ECOLOGICAL AND SOCIETAL CONTEXT OF CATCH AND DISCARDS: IDENTIFYING OPPORTUNITIES FOR BYCATCH MITIGATION IN SWORDFISH AND TUNA PELAGIC LONGLINE FISHERIES

ERIN H. CARRUTHERS

Ecological and Societal Context of Catch and Discards: Identifying Opportunities for Bycatch Mitigation in Swordfish and Tuna Pelagic Longline Fisheries

by

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ABSTRACT

Bycatch, defined here as catch discarded for regulatory, economic or personal reasons, from pelagic longline fisheries has contributed to wide spread population declines of sharks and sea turtles. Opportunities to reduce impacts in these fisheries occur throughout the fishing process and depend upon the fishing practices within fleets, and upon the behaviour of target and bycatch species. The overall objective of this thesis was to identify bycatch mitigation opportunities within the Canadian Atlantic pelagic longline fishery, which targets swordfish (*Xiphias gladius*), warm-water tunas (bigeye, *Thunnus obesus;* yellowfin *T. albacares;* and albacore, *T. alalunga*) and mahi-mahi (*Coryphaena hippurus*). Bycatch includes common sharks and rays (blue shark, *Prionace glauca;* pelagic stingray, *Pteroplatytrygon violacea*), and endangered sea turtles (leatherback *Dermochelys coriacea*; loggerhead, *Caretta caretta*). Bycatch mitigation approaches such as shifting to circle hooks, increased the likelihood that shark bycatch would be released alive and with less severe hooking injuries. Shorter longline soak times also increased hooking survival among most of the common bycatch species. Shorter soak times would not decrease catch of the most common landed species (swordfish), but this shift in fishing practices could negatively impact fisher safety. Interviews with active longline captains revealed operational difficulties and unintended ecological impacts with proposed bycatch mitigation approaches. Longline captains also reported innovative uses of bycatch mitigation tools that could increase post-release survival of common

bycatch species in this and other pelagic longline fleets. Finally, the combined analysis of fisheries observer data, qualitative data from fishers' knowledge interviews, and concurrent environmental data suggested that high blue shark catch rates were related to local oceanography – and did not reflect behavioural differences between blue shark and swordfish. Clearly, there are opportunities for bycatch mitigation within the Canadian pelagic longline fishery for swordfish and tunas. However, the process of interviewing pelagic longline captains revealed both interest in reducing bycatch, but also suspicion of research efforts. Such trust issues will need to be addressed in subsequent research as the combined use of fishery assessments, detailed oceanographic data, practical fishing knowledge, and on-the-water observations will be needed to decrease the amount of and harm to discarded bycatch.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

Acronyms

COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CPUE	Catch Per Unit Effort
DFO	Canadian Department of Fisheries and Oceans
EEZ	Exclusive Economic Zone
GAM	Generalized Additive Model
GLM	Generalized Linear Model
ICCAT	International Commission for the Conservation of Atlantic Tunas
ICEHR	Interdisciplinary Committee on Ethics in Human Research
ITQ	Individual Transferable Quota
MSC	Marine Stewardship Council
NSSA	Nova Scotia Swordfishermen's Association
SST	Sea Surface Temperature
TDR	Temperature Depth Recorder
TR	Temperature Recorder

Statistical symbols

CI	Confidence Interval
df	degrees of freedom
k^{-1}	dispersion parameter
LRT	Likelihood Ratio Test
p	proportion
p	p-value
var	variance
ß	model coefficient
μ	mean
θ	angle

CHAPTER 1: INTRODUCTION AND OVERVIEW

1.1 Introduction

1.1.1 Bycatch mitigation

Fisheries bycatch, that portion of the catch that is released alive or discarded dead, has contributed to widespread population declines of marine species (D'Agrosa et al. 2000; Lewison et al. 2004), has altered ocean ecosystems (Garthe et al. 1996; Hall et al. 2000), and constitutes substantial waste from fisheries globally (Alverson et al. 1994; Hall et al. 2000). Thus, reducing bycatch has become a critical fisheries management and conservation issue (Hall and Mainprize 2005). While the amount of and impacts from bycatch differ among fisheries, gear types, and regions (Alverson et al. 1994), here I focus on two fundamental concepts for addressing bycatch issues. First, opportunities to reduce bycatch or harm occur throughout the fishing process. Secondly, the efficacy of mitigation depends upon the larger ecological and societal context.

Fishing decisions, fish behaviour and the interactions between these two processes affect catch rates and condition. At a broad scale, fishing decisions of where and when to fish are largely based on expected distribution and abundance patterns of targeted species. These fishing decisions may also be shaped by other factors, such as individual fishing preferences, regulatory limits, or changing costs and markets (Béné and Tewfik 2001; Branch and Hilborn

2008; de Mutsert et al. 2008) but migration patterns and seasonal aggregations of target species are key factors in the choice of fishing grounds and seasons (Yamaguchi 1989a; Grant and Berkes 2007). Within fishing grounds or seasons, setting practices (e.g., time of day, depth fished, baits used, or location relative to oceanographic or geographic features) are chosen with the movement and feeding behaviours of target species in mind (Yamaguchi 1989b; Beverly et al. 2009; Hobday and Campbell 2009). During the last stage of the capture process, landing and handling practices affect catch quality, and therefore price (Willis and Millar 2001). Similarly, fishing decisions made throughout the fishing process may be used to reduce the amount of bycatch and harm to discarded catch, particularly if bycatch distribution patterns, feeding behaviours, and interactions with fishing gear differ from those of target catch.

Fishing decisions, such as choice of fishing grounds to improved handling and release practices, affect bycatch levels and release condition. Differences in the ecology and behaviour of target and bycatch species can be used to identify mitigation opportunities, reducing the amount of and harm to unwanted catch. For example, marine protected areas or closures may be most effective where bycatch species' distribution is clustered and predictable, and where such distributions differ from those of targeted species (Hall 1996; Game et al. 2009). Modified fishing practices, such as depths fished, may be used where there are clear habitat differences between target and bycatch species (Deitrich et al.

2008; Beverly et al. 2009). Other bycatch mitigation approaches utilize differences in how species prey upon baited gear (Willis and Millar 2001) or differences in species' behaviour after capture (Broadhurst 2000; Wade et al. 2007). Finally, improved handling and discarding practices can increase the likelihood of post-release survival (Farrell et al. 2001; Campana et al. 2009; Milliken et al. 2009).

The efficacy of bycatch mitigation approaches depends upon the larger ecological and societal context. Closed areas may increase bycatch levels and harm for highly migratory species if fishing effort shifts to regions with higher bycatch abundance or to fisheries with fewer regulations or protections (Hall 1998; Baum et al. 2003; Hall et al. 2007). Thus, the efficacy this bycatch mitigation approach depends upon both species distributions and upon the fishing and management context. Within fisheries, changing regulations, targeting practices, and species associations will affect the efficacy and uptake levels of bycatch mitigation approaches (Wade et al. 2009). Further, the social structure within fisheries, and the relationship between fishers and management affects development and acceptance of bycatch mitigation approaches – and consequently their efficacy (Hall et al. 2007; Campbell and Cornwell 2008).

Before introducing the focal fishery and overall objective of this thesis, additional information is needed on the bycatch definition used here. Bycatch is a contentious term and it is central to this thesis. Bycatch may refer to non-target catch that is subsequently landed; species, or sizes and sexes of species that are discarded for economic, regulatory, or personal reasons; or the combination of non-target catch and discards (Alverson et al. 1994). Bycatch limits or quotas use the first definition, and refer to landed species that are not the primary target but for which there are limiting quotas (e.g., Benoît and Allard 2009). Hall (1996) proposed a restricted version of the second definition and used the term for catch that are discarded dead or injured to the point that post-release mortality is likely. By contrast, Davies et al. (2009) proposed a broader version of the third definition, that "bycatch is the catch that is either unused or unmanaged". In this thesis bycatch refers to catch that is released alive or discarded dead for economic, regulatory, or personal reasons. I chose this definition for three reasons. First, incidental landed catch may constitute a desired and an economically important portion of the catch. Differentiating target and incidental landed catch is problematic in multispecies fisheries as targets shift over time (Hall et al. 2000). Second, post-release survival is unknown or underestimated for many species and fisheries (e.g., Davis 2002; Casale et al. 2008; Campana et al. 2009), thus including release condition or likely post-release survival in the definition would either be untenable or would underestimate bycatch and consequently fishery impacts. Third, conservation, fishing, and management efforts to reduce bycatch typically refer to unwanted and discarded catch – this is the research and management context within which I am working.

1.1.2 Pelagic longline fisheries

Pelagic longlines, consisting of a main line suspended by floats with a series of baited hooks hanging below, are used to target swordfish (*Xiphias gladius*) and tunas (*Thunnus* spp.) throughout the Atlantic, Pacific, and Indian Oceans, and the Mediterranean Sea. Discarding practices, and therefore bycatch, differ among pelagic longline fisheries depending on fishing regulations, local markets and price (e.g., Gilman et al. 2008; Swimmer et al. 2011). Because of the global extent and effort levels of pelagic longline fisheries, catch and bycatch from these fisheries has contributed to widespread population declines of teleosts, sharks, and turtles (e.g., Baum et al. 2003; Myers and Worm 2003; Lewison et al. 2004). While the magnitude of decline (e.g., Burgess et al. 2005; Sibert et al. 2006), and the contribution of pelagic longline fisheries within particular regions (James et al. 2005; Ivarez de Quevedo et al. 2010) has been debated, impacts from pelagic longline fisheries are such that mitigation efforts (e.g., time/area closures and modified fishing gear) have been implemented in some fisheries (e.g., Watson et al. 2005; Hall et al. 2007).

