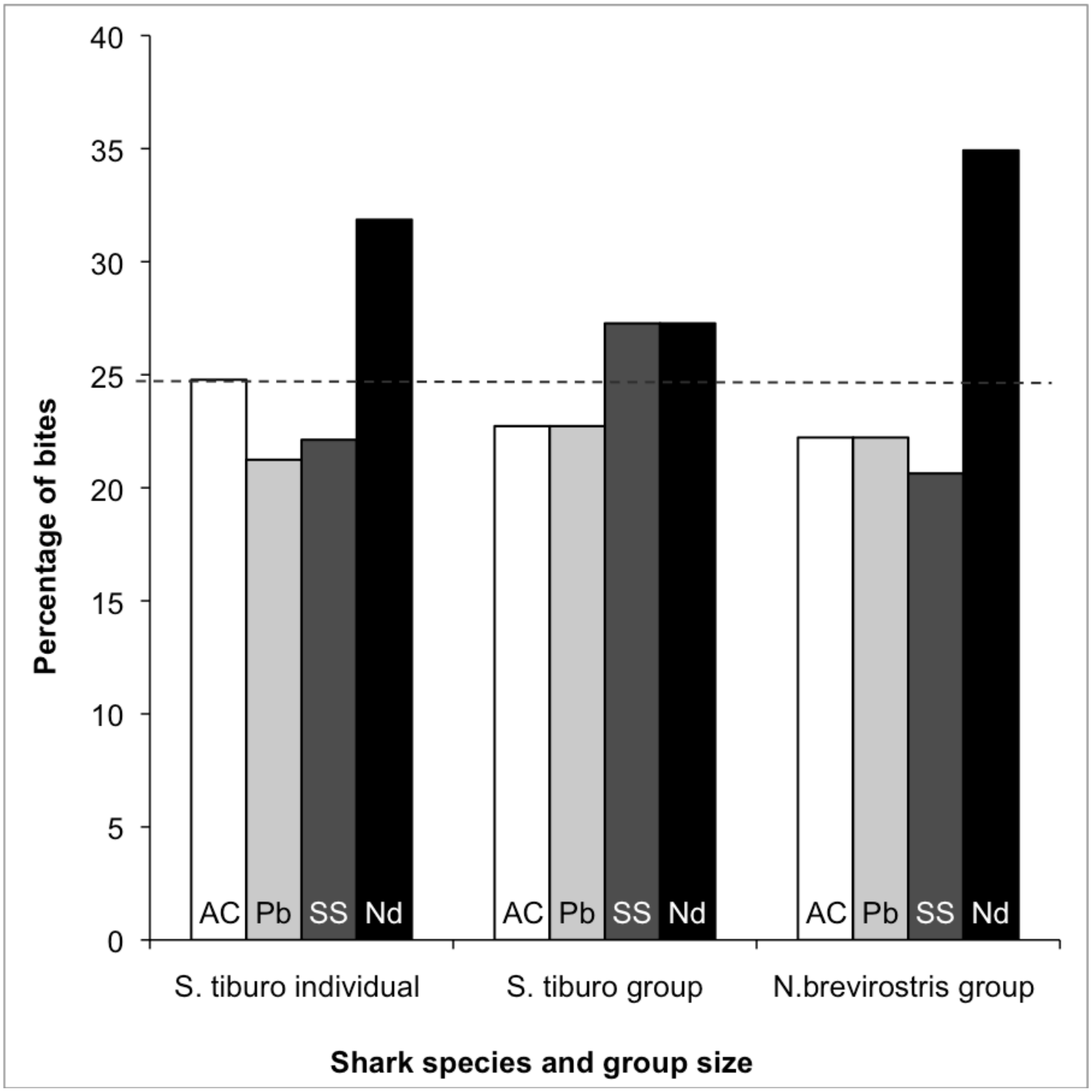


Figure 9-7. An acrylic array with each of the sample materials (acrylic: AC, lead: Pb, stainless steel: SS, and Neodymium: Nd) was placed into the tank with the sharks and the frequency with which bait was removed from each material was recorded. The sharks were tested individually or in groups: *Sphyrna tiburo* individually (N=12 sharks, n=113 bites), *Sphyrna tiburo* in groups (N=12 sharks, n=110 bites), and *Negaprion brevirostris* in groups (N=13 sharks, n=126 bites). *Negaprion brevirostris* were tested individually, but would not feed in isolation. Each treatment has an equal chance of being removed (25%, as indicated by the dashed line). The sharks did not preferentially feed from or avoid any of the treatments (*S. tiburo* individually X^2=3.1416, p=0.3703; *S. tiburo* group X^2=0.9091, p=0.8232; *N. brevirostris* group X^2=6.6984, p=0.0822).

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