The Canadian Atlantic pelagic longline fishery targets swordfish, warm-water tunas (albacore, *T. alalunga*; yellowfin, *T. albacares*; and bigeye, *T. obesus*) and mahi-mahi (*Coryphaena hippurus*). Bycatch from the fishery includes common sharks and rays (blue shark, *Prionace glauca*; pelagic stingray, *Pteroplatytrygon* *violacea*), endangered porbeagle shark (*Lamna nasus*; COSEWIC 2004; DFO 2005), and endangered sea turtles (leatherback *Dermochelys coriacea*; loggerhead, *Caretta caretta*). During the time this research was being conducted, incentives and pressures to reduce bycatch and harm were increasing. The fishery initiated an assessment for Marine Stewardship Council certification (MSC 2011), bycatch impacts were a key consideration during the assessment. Further, bycatch species were being assessed under Canadian endangered species legislation (e.g., COSEWIC 2010; DFO 2010).

The overall objective of this thesis is to identify bycatch mitigation opportunities within the Canadian pelagic longline fishery for swordfish and tunas. Given that estimates of fishery impacts from pelagic longlines have been made for the Canadian fishery (e.g., Campana et al. 2006; Brazner and McMillan 2008) and for migratory populations that encounter this fishery (e.g., Baum et al. 2003; Lewison et al. 2004), I chose to focus on identifying possible solutions within the fishery. As such, fisheries observer data were used as the primary data source. At-sea fisheries observers record information on landed catch and bycatch, as well as details of the fishing practices and fished environment. Fisheries observer data are available from 5-18% of the sea days each year (Javitech 2002; Lester et al. 2009). Bycatch information is not available in logbook or landings data, which are collected from the entire fleet. In addition to fisheries observer data, within set temperature and soak time data collected during a chartered research trip, data from qualitative fishers' knowledge interviews with active members of the longline fleet, and concurrent environmental data were used. These additional data sources allowed me to differentiate fishing decisions from fish behaviour and to focus on different stages of the fishing process.

1.2 Statement of co-authorship

The chapters of this thesis were written as separate manuscripts. My co-authors either contributed to research design or to the interpretation of data analysis. They also made intellectual contributions through their revisions to and comments on draft manuscripts. I designed the research with guidance from my co-authors, analysed the qualitative and quantitative data used in this thesis, and wrote initial drafts of the following manuscripts:

Carruthers, E.H., Schneider, D.C., Neilson, J.D. 2009. Estimating the odds of survival and identifying mitigation opportunities for common bycatch in pelagic longline fisheries. Biological Conservation 142, 2620-2630. (Chapter 2)

Carruthers, E.H., Neilson, J.D., Smith, S.C. 2011. Overlooked bycatch mitigation opportunities in pelagic longline fisheries: soak time and temperature effects on swordfish (*Xiphias gladius*) and blue shark (*Prionace glauca*) catch. Fisheries Research 108, 112-120. (Chapter 3)

Carruthers, E.H., Neis, B. 2011. Bycatch mitigation in context: using qualitative interview data to improve assessment and mitigation in a data-rich fishery. Biological Conservation 144, 2289-2299. (Chapter 4)

Carruthers, E.H., Schneider, D.C. Identifying opportunities to reduce blue shark (*Prionace glauca*) bycatch: using fisheries observer data and fishers' knowledge to differentiate fishing decisions and fish behaviour. Prepared for submission to ICES Journal of Marine Science. (Chapter 5)

Fisheries observer data (used in Chapters 2, 3, and 5) were collected by at-sea observers. The fishery observer database is maintained by the Population Ecology Division of the Maritimes Region of Fisheries and Ocean Canada. I wrote custom MATLAB programs to organize and analyse fisheries observer data, instrumented longline data, and weather data used in these chapters. Instrumented longline data used in Chapter 3 were collected by S.C. Smith and the crew of the Oran II during a chartered research trip. I collected the qualitative data analysed in Chapter 4 using an interview guide developed with B. Neis (Appendix I). Chapter 5 is based on fisheries observer data, qualitative interview data, and publicly available data recorded by moored weather buoys.

1.3 References

Alverson, D. L., Freeberg, M.K., Murawski, S.A., Pope, J.G., 1994. A global assessment of fisheries bycatch and discards. FAO Fisheries Technical Paper 339.

Baum, J.K., Myers, R.A., Kehler, D.G., Worm, B., Harley, S.J., Doherty, P.A., 2003. Collapse and conservation of shark populations in the Northwest Atlantic. Science 299, 389-392.

Béné, C., Tewfik, A., 2001. Fishing effort allocation and fishermen's decision making process in a multi-species small-scale fishery: analysis of the conch and lobster fishery in Turks and Caicos Islands. Human Ecology 29, 157-186.

Benoît, H.P., Allard, J., 2009. Can the data from at-sea observer surveys be used to make general inferences about catch composition and discards? Canadian Journal of Fisheries and Aquatic Sciences 66, 2025-2039.

Beverly, S., Curran, D., Musyl, M., Molony, B., 2009. Effects of eliminating shallow hooks from tuna longline sets on target and non-target species in the Hawaii-based pelagic tuna fishery. Fisheries Research 96, 281-288.

Branch, T.A., Hilborn, R., 2008. Matching catches to quotas in a multispecies trawl fishery: targeting and avoidance behaviour under individual transferable quotas. Canadian Journal of Fisheries and Aquatic Sciences 65, 1435-1446.

Brazner, J.C., McMillan, J., 2008. Loggerhead turtle (*Caretta caretta*) bycatch in Canadian pelagic longline fisheries: relative importance in the western North Atlantic and opportunities for mitigation. Fisheries Research 91, 310-324.

Broadhurst, M.K. 2000. Modifications to reduce bycatch in prawn trawls: a review and framework for development. Reviews in Fish Biology and Fisheries 10, 27-60.

Burgess, G. H., Beerkircher, L.R., Cailliet, G.M., Carlson, J.K., Cortes, E., Goldman, K. J., Grubbs, R. D., Musick, J.A., Musyl, M.K., Simpfendorfer, C.A., 2005. Is the collapse of shark populations in the northwest Atlantic Ocean and Gulf of Mexico real? Fisheries 30, 20-26.

Campbell, L.M., Cornwell, M.L., 2008. Human dimensions of bycatch reduction technology: current assumptions and directions for future research. Endangered Species Research 5, 325-334.

Campana, S.E., Joyce, W., Manning, M.J., 2009. Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. Marine Ecology Progress Series 387, 241-253.

Campana, S.E., Marks, L., Joyce, W., Kohler, N.E., 2006. Effects of recreational and commercial fishing on blue sharks (*Prionace glauca*) in Atlantic Canada, with inferences on the North Atlantic population. Canadian Journal of Fisheries and Aquatic Sciences 63, 670-682.

Casale, P., Freggi, D., Rocco, M., 2008. Mortality induced by drifting longline hooks and branchlines in loggerhead sea turtles, estimated through observation in captivity. Aquatic Conservation Marine and Freshwater Ecosystems 18, 945-954.

COSEWIC, 2004. Assessment and status report on the porbeagle shark *Lamna nasus* in Canada. Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Ottawa.

COSEWIC, 2010. Assessment and status report on the loggerhead sea turtle (*Caretta caretta*), Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Ottawa.

D'Agrosa, C., Lennert-Cody, C.E., Vidal, O., 2000. Vaquita bycatch in Mexico's artisanal gillnet fisheries: driving a small population to extinction. Conservation Biology 14, 1110–1119.

Davies, R.W.D., Cripps, S.J., Nickson, A., Porter, G., 2009. Defining and estimating global marine fisheries bycatch. Marine Policy 33, 661-672.

Davis, M.W., 2002. Key principles for understanding fish bycatch discard mortality. Canadian Journal of Fisheries and Aquatic Sciences 59, 1834-1843.

de Mutsert, K., Cowan Jr., J.H., Essington, T.E., Hilborn, R., 2008. Reanalyses of Gulf of Mexico fisheries data: landings can be misleading in assessments of fisheries and fisheries ecosystems. Proceedings of the National Academy of Sciences 105, 2740-2744.

Dietrich, K.S., Melvin, E.F., Conquest, L., 2008. Integrated weight longlines with paired streamer lines — best practice to prevent seabird bycatch in demersal longline fisheries. Biological Conservation 141, 1793-1805.

DFO, 2005. Recovery Assessment Report on NAFO Subareas 3 – 6 Porbeagle Shark. In DFO Canadian Science Advisory Secretariate Science Advisory Report 2005/043.

DFO, 2010. Recovery Potential Assessment for Loggerhead Turtles (*Caretta caretta*) in Atlantic Canada, In DFO Canadian Science Advisory Secretariate Science Advisory Report 2010/042.

Farrell, A.P., Gallaugher, P.E., Fraser, J. Pike, D., Bowering, P., Hadwin, A.K.M., Parkhouse, W., Routedge, R., 2001. Successful recovery of the physiological status of coho salmon on board a commercial gillnet vessel by means of a newly designed revival box. Canadian Journal of Fisheries and Aquatic Sciences 58, 1932-1946.

Game, E.T., Grantham, H.S., Hobday, A.J., Pressey, R.L., Lombard, A.T., Beckley, L.E. Gjerde, K., Bustamante, R., Possingham, H.P., Richardson, A.J., 2009. Pelagic protected areas: the missing dimension in ocean conservation. Trends in Ecology and Evolution 24, 360-369.

Garthe, S., Camphuysen, K., Furness, R.W., 1996. Amounts of discards by commercial fisheries and their significance as food for seabirds in the North Sea. Marine Ecology Progress Series. 136, 1-11.

Gilman, E., Clarke, S., Brothers, N., Alfaro-Shigueto, J., Mandelman, J., Mangel, J., Petersen, S., Piovano, S., Thomson, N., Dalzell, P., Donoso, M., Goren, M., Werner, T., 2008. Shark interactions in pelagic longline fisheries. Marine Policy 32, 1-18.

Grant, S., Berkes, F., 2007. Fisher knowledge as expert system: A case from the longline fishery of Grenada, the Eastern Caribbean. Fisheries Research 84, 162-170.

Hall, M.A., 1996, On bycatches. Reviews in Fish Biology and Fisheries 6, 319-352.

Hall, M.A., 1998. An ecological view of the tuna-dolphin problem: impacts and trade-offs. Reviews in Fish Biology and Fisheries 8, 1-34.

Hall, M.A., Alverson, D.A., Metzuels, K.I., 2000. By-catch: problems and solutions. Marine Pollution Bulletin 41, 204-219.

Hall S.J., Mainprize, B.M., 2005. Managing by-catch and discards: how much progress are we making and how can we do better? Fish and Fisheries 6, 134–155

Hall, M., Nakano, H., Clarke, S., Thomas, S., Molloy, J., Peckham, S., Laudino-Santillan, J., Nichols, W., Gilman, E., Cook, J., Martin, S., Croxall, J., Rivera, K., Moreno, C., Hall, S., 2007. Working with fishers to reduce by-catches, In By-catch Reduction in the World's Fisheries. ed. S. Kennelly, pp. 235-288. Springer, Dordrecht.

Hobday, A.J., Campbell, G., 2009. Topographic preferences and habitat partitioning by pelagic fishes off southern Western Australia Fisheries Research 95, 332-340.

Ivarez de Quevedo, I., Cardona, L., De Haro, A., Pubill, E., and Aguilar, A., 2010. Sources of bycatch of loggerhead sea turtles in the western Mediterranean other than drifting longlines. ICES Journal of Marine Science 67, 677–685.

James, M.C., Ottensmeyer, C.A., Myers, R.A., 2005. Identification of high-use habitat and threats to leatherback sea turtles in northern waters: new directions for conservation. Ecology Letters 8, 195-201.

Javitech, 2002. Report on Sea Turtle Interactions in the 2001 Pelagic Longline Fishery. Dartmouth, Nova Scotia.

Jenkins, L., 2007. Bycatch: interactional expertise, dolphins and the US tuna fishery. Studies in History and Philosophy of Science 38, 698-712.

Lester, B., Paul, S., Neilson, J., Campana, S., Hussey, L., 2009. Annual Report of Canada, In Report for biennial period 2008-09, Part II (2009) - Vol. 3 Annual Reports, ICCAT, 25-35.

Lewison, R.L., Freeman, S.A., Crowder, L.B., 2004. Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. Ecology Letters 7, 221-231.

Milliken, H.O., Farrington, M. Rudolph, T., Sanderson, M., 2009. Survival of sub-legal Atlantic cod in the Northwest Atlantic demersal longline fishery. North American Journal of Fisheries Management 29, 985-995.

MSC, 2011. North West Atlantic Canada longline swordfish. <http://www.msc.org/track-a-fishery/in-assessment>.

Myers, R.A., Worm, B., 2003. Rapid worldwide depletion of predatory fish communities. Nature 423, 280-283.

Sibert, J., Hampton, J., Klieber, P., Maunder, M., 2006. Biomass, size, and trophic status of top predators in the Pacific Ocean. Science 314, 1773-1776.

Swimmer, Y., Suter, J., Arauz, R., Bigelow, K., López, A., Zanela, I., Bolaños, A., Ballestero, J., Suárez, R., Wang, J., Boggs, C., 2011. Sustainable fishing gear: the case of modified circle hooks in a Costa Rican longline fishery. Marine Biology 158, 757-767.

Wade, P.R., Watters, G.M., Gerrodette, T., Reilly, S.B., 2007. Depletion of spotted and spinner dolphins in the eastern tropical Pacific: modeling hypotheses for their lack of recovery. Marine Ecology Progress Series 343, 1-14.

Wade, O., Revill, A.S., Grant, A., Sharp, M., 2009. Reducing the discards of finfish and benthic invertebrates of UK beam trawls. Fisheries Research 90, 140-147.

Watson, J.W., Epperly, S.P., Shah, A.K., Foster, D.G., 2005. Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Canadian Journal of Fisheries and Aquatic Sciences 62, 965-981.

Willis, T. J., Millar, R.B., 2001. Modified hooks reduce incidental mortality of snapper (*Pagrus auratus*: Sparidae) in the New Zealand commercial longline fishery. ICES Journal of Marine Science 58, 830-841.

Yamaguchi, Y. 1989a. Tuna longline fishing III: selection of a fishing ground. Marine and Freshwater Behaviour and Physiology 15, 37-44.

Yamaguchi, Y. 1989b. Tuna longline fishing IV: fish ecology in the context of tuna long-line fishing. Marine and Freshwater Behaviour and Physiology 15, 45-73.

CHAPTER 2: ESTIMATING THE ODDS OF SURVIVAL AND IDENTIFYING MITIGATION OPPORTUNITIES FOR COMMON BYCATCH IN PELAGIC LONGLINE FISHERIES

In this chapter I identified bycatch mitigation opportunities during the later stages of the capture process using fisheries observer data. For those species or size classes which have a high probability of surviving the capture process, there may be opportunities to decrease impacts from this fishery by modifying handling and discarding practices.

The following chapter builds upon this one by refining the metric used to estimate soak time effects on landed catch, and therefore possible economic impacts of modified setting practices. During fishers' knowledge interviews, detailed in Chapter 4, longline captains described opportunities to decrease fishery impacts by modifying their discarding practices.

Abstract

To evaluate how fishing practices affect bycatch survival and to identify opportunities to reduce bycatch mortality, I estimated the odds of hooking survival for common bycatch species in the Canadian longline fishery for swordfish (*Xiphias gladius*) and tunas (*Thunnus* spp.) fishing in the North Atlantic. Generalized linear models, with binomial response, were based on 859 sets observed between 2001 and 2004 and were tested using data from 2005 and 2006. Bycatch included targeted species in poor condition or below regulatory size limits. Odds of survival were two to five times higher for swordfish, yellowfin tuna (*T. albacares*), pelagic stingray (*Pteroplatytrygon violacea*), porbeagle (*Lamna nasus*) and blue shark (*Prionace glauca*) caught on circle hooks compared to J-hooks during the 2001-2004 period. Further, odds of severe hooking injuries decreased for three shark species caught on circle hooks. I found no conservation benefit for loggerhead turtles (*Caretta caretta*) from circle hook use. Increased circle hook use coincided with increased targeting and higher landings of tunas. Hooking survival rates and, therefore opportunities to reduce bycatch mortalities differed among the ten species commonly discarded or released. Where the odds of survival to the time of release are high (e.g., loggerhead turtles, pelagic stingray, blue shark), methods to reduce post-release mortality can be considered. Where the odds of hooking survival are low (e.g., swordfish and longnose lancetfish, *Alepisaurus ferox*), methods to reduce encounter rates would have greater conservation impact.

2.1 Introduction

Opportunities to reduce bycatch mortality occur throughout the fishing process, from avoidance of areas or seasons with high concentrations of unwanted catch to handling practices that increase post-release survival (Hall 1996). Multispecies commercial fisheries, such as pelagic longline fisheries for swordfish (*Xiphias gladius*) and tunas (*Thunnus* spp.), discard or release a range of species and size classes. Understanding differences in the likelihood of survival among these groups of animals helps identify opportunities to reduce bycatch mortality. For species, or sizes classes, that can survive the capture process, methods to reduce post-hooking mortality can be considered in fisheries and conservation management strategies. For bycatch with high hooking mortality levels, management strategies should focus on earlier stages in the capture process, such as minimizing encounter rates.

Hooking survival rates may differ among species and among size classes within species. In catch and release recreational fisheries, fishing choices such as hook and bait types used, retrieval time, and handling practices affect both hooking survival rates and likely post-hooking survival, through hooking injury and severity (e.g., Muoneke and Childress 1994; Prince et al. 2007; Reeves and Bruesewitz 2007). Size effects, with smaller fish having lower survival rates, have been reported in commercial hook and line fisheries (e.g., Neilson et al. 1989; Milliken et al. 1999; Diaz and Serafy 2005). Hooking survival rates for species caught on pelagic longline gear ranges from less than 10% to nearly 100% survival at haulback when the gear is retrieved (Ward et al. 2004; Kerstetter and Graves 2006a). Estimates of post-release survival are similarly variable. Research using satellite telemetry has shown survival levels of 31% to 100% for a few bycatch species released from pelagic longline fisheries (e.g., Hays et al. 2003; Chaloupka et al. 2004; Kerstetter and Graves 2006b; Moyes et al. 2006).

Pelagic longlines, consisting of a main line suspended by floats and with baited hooks hanging below, are used to fish swordfish and tuna worldwide. Although the general design is simple, differences in how and where the gear is fished (such as fishing depth, baits and hooks used, setting time and locations) affect catch rates of target and bycatch species (e.g., Stone and Dixon 2001; Ward et al. 2004; Beverly et al. 2008). Much research in swordfish and tuna longline fisheries has focused on the use of circle hooks to reduce bycatch catch rates, hooking mortality and post-hooking mortality – especially among marine turtles (Watson et al. 2005; Read 2007; Brazner and McMillan 2008). The Canadian fleet began switching to circle hooks in 1996. Now, over three-quarters of the hooks fished are circle hooks (DFO 2004; T. Atkinson, Hi-Liner Fishing Gear pers. comm. 2008). Increased circle hook use coincided with increased targeting and catch rates of bigeye (*T. obesus*) and yellowfin tunas (*T. albacares*) and a shift from a competitive to an individual quota management system. Because of these changes in the Canadian pelagic longline fleet in the North Atlantic, this fishery offers a unique opportunity to evaluate efficacy of this bycatch reduction method in a rapidly changing commercial fishery.

Reducing harm to or mortality of bycatch – defined here as captured animals returned to the sea, either discarded dead or released alive – is a management and conservation focus. Bycatch from this pelagic longline fishery includes species listed by international conservation organizations, such as leatherback (*Dermochelys coriacea*) and loggerhead turtles (*Caretta caretta*); commercially fished species for which there are landings or size-based regulations such as bluefin tuna (*Thunnus thynnus*) and swordfish; and species such as pelagic stingray (*Pteroplatytrygon violacea*) and blue shark (*Prionace glauca*), for which there are limited or non-existent markets. Many of these species are common bycatch in other pelagic longline fisheries. My objectives here are 1) to identify bycatch species or size classes more (or less) likely to survive the capture process, 2) to identify those fishing variables that increase the odds of bycatch survival during capture and post-release, and 3) to evaluate how changes to fishing practices, directed at reducing harm or mortality levels of bycatch, affect numbers of landed catch. Information on species and size-specific hooking survival will help in evaluating mitigation strategies, and in developing fishery and conservation management plans for the suite of species discarded or released from pelagic longline gear.

2.2 Methods

2.2.1 Fisheries observer data

Data were obtained from the international observer program database, created and maintained by the Population Ecology Division of the Canadian Department of Fisheries and Oceans (DFO). As part of an ongoing monitoring program, fisheries observers identify species, estimate or measure animal length, and record whether bycatch were discarded dead or released alive. Fisheries observers do not record fish status (alive or dead) for fish brought onboard and later landed. Observers quickly assess bycatch release status, based on injuries and movement, when the gear is retrieved and bycatch are alongside the vessel. Bycatch release status is coded as unable to determine, alive (with and without injury), dead, shark bit and moribund. I reduced the release status category to alive and dead. Shark bit, moribund, and dead bycatch were coded as dead. Bycatch of unknown status were not included in these analyses.

Information on fishing operations such as location, starting and ending time, and details of gear configuration (i.e., longline length, hook type, bait used) are also recorded. The Canadian pelagic longline fleet fishes in the Northwest Atlantic along the Scotian Shelf and Grand Banks, and in international waters where other fleets also target pelagic fish (Figure 2.1). The fleet is active from May through to November. There is no Canadian pelagic longline fleet fishing for swordfish or tunas in the Pacific. Since 2001, observer deployments are intended to reflect the spatial and temporal distribution of the fleet. Annual observer coverage, expressed as a percentage of sea days, has ranged from 5% to 18%. Gear is generally set shallow, to fish in the upper 20 m (Brazner and Macmillan 2008).

Prior to the 2001 fishing season, observers' tasks were primarily related to landed species; length estimates or release condition of bycatch were not consistently recorded (M. Showell, DFO, pers. comm. 2006). We, therefore, chose data collected during the period 2001-2004 to model the effects of hook type, soak time, and animal length on the odds of bycatch survival. Circle hooks (size 16/0) are the most common hook type used in this fishery (Brazner and McMillan 2008) followed by J-hooks and offset J-hooks, either 8/0 or 9/0 (Figure 2.2). Offset J-hooks had a 20°-30° offset, similar to control hooks used by Watson et al. (2005). Soak time (T) was calculated as median set duration. Times were recorded at four points during each set: start and end of setting and start and end of hauling. To determine the mid-point or median soak time, I averaged the shortest time hooks were in the water (end of setting until start of hauling) with the longest soak time (start of setting to end of hauling). Lengths (L), measured or estimated, included sea turtle carapace length, swordfish lower jaw fork length and fork length for other fish species. Other possible explanatory variables recorded in the observer data, such as water temperature or bait type, were excluded from these analyses because of incomplete information or because categories were not clearly differentiated. For example, water temperatures were recorded for approximately half of the sets observed between 2001 and 2004, and bait was commonly recorded as a mix of herring, mackerel and squid.

I identified common bycatch species based on abundance (accounting for greater than 1% of individuals discarded or released) and frequency of occurrence (present in more than 10% of observed sets) in any year between 2001 and 2004. Data collected in 2005 and 2006 were then used to test whether the relationships held, whether survival estimates changed when data not used in the model-building process were added.

2.2.2 Odds of survival models

Because survival is a binomial variable (i.e. alive or dead), I used a Generalized Linear Model (GLM) with logit response (McCullagh and Nelder 1989), also known as logistic regression, to estimate the odds of common bycatch species surviving the capture process. The response variable was odds of survival,

$$\text{Odds} = p/(1-p) \qquad (2.1)$$

where p is the proportion of bycatch of a given species released alive. A categorical variable with 3 levels was included for hook type (H), which may affect hooking survival (e.g., Watson et al., 2005; Kerstetter and Graves, 2006a), was included in the models. Continuous variables for individual lengths and soak time were used. Model selection was based on likelihood ratio tests (LRT), which compared the change in deviance between models with two-way interactions and simpler models (Agresti 2007). Simpler models were chosen if the change in deviance was not significant or if more complex models failed to converge to a maximum likelihood estimate. Models used to estimate the odds of survival for each species, including all two-way interactions, were

$$\text{Odds} = e^{\mu} + \text{error} \tag{2.2a}$$

and,

$$\mu = \beta_0 + \beta_H H + \beta_L L + \beta_T T + \beta_{HL} H \cdot L + \beta_{HT} H \cdot T + \beta_{LT} L \cdot T \tag{2.2b}$$

where β corresponds to the intercept and parameters to be estimated for each explanatory variable. Mean response (μ) is the probability of survival calculated for a given hook type, and for the rate of change in survival with respect to soak time (T) and animal length (L).

The fishery management system changed during the 2001-2004 period, which likely affected targeting, handling and discarding practices. Swordfish and tuna longliners fished within a competitive quota fishery until 2002, then an Individual Transferable Quota (ITQ) management system was introduced and targeting of tunas increased (DFO 2004). Under ITQ management fishers are no longer racing to catch quota before other fishers, they may make different decisions about which species to target and retain. Because these analyses were limited to data on animals discarded or released, changes in discarding practices of target species affect survival estimates. To evaluate whether the switch to an ITQ system of fisheries management affected the relationship between main effects (hook type, animal length and soak time) and odds of survival, I added a categorical variable for management system (M) to the model:

$$\mu = \beta_0 + \beta_H H + \beta_L L + \beta_T T + \beta_M M + \beta_{HM} H \cdot M + \beta_{LM} L \cdot M + \beta_{TM} T \cdot M, \qquad (2.3)$$

If interaction terms were significant, indicating that the relationship between main effects and odds of survival differed between the two management periods, I excluded data collected in 2001 under a competitive management system.

To determine if relationships between main effects and hooking survival held (model stability), observer data from subsequent years were added to the data set. An additional categorical explanatory variable (D) indicated whether data were collected between 2001-2004 or were from the test data set (2005-2006). If interaction terms between data set and main effects were significant then the relationship between the main effects and the odds of survival was not stable across the two data sets:

$$\mu = \beta_0 + \beta_H H + \beta_L L + \beta_T T + \beta_D D + \beta_{HD} H \cdot D + \beta_{LD} L \cdot D + \beta_{TD} T \cdot D, \qquad (2.4)$$

2.2.3 Effects on landed catch and post-hooking survival

Because bycatch mitigation measures will likely be more readily accepted in commercial fisheries if modifications do not decrease the value of landed catch (e.g., Gilman et al. 2006a; Read 2007), I estimated the effects of fishing variables on landed catch. Landed catch was used as a simple measure of possible impacts for the fleet. Residual plots for initial GLMs (with log links and Poisson error distributions) were unacceptable. Dispersion of residuals increased with fitted values. Using a negative bionomial error distribution, which includes a dispersion parameter (k^{-1}) in the equation (Agresti 2007), resulted in acceptable residual plots. Total landed catch was calculated as the number of all fish retained per set and included swordfish, tunas, and other landed species such as mahi-mahi (*Coryphaena hippurus)* and shortfin mako (*Isurus oxyrinchus*). Again, two-way interactions were evaluated using likelihood ratio tests, comparing change in deviance between models (Agresti 2007). Number of hooks fished per set was included in landed catch models to account for effort (E) differences among hook types (H) and soak times (T):

$$E(Y) = \mu, \quad (2.5a)$$

$$\mathrm{var}(Y) = \mu + \mu^2 \cdot k^{-1} \quad (2.5b)$$

and,

$$\log(\mu) = ß_0 + ß_H H + ß_T T + ß_E E + ß_{HT} H \cdot T + ß_{HE} H \cdot E + + ß_{TE} T \cdot E \quad (2.5c)$$

Further, because post-hooking survival likely depends on injury type and hooking location (Epperly and Boggs 2004; Horodysky and Graves 2005; Campana et al. 2006), I used logistic regression to determine if hooking location differed between hook types for bycatch species commonly released alive. When animals swallowed the hook (e.g., hooks were embedded in the esophagus) they were categorized as 'gut-hooked'. I limited analysis of hooking injury to species with high likelihood of hooking survival, where more than 60% of the bycatch was released alive. Observer data collected between 2001 and 2006 was used in the landed catch and hooking location models.

Likelihood ratio tests were used in model selection and to evaluate overall model significance (Agresti 2007). The significance level of p=0.05 was used in all analyses. When models failed to converge or when wide confidence intervals indicated poorly resolved model terms, I considered whether sparse data in categorical variables affected estimates. Few individuals within categorical variables or few instances of a binomial response (e.g., 3 gut-hooked versus 250 mouth-hooked individuals) will produce inefficient parameter estimates, with wide confidence intervals (Menard 1995; Agresti 2007). Because sparse data within categorical variables limited parameter estimates, I removed categories containing less than 10 observations. I used the open-source statistical package R, with 'MASS' and 'car' packages for GLM confidence intervals and diagnostics, to implement and evaluate the models (Venables and Ripley 2002; Fox 2007; R Development Core Team 2007).

2.3 Results

Ten species were identified as common bycatch, species that were discarded from more than 10% of observed sets or accounting for more than 1% of bycatch for any year between 2001 and 2004. During this time period, 859 sets were observed and approximately 950,000 hooks fished on observed sets (Table 2.1). Median set duration for sets fishing J-hooks, offset J-hooks and circle hooks were 13.5, 13.8 and 12.9 h, respectively. Common bycatch included species such as swordfish and bigeye tuna, which are generally landed, and loggerhead turtles and pelagic stingray, which are always released or discarded (Figure 2.3). Hooking survival was calculated only for bycatch – animals returned to the sea – and differed among species. Over 90% of loggerhead turtles, pelagic stingray and blue shark bycatch were released alive from the gear but only one-third of swordfish and longnose lancetfish (*Alepisaurus ferox*) bycatch were released alive (Figure 2.3).

2.3.1 Odds of survival estimates

Yellowfin and bigeye tunas, shortfin mako and longnose lancetfish hooking survival estimates were not affected by the change from competitive fishery to an

ITQ management system; interaction terms between management system and main effects were not significant. Interaction terms between management system and main effects were significant for swordfish, porbeagle (*Lamna nasus*) and blue shark; therefore, I used data from the ITQ management system, caught between 2002 and 2004 (Table 2.2). I was unable to model the effects of management system on bluefin tuna or pelagic stingray hooking survival. The bluefin tuna model, with a management system interaction term, did not converge to a maximum likelihood estimate. Few pelagic stingray were discarded dead under either management system, causing poorly resolved model coefficients. Data from 2001 to 2004 were used in the models for these species. I did not build logistic regression models for loggerhead turtles because almost all survived the hooking process – 404 out of 407 hooked loggerhead turtles were released alive.

Odds of survival were significantly higher on circle hooks than on J-hooks for all common bycatch species, except shortfin mako and longnose lancetfish (Table 2.3). There was no significant difference in the odds of survival for longnose lancetfish, porbeagle, shortfin mako, and blue sharks caught on J-hooks and those caught on offset J-hooks (Tables 2.3 and 2.4). Logistic regression models for porbeagle and blue shark included two-way interactions (Table 2.4); the effect of soak time on hooking survival differed between hook types for both species.

Logistic regression models were not significant for three species which were both discarded as bycatch (for regulatory or other reasons) and were also retained for sale. Likelihood ratio tests for the bluefin tuna logistic regression model showed that the odds of survival were not related to hook type, soak time, and fish length (LRT=2.3, *df*=4, *p*=0.68). Few bigeye tuna were caught on J-hooks; one of ten caught on this hook type was discarded dead. Similarly, no bigeye tuna were discarded or released from offset J-hooks (Table 2.1). Therefore, the logistic regression model for bigeye tuna did not include a model term for hook type. Bigeye survival odds were not related to fish length or soak time (LRT=2.5, *df*=2, *p*=0.28). None of the model coefficients for bluefin or bigeye tuna were significant. While the overall model for shortfin mako was not significant at $p<0.05$ level (LRT=8.8, *df*=4, *p*=0.66), odds of survival were positively related to fish length for this species (Table 2.3).

Swordfish, yellowfin tuna, porbeagle, and blue shark were 2 to 5 times more likely to survive the capture process on circle hooks than on J-hooks (Figure 2.4). Pelagic stingray also had higher odds of survival on circle hooks. Few pelagic stingray were discarded dead from either circle hooks (2%) or J-hooks (10%). Wide confidence intervals for this species indicated that the estimate was poorly resolved, due to low occurrence of one of the binomial responses (Menard 1995). Odds of survival of porbeagle and blue shark differed between hook types and with soak time – for both shark species caught on J-hooks the probability of hooking survival decreased significantly with increased soak time (Figure 2.5).

The probability of swordfish, yellowfin tuna, and longnose lancetfish survival decreased with increased soak time. Using model coefficients (Table 2.3), I calculated that 42% of longnose lancetfish (average fork length 110 cm) caught on J-hooks were released alive from 12 h sets. Only 28% were released alive from 16 h sets. Similarly, the probability of average-sized swordfish and yellowfin tuna bycatch (e.g., 106 and 81 cm) survival decreased 6% and 15%, respectively on longer soak times. Larger mako sharks had higher odds of being released alive (Table 3). Larger swordfish and pelagic stingray bycatch were less likely to be alive at haulback. Fish length did not significantly affect the odds of survival for yellowfin tuna, blue shark, and longnose lancetfish (Tables 2.3 and 2.4).

The odds of survival of swordfish and blue shark caught on circle hooks (relative to J-hooks) changed when data from 2005 and 2006 was added to the models. Likelihood ratio tests for swordfish (LRT=50.4, df=9, p<0.001), and blue shark (LRT=184.3, df=9, p<0.001) logistic regression models were significant. Interaction terms for hook type and data set represented survival odds for fish caught on circle hooks relative to those for fish caught on the reference hook (J-hook) for the two time periods (hook x data set: swordfish, Deviance=6.408, df=2, p=0.04; blue shark, Deviance=37.515, df=2, p<0.001). The change in relative survival probabilities reflected an increase in survival probabilities on J-hooks. For example, 13% more swordfish bycatch were released alive from J-hooks during the 2005-2006 time period than during the 2001-2004 period. For other common bycatch species, I was unable to estimate the odds of hooking survival relative to hook type during the latter time period because either few bycatch were observed on J- or offset J-hooks (bluefin or yellowfin tuna, longnose lancetfish), or few were discarded dead (pelagic stingray, shortfin mako, bigeye tuna, porbeagle shark). Similarly, no loggerhead turtles were discarded dead from observed trips in 2005 and 2006.

2.3.2 Landed catch and post-hooking survival

Swordfish landed catch was higher on sets that fished J-hooks or offset J-hooks. Numbers of tunas and of all landed catch were higher on sets that fished circle hooks (Figure 2.6). Few bigeye, yellowfin or albacore (*T. alalunga*) tunas were landed from sets that fished J-or offset J-hooks, indicating these hooks were not used when targeting tunas. Negative binomial regression models for swordfish and all landed catch included an interaction term for median set duration and the effort measure (number of hooks hauled), whereas models of tunas landed included an interaction term between hook type and effort. Estimated landed catch was based on average number of hooks fished (1115 hooks per set), and 12 and 16 h soak times (Figure 2.6). All landed catch estimates increased with increased soak times.

Hooking location differed between circle and J-hooks. Among the five species commonly released alive, sharks caught on circle hooks were more likely mouth-hooked. Porbeagle were four times (95% CI: 2.1 - 7.2) more likely mouth-hooked on circle hooks. Shortfin mako and blue shark were twice as likely mouth-hooked on circle hooks (95% CI: 1.1 - 3.7 and 1.9 - 2.7, respectively). Hooking location did not significantly differ for loggerhead sea turtles hooked on the three hook types (LRT=4.64, df=3, p=0.20). The odds ratio for loggerhead turtles caught on circle hooks relative to J-hooks was 0.97, not significantly different from a 1:1 relationship. Few pelagic stingray swallowed hooks of either type; only 10 out of 942 pelagic stingray caught between 2001 and 2006 swallowed the hooks. I therefore did not model the odds of hooking location for this species.

2.4 Discussion

Hooking survival rates and, therefore, opportunities to reduce bycatch mortalities, differed among the ten species commonly discarded or released from the Canadian Atlantic longline fishery for swordfish and tuna. My objectives were to determine species or size-specific hooking survival rates, to determine which fishing practices increased the odds of survival and what, if any, effects those fishing practices had on landed catch or post-release survival. In the Canadian longline fleet, the switch from J-hooks to circle hooks likely increased bycatch hooking survival and decreased post-release mortality. The switch to circle hooks coincided with increased targeting of tunas and higher landings of those fish. Longer soak times increased landed catch, however, this fishing practice also increased the likelihood of hooking mortalities.

2.4.1 Species and size-specific survival probabilities

Common bycatch for the Canadian fishery are discarded or released from other pelagic longline fisheries in the North and South Atlantic (e.g., Watson et al. 2005; Kerstetter and Graves 2006a; Kerstetter et al. 2007) and in the Western Pacific (e.g., Ward et al. 2004). Survival rates were comparable among the different fisheries. Most loggerhead turtles, blue sharks, and pelagic stingrays were released alive (Kerstetter and Graves 2006a; Kerstetter et al. 2007; Read 2007). Kerstetter and Graves (2006a) also reported low survival rates for lancetfish (*Alepisaurus* sp.). Swordfish hooking survival levels in US Atlantic (Kerstetter and Graves 2006a) and Brazilian fleets (Kerstetter et al. 2007) were similar to those reported here with only 20% to 30% of swordfish alive at haulback. These hooking survival rates suggest opportunities for bycatch mitigation may be similar among these different fisheries. Mitigation strategies for loggerhead turtles, blue sharks, and pelagic stingray could include careful handling and release, whereas strategies to reduce swordfish and longnose lancetfish mortalities would have to focus earlier in the capture process.

Our results did not support the expected positive relationship between fish length and survival (e.g., Neilson et al. 1989; Diaz and Serafy 2005); only shortfin mako showed an increase in the odds of survival with fish length. Size-related handling and discarding practices likely affected survival rates (Muoneke and Childress 1994). For landed species, such as swordfish, bigeye, and yellowfin tunas, discarding practices reflect minimum size regulations and commercial marketability. Swordfish, for example, were discarded if below minimum landing regulations or if damaged by predation (coded as shark bit). When GLMs were run without 45 shark bit swordfish, the negative relationship between fish length and survival was no longer significant (Deviance=1.699, df=1, p=0.19). Handling practices likely affected hooking survival of bycatch such as blue shark, which are rarely landed by the Canadian fleet, and may account for differences in survival estimates reported here and by Diaz and Serafy (2005). For small (75 cm) blue shark caught by US longliners off the Grand Banks, Diaz and Serafy (2005) estimated 47% would be released alive after 14 h soak times. Since J-hooks were the predominant hook type for the US fleet between 1992 and 2002 (Hoey and Moore 1999; Watson et al. 2005), I based my calculations on this hook type and estimated 87% of small blue shark would be released alive. Either observer protocols differed markedly or survival rates reflect differences in fishing and discarding practices. Hoey and Moore (1999) reported that hooks were removed from blue sharks - and accounted for high mortality levels - on several US longline fishing trips to the Grand Banks during the same time period. These were likely included in Diaz and Serafy's (2005) models. A direct comparison of observer protocols is warranted because hooking mortality estimates affect stock assessment and management decisions (Diaz and Serafy 2005; Campana et al. 2006). If, however, the difference in survival rates reflect fishing and discarding practices then the difference in survival estimates identifies an important opportunity to reduce blue shark bycatch mortalities.

Despite limitations of using fisheries observers' estimates of hooking survival, these data provide the basis for building demographic models to estimate population-level impacts of existing fishing practices. Because observers did not record the capture status of fish that were landed, I was unable to determine the physiological relationship between length and survival for species such as swordfish, bigeye and yellowfin tuna. Discard mortality data are, however, needed to evaluate how discards affect overall fishing mortality levels and consequently, the efficacy of conservation or fisheries management plans (Coggins et al. 2007). Further, for bycatch species which are rarely landed and for which assessments are limited by data availability (e.g., loggerhead turtles and blue shark), species and size-specific survival data can be used in stage-based demographic models to identify key stages for conservation (Crouse et al. 1987; Aires da Silva and Gallucci 2007).

2.4.2 Fishing practices

Much conservation research on pelagic longline fisheries has focused on differences in catch rates and mortality levels – both at haulback and post-release mortality estimated from injury type and release condition – between straight-shank (J-hooks or Japanese tuna hooks) and circle hooks (e.g., Watson et al. 2005; Yokota et al. 2006; Read 2007). Odds of hooking survival were significantly higher for common bycatch species caught on circle hooks in the Canadian pelagic longline fishery (Figure 3). Similarly, Kerstetter and Graves (2006a) showed survival rates were higher on circle hooks for almost all of the commonly caught fish. I found, however, odds ratios for swordfish and blue shark hooking survival changed during the latter time period, reflecting an increase in the odds of survival on J-hooks. Increased odds of survival likely does not reflect differences in observers' assessments because many of them were onboard vessels fishing circle hooks or were onboard vessels fishing during the earlier period. Increased targeting of tunas and decreased observer coverage meant that survival estimates for fish caught on J-hooks were based on fewer vessels. Decreased variability or improved practices among observed vessels may have affected survival estimates. For example, the swordfish and tuna longline fleet purchased turtle dehooking kits to be used on all vessels starting in 2005 (DFO 2004). These line cutters and dehookers can be used to remove hooks from other bycatch species (Watson et al. 2005). Increased use of these kits could have contributed to higher bycatch survival rates in recent years.

Circle hooks are widely used in catch and release recreational fisheries to decrease the amount of deep-hooking or gut-hooking (Cooke and Suski, 2004), which is considered one of the worst hooking injuries for post-release survival (Prince et al. 2007; Reeves and Bruesewitz 2007). Odds of mouth-hooking relative to gut-hooking were higher on circle hooks for three shark species. Similarly, Watson et al. (2005) reported a significant decrease in gut-hooking of blue sharks caught on circle hooks. Unlike Watson et al. (2005), Brazner and McMillan (2008), Gilman et al. (2007) and the studies reviewed by Gilman et al. (2006a) and Read (2007), I found no conservation benefit for loggerhead turtles – one of the bycatch species for which conservation benefits were expected. Conflicting results reported here and by Brazner and McMillan (2008) result from differing statistical approaches. Both studies used observer data from the Canadian longline fleet. Brazner and McMillan (2008) tested for difference in the proportion of turtles gut-hooked relative to all loggerheads captured, including entangled turtles and those for which hooking location was not recorded. In contrast, the logistic regression approach used here allows the direct comparison of one outcome relative to the other (McCullagh and Nelder 1989), in this case mouth-hooking relative to gut-hooking. Because I show no difference in hook location, any conservation benefit for this species depends on differences in dehooking and handling practices for loggerhead turtles caught on different hook types. There were conservation benefits for other common bycatch species; odds of severe hooking injuries were significantly lower for porbeagle, shortfin mako and blue shark caught on circle hooks than for those caught on J-hooks.

Increased soak time generally increases hooking mortality although magnitude of the effect differs among species (Ward et al. 2004). Odds of survival decreased with longer soak times for swordfish, yellowfin tuna and longnose lancetfish. Landed catch, however, increased with longer soak times. Thus, there appears to be a trade-off between landed catch and numbers of these fish available for live release. When circle hooks were fished, there was no trade-off between landed catch and hooking mortalities among porbeagle or blue shark. Hooking survival for these species only decreased, with longer soak time, when caught on J-hooks. The unexpected slight increase in survival probabilities of porbeagle caught on circle hooks (Figure 2.5) was driven by few surviving porbeagle caught on the longest duration sets (>16 h).

Our analysis showed that switching to circle hooks and shorter soak times increased hooking survival for a number of common bycatch species caught by the Canadian Atlantic longline fishery. Similar fishing practices may increase bycatch survival odds in other longline fisheries. Comparable observer data from other nations' fleets could be used to evaluate this possibility. If observers recorded capture status (live, dead or unknown) for all catch (e.g., Kerstetter and Graves 2006a), researchers could better determine the relationship between fish length and hooking survival for both landed and discarded catch. Recorded soak time per hook or longline section would better reflect time spent on hooks than median soak time used here (e.g., Ward et al. 2004; Yokota et al. 2009). Further, systematic records of dehooking and discarding practices could help identify bycatch mitigation opportunities in this and other pelagic longline fisheries. Existing data from other pelagic longline fisheries – in the North Atlantic (e.g., Diaz and Serafy 2005), throughout the Pacific (e.g., Ward et al. 2004) and elsewhere – could be used to identify species or size-specific vulnerabilities and to identify mitigation opportunities.

Our data show conservation benefits of circle hook use for a number of common bycatch species, but circle hook use may not decrease catch rates of common bycatch species, such as blue shark and loggerhead turtles (Watson et al. 2005; Yokota et al. 2006; Mejuto et al. 2008). Catch rates of loggerhead turtles increased when hooks were baited with squid (e.g., Yokota et al. 2009). Mejuto et al. (2008) reported increased loggerhead catch rates with squid bait irrespective of hook type, whereas Watson et al. (2005) noted lower catch rates on circle hooks. Conversely, results from experimental fishing trials, using alternating hook types within longline sets, showed reduced swordfish catch rates on circle hooks baited with squid (Watson et al. 2005). Watson et al. (2005) reported small increases in swordfish catch rates when circle hooks were baited with mackerel. Few vessels in the Canadian longline fishery used J-hooks when targeting tunas; indicated by the low numbers of tunas landed when fishing J- or offset J-hooks (Figure 2.6). Increased swordfish catch when vessels were fishing J-hooks likely reflect targeting decisions such as location, setting time, and bait, as well as hook type. Mandating a complete shift to circle hooks would have a greater impact on vessels targeting swordfish than those targeting tunas. Such a mandated change would likely increase hooking survival and decrease the severity of hooking injuries, but may not decrease incidence of common bycatch.

2.4.3 Broader implications

Knowledge of hooking survival helps evaluate current mitigation strategies. For example, Canada, like other countries contributing to International Commission for the Conservation of Atlantic Tunas (ICCAT) management in the North Atlantic, regulates the proportion of small swordfish that can be landed (DFO 2004). As a conservation measure, minimum-size regulations either encourage fishing effort in times and places where small fish are not abundant or mandate release of undersized fish. If minimum size regulations increase discard rates but not encounter rates, then conservation benefits depend upon a high proportion of small fish released live and high post-release survival rates (Muoneke and Childress 1994; Reeves and Bruesewitz 2007). This was not the case for small swordfish released from pelagic longline gear. Because 60% to 75% of swordfish bycatch are discarded dead, minimum size regulations have limited conservation benefit. Efforts to reduce mortality of small swordfish should focus earlier in the capture process, such as avoiding areas or time periods with high abundances of small swordfish. This could be achieved by fleet-wide communication systems and bycatch caps (Gilman et al. 2006b), or by implementing time or area closures where catches of small swordfish occur. Similarly, if reducing mortalities of longnose lancetfish bycatch is identified as a priority, then mitigation strategies should focus on reducing encounter rates.

Our research identified opportunities to reduce bycatch mortality at one stage during the capture process, based on available data from the commercial fishery and applied to a suite of species. Even though I was unable to estimate the odds of survival for loggerhead turtles or the odds of hooking injuries in pelagic stingray, these data did point toward important conservation opportunities. Few loggerhead turtles were discarded dead and few pelagic stingray were deeply hooked. This suggests bycatch mitigation strategies for these species could include gear removal and careful release. These species, as well as porbeagle and blue sharks, are possible candidates for post-release survival studies. I recognize sub-lethal capture effects increase post-hooking mortality (e.g., Borucinska et al. 2002; Davis 2002; Horodysky and Graves 2005). Further, bycatch mitigation strategies that reduce interaction rates also reduce capture stressors. For example, using mackerel bait would likely be a better mitigation strategy for loggerhead turtles, reducing catch rates and, therefore, sub-lethal effects. Research on post-release mortality or behavioural effects of capture on large pelagic species using satellite tags has, thus far, been limited to a few species (Polovina et al. 2000; Chaloupka et al. 2004; Horodysky and Graves 2005; Moyes et al. 2006). In contrast, existing fisheries observer data, and the methods described here, could be used to determine current hooking mortality levels and identify mitigation opportunities for a suite of species throughout the world's oceans. In the Canadian Atlantic longline fisheries for swordfish and tunas, methods to reduce post-release mortality can be considered for some – but not all – common bycatch.

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2.5 References

Agresti, A., 2007. An Introduction to Categorical Data Analysis, John Wiley & Sons, Inc., Hoboken, New Jersey.

Aires da Silva, A.M., Gallucci, V.F., 2007. Demographic and risk analyses applied to management and conservation of the blue shark (*Prionace glauca*) in the North Atlantic Ocean. Marine and Freshwater Research 58, 579-580.

Beverly, S., Curran, D., Musyl, M., Molony, B., 2009. Effects of eliminating shallow hooks from tuna longline sets on target and non-target species in the Hawaii-based pelagic tuna fishery. Fisheries Research 96, 281-288.

Borucinska, J., Kohler, N., Natanson, L., Skomal, G., 2002. Pathology associated with retained fishing hooks in blue sharks, *Prionace glauca* (L.), with implications for their conservation. Journal of Fish Diseases 25, 515-521.

Brazner, J.C., McMillan, J., 2008. Loggerhead turtle (*Caretta caretta*) bycatch in Canadian pelagic longline fisheries: relative importance in the western North Atlantic and opportunities for mitigation. Fisheries Research 91, 310-324.

Campana, S.,E., Marks, L., Joyce, W., Kohler, N.E., 2006. Effects of recreational and commercial fishing on blue sharks (*Prionace glauca*) in Atlantic Canada, with inferences on the North Atlantic population. Canadian Journal of Fisheries and Aquatic Sciences 63, 670-682.

Chaloupka, M., Parker, D., Balazs, G., 2004. Modeling post-release mortality of loggerhead sea turtles exposed to the Hawaii-based pelagic longline fishery. Marine Ecology Progress Series 280, 285-293.

Coggins, L.G., Catalano, M.J., Allen, M.M., Pine III, W.E., Walters, C.J., 2007. Effects of cryptic mortality and the hidden costs of using length limits in fishery management. Fish and Fisheries 8, 196-210.

Cooke, S.J., Suski, C.D., 2004. Are circle hooks an effective tool for conserving marine and freshwater recreational catch-and-release fisheries? Aquatic Conservation Marine and Freshwater Ecosystems 14, 299-326.

Crouse, D.T., Crowder, L.B., Caswell, H. 1987. A stage-based population model for loggerhead sea tuttles and implications for conservation. Ecology 68, 1412-1423.

Davis, M.W., 2002. Key principles for understanding fish bycatch discard mortality. Canadian Journal of Fisheries and Aquatic Sciences 59, 1834-1843.

DFO Fisheries and Aquatic Management, 2004. Canadian Atlantic Swordfish and Other Tunas 2004-2006 Integrated Management Plan. <http://www.dfo-mpo.gc.ca/communic/fish_man/ifmp/swordfish/index_ehtm>.

Diaz, G.A., Serafy, J.E., 2005. Longline-caught blue shark (*Prionace glauca*): factors affecting the numbers available for live release. Fishery Bulletin 103, 720-724.

Epperly S.P., Boggs, C., 2004. Post-hooking mortality in pelagic longline fisheries using "J" hooks and circle hooks. Application of new draft criteria to data from the Northeast Distant Experiments in the Atlantic. Contribution #PRD-03/04-04 of NOAA National Marine Fisheries Service USA. <http://www.sefsc.noaa.gov/PDFdocs/UPR_Epperly_Boggs_2004.pdf>.

Fox, J., 2007. car: Companion to Applied Regression R Foundation for Statistical Computing, Vienna, Austria.

Gilman, E., Zollett, E., Beverly, S., Nakano, H., Davis, K., Shiode, D., Dalzell, P., Kinan, I., 2006a. Reducing sea turtle by-catch in pelagic longline fisheries. Fish and Fisheries 7, 2-23.

Gilman, E., Dalzell, P., Martin, S., 2006b. Fleet communication to abate fisheries bycatch. Marine Policy 30 (4), 360–366.

Gilman, E., Kobayashi, D., Swenarton, T., Brothers, N., Dalzell, P., 2007. Reducing sea turtle interactions in the Hawaii-based longline swordfish fishery. Biological Conservation 139, 19-38.

Hall, M.A., 1996, On bycatches. Reviews in Fish Biology and Fisheries 6, 319-352.

Hall, M.A., Alverson D.L., Metuzals K.I., 2000. By-catch: problems and solutions. Marine Pollution Bulletin 41, 204-219.

Hays, G.C., Broderick, A.C., Godley, B., Luschi, P., Nichols, W.J., 2003. Satellite telemetry suggests high levels of fishing induced mortality in marine turtles. Marine Ecology Progress Series 266, 305-309.

Hoey, J.J., Moore, N., 1999. Captain's report: Multi-species catch characteristics for the U.S. Atlantic pelagic longline fishery. National Fisheries Institute Report to NOAA, National Marine Fisheries Service USA.

Horodysky, A.Z., Graves, J.E., 2005. Application of pop-up satellite archival tag technology to estimate postrelease survival of white marlin (*Tetrapturus albidus*) caught on circle and straight-shank ("J") hooks in the western North Atlantic recreational fishery. Fishery Bulletin 103, 84-96.

Kerstetter, D.W., Graves, J.E., 2006a. Effects of circle versus J-style hooks on target and non-target species in a pelagic longline fishery. Fisheries Research 80, 239-250.

Kerstetter, D.W., Graves, J.E., 2006b. Survival of white marlin (*Tetrapturus albidus*) released from commercial pelagic longline gear in the western North Atlantic. Fishery Bulletin 104, 434-444.

Kerstetter, D.W., Pacheco, J.C., Hazin, F.H., Travassos, P.E., Graves, J.E., 2007. Preliminary results of circle and J-hook comparisons in the Brazilian pelagic longline fishery. ICCAT Collective Volume of Scientific Papers 60, 2140-2147.

McCullagh, P., Nelder, J.A., 1989. Generalized Linear Models, 2nd edn. Chapman & Hall, London.

Mejuto, J., Garcia-Cortés, B., Ramos-Cartelle, A., 2008. Trials using different hook and bait types in the configuration of the surface longline gear used by the Spanish swordfish (*Xiphias gladius*) fishery in the Atlantic Ocean. ICCAT Collective Volume of Scientific Papers 62, 1793-1830.

Menard, S., 1995. Applied Logistic Regression Analysis. Sage Publications, Thousand Oaks, California.

Milliken, H.O., Farrington, M., Carr, H.A., Lent, E., 1999. Survival of Atlantic cod (*Gadus morhua*) in the northwest Atlantic longline fishery. Marine Technology Society Journal 33, 19-24.

Moyes, C.D., Fragoso, N., Musyl, M.K., Brill, R.W., 2006. Predicting postrelease survival in large pelagic fish. Transactions of the American Fisheries Society 135, 1389-1397.

Muoneke, M.I., Childress, W.M., 1994. Hooking mortality: a review for recreational fisheries. Reviews in Fisheries Science 2, 123-156.

Neilson, J.D., Waiwood, K.G., Smith, S.J., 1989. Survival of halibut (*Hippoglossus hippoglossus*) caught by longline and otter trawl gear. Canadian Journal of Fisheries and Aquatic Sciences 46, 887-897.

Polovina, J.J., Kobayashi, D.B., Parker, D.M., Seki, M.P., Balazs, G.H., 2000. Turtles on the edge: movement of loggerhead turtles (*Caretta caretta*) along oceanic fronts, spanning longline fishing grounds in the central North Pacific, 1997-1998. Fisheries Oceanography 9, 71-82.

Prince, E.D., Snodgrass, D., Orbesen, E.S., Hoolihan, J.P., Serafy, J.E., Schratwieser, J.E., 2007. Circle hooks, 'J' hooks and drop-back time: a hook performance study of the south Florida recreational live-bait fishery for sailfish, *Istiophorus platypterus*. Fisheries Management and Ecology 14, 173-182.

Read, A.J., 2007. Do circle hooks reduce the mortality of sea turtles in pelagic longlines? A review of recent experiments. Biological Conservation 135, 155-169.

Reeves, K.A., Bruesewitz, R.E., 2007. Factors influencing the hooking mortality of walleyes caught by recreational anglers on Mille Lacs, Minnesota. North American Journal of Fisheries Management 27, 443-452.

R Development Core Team, 2007. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Stone, H.H., Dixon, L.K., 2001. A comparison of catches of swordfish, *Xiphias gladius*, and other pelagic species from Canadian longline gear configured with alternating monofilament and multifilament nylon gangions. Fishery Bulletin 99, 210-216.

Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S. Springer, New York.

Ward, P., Myers, R.A., Blanchard, W., 2004. Fish lost at sea: the effect of soak time on pelagic longline catches. Fishery Bulletin 102, 179-195.

Watson, J.W., Epperly, S.P., Shah, A.K., Foster, D.G., 2005. Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Canadian Journal of Fisheries and Aquatic Sciences 62, 965-981.

Yokota, K., Kiyota, M., Minami, H., 2006. Shark catch in a pelagic longline fishery: Comparison of circle and tuna hooks. Fisheries Research 81, 337-341.

Yokota, K., Kiyota, M., Okamura, H., 2009. Effect of bait species and colour on sea turtle bycatch and fish catch in a pelagic longline fishery. Fisheries Research 97, 53-58.

Table 2.1. Summary of bycatch (limited to animals discarded dead or released alive) lengths and numbers observed in each hook category (J: J-hooks, size 8/0 or 9/0 J-hooks, OJ: size 8/0 or 9/0 offset J-hooks; C: size 16/0 circle hooks). Sample sizes (in parentheses) for hook categories indicate number of sets observed for each hook type.

Species	Number	Length (cm)			Hook type (859)		
	observed	Mean	s.d.	Range	J (193)	OJ (70)	C (596)
Swordfish *Xiphias gladius*	1271	106.1	20.1	45-200	358	119	794
Bluefin tuna *Thunnus thynnus*	164	171.3	47.1	57-305	28	13	123
Yellowfin tuna *Thunnus albacares*	642	81.3	10.9	50-118	113	6	523
Bigeye tuna *Thunnus obesus*	133	109.2	25.1	40-175	10	0	123
Porbeagle shark *Lamna nasus*	611	95.8	18.9	50-250	306	129	176
Blue shark *Prionace glauca*	10549	157.2	51.0	30-450	1684	468	8397
Shortfin mako *Isurus oxyrinchus*	389	89.9	35.0	45-300	111	33	245
Pelagic stingray *Pteroplatytrygon violacea*	781	72.3	19.4	12-140	157	29	595
Longnose lancetfish *Alepisaurus ferox*	218	114.9	31.6	50-210	45	12	161
Loggerhead turtle *Caretta caretta*	407	90.9	26.1	40-150	73	11	323

Note: These data were used in logistic regression models. Swordfish, blue shark and porbeagle counts were based on 565 sets observed during 2002-2004: 100 sets fished J-hooks, 50 sets fished offset-J hooks and 415 sets fished circle hooks.

Table 2.2. Modeled effects of management system on odds of survival estimates for swordfish, porbeagle, and blue shark. Likelihood ratio tests (LRT) were conducted to determine overall model significance (*df*=9, *p*<0.001).

Species	Term	Coefficient	SE	z value	Pr(>|z|)
Swordfish (LRT=145.8, *df*=9, *p*<0.001)					
	J-hook	0.073	0.811	0.090	0.928
	Circle hook	-1.286	0.221	-5.807	<0.001
	Offset J-hook	-0.077	0.458	-0.169	0.866
	Soak time	-0.155	0.047	-3.339	<0.001
	Length	-0.017	0.004	4.447	<0.001
	Management system	-0.303	0.879	-0.345	0.730
	Management system x circle hook	2.052	0.263	7.803	<0.001
	Management system x offset J	0.753	0.510	1.477	0.140
	Management system x soak time	0.158	0.047	3.388	<0.001
	Management system x length	-0.025	0.005	-5.244	<0.001
Porbeagle (LRT=62.3, *df*=9, *p*<0.001)					
	J-hook	-0.549	1.313	-0.418	0.676
	Circle hook	-0.608	0.771	-0.788	0.430
	Offset J-hook	0.849	0.313	2.713	0.007
	Soak time	0.013	0.096	0.132	0.895
	Length	0.015	0.009	1.633	0.102
	Management system	3.579	1.528	2.343	0.019
	Management system x circle hook	1.505	0.815	1.846	0.065
	Management system x offset J	-1.662	0.384	-4.329	<0.001
	Management system x soak time	-0.053	0.106	-0.497	0.619
	Management system x length	-0.034	0.011	-3.203	0.001

Blue shark (LRT=319.2, *df*=9, *p*<0.001)				
J-hook	1.048	0.345	3.038	0.002
Circle hook	0.881	0.114	7.757	<0.001
Offset J-hook	0.889	0.250	3.564	<0.001
Soak time	-0.019	0.024	-0.794	0.427
Length	0.004	0.001	4.620	<0.001
Management system	0.778	0.373	2.082	0.037
Management system x circle hook	-0.124	0.143	-0.872	0.383
Management system x offset J	-1.397	0.285	-4.908	<0.001
Management system x soak time	-0.019	0.024	0.793	0.427
Management system x length	-0.004	0.001	-3.434	<0.001

Table 2.3. Modeled effects of hook type, soak time, and animal length on the odds of survival of common bycatch species. Likelihood ratio tests (LRT) were conducted to determine overall model significance.

Species	Term	Coefficient	SE	z value	Pr (>|z|)
Swordfish[a]					
(LRT=45.5, *df*=4, *p*<0.001)	J-hook	0.781	0.572	1.364	0.172
	Circle hook	0.740	0.143	5.179	<0.001
	Offset J-hook	0.670	0.225	2.985	0.003
	Soak time	-0.068	0.033	-2.090	0.037
	Length	-0.008	0.003	-2.849	0.004
Yellowfin tuna					
(LRT=31.0, *df*=3, *p*<0.001)	J-hook	2.427	1.068	2.274	0.023
	Circle hook	1.418	0.277	5.128	<0.001
	Soak time	-0.220	0.063	-3.495	<0.001
	Length	-0.008	0.007	-1.018	0.309
Shortfin mako					
(LRT=8.8, *df*=4, *p*=0.066)	J-hook	0.211	1.249	0.169	0.866
	Circle hook	0.293	0.305	0.961	0.337
	Offset J-hook	0.582	0.587	0.991	0.322
	Soak time	-0.001	0.079	-0.021	0.984
	Length	0.013	0.005	2.254	0.024
Pelagic stingray					
(LRT=17.2, *df*=3, *p*<0.001)	J-hook	4.196	1.888	2.223	0.026
	Circle hook	1.594	0.467	3.412	<0.001
	Soak time	0.034	0.111	0.306	0.759
	Length	-0.028	0.013	-2.123	0.034
Longnose lancetfish					
(LRT=16.9, *df*=4, *p*=0.002)	J-hook	1.113	1.147	0.971	0.332
	Circle hook	-0.558	0.387	-1.442	0.149
	Offset J-hook	1.567	0.747	2.099	0.036
	Soak time	-0.157	0.068	-2.308	0.021
	Length	0.004	0.005	0.905	0.365

[a] The swordfish logistic regression model was based on 565 sets observed between 2002 and 2004. Other models were based on 859 sets observed between 2001 and 2004.

Table 2.4. Logistic regression models, including interaction terms, for porbeagle and blue shark were based on 565 sets observed between 2002 and 2004. Likelihood ratio tests (LRT) were conducted to determine overall model significance.

Species	Term	Coefficient	SE	z value	Pr (> |z|)
Porbeagle shark					
(LRT=67.4, *df*=9, *p*<0.001)	J-hook	8.477	1.647	5.145	<0.001
	Circle hook	-7.166	1.967	-3.643	<0.001
	Offset J-hook	-3.965	3.654	-1.085	0.278
	Soak time	-0.301	0.095	-3.180	0.001
	Length	-0.038	0.008	-4.566	<0.001
	Circle hook x soak time	0.348	0.111	3.148	0.002
	Offset J-hook x soak time	0.061	0.181	0.335	0.738
	Circle hook x length	0.034	0.013	2.518	0.012
	Offset J-hook x length	0.025	0.022	1.118	0.263
Blue shark					
(LRT=184.0, *df*=6, *p*<0.001)	J-hook	6.787	0.873	7.778	<0.001
	Circle hook	-3.621	0.914	-3.963	<0.001
	Offset J-hook	-2.231	1.384	-1.612	0.107
	Soak time	-0.341	0.059	-5.762	<0.001
	Length	-0.0001	0.0007	-0.253	0.800
	Circle hook x soak time	0.305	0.063	4.818	<0.001
	Offset J-hook x soak time	0.125	0.094	1.334	0.182

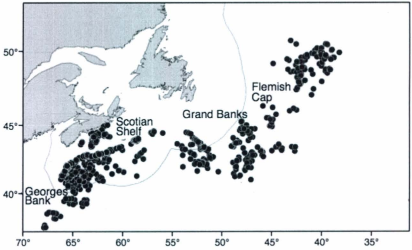

Figure 2.1 Distribution of observed sets of the Canadian Atlantic pelagic longline fisheries for swordfish and tuna fished between 2001 and 2004. Boundary of the Canadian Exclusive Economic Zone shown.

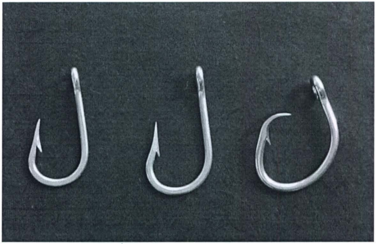

Figure 2.2 Straight shank J-hooks (8/0 and 9/0) and 16/0 circle hooks (from left to right) are used in the Canadian swordfish and tuna pelagic longline fishery. Maximum hook widths are 36, 41, and 50 mm, respectively. Offset J-hooks used had the same maximum hook widths as J-hooks (8/0 and 9/0) but barbs were offset 20-30°.

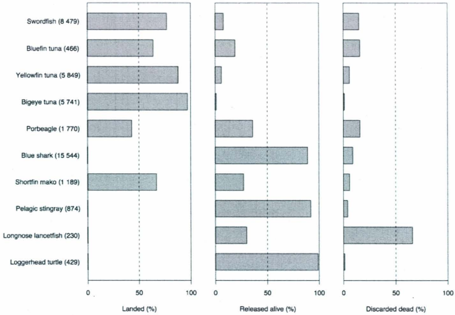

Figure 2.3 Species identified as common bycatch, based on frequency or amount of discarding, included species that are commonly landed. Sample sizes, indicated in parentheses, include all individuals caught during observed trips in the Canadian longline fishery for swordfish and tuna between 2001 and 2004. Hooking survival models were limited to bycatch; therefore, they only included proportions released alive and discarded dead.

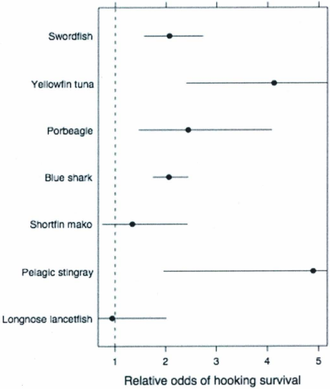

Figure 2.4 Odds ratio of common bycatch released from circle hooks relative to previously used J-hooks. An odds ratio of 1 (dashed line) indicated no change in the odds of survival. An odds ratio of 2 indicated the bycatch were twice as likely to be released alive from circle hooks than from J-hooks. Confidence intervals (95%) indicated by horizontal lines.

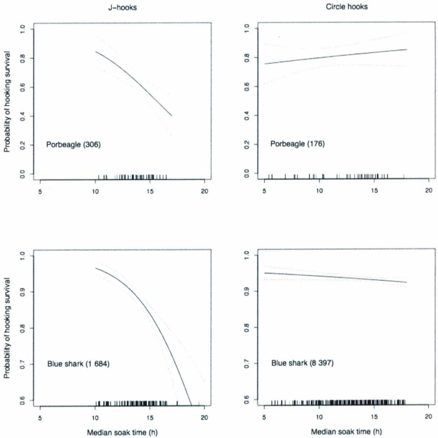

Figure 2.5 Probability of porbeagle and blue shark survival (± 95% CI) compared between hook types and with soak times. Soak times were calcuated as the median time baited hooks were in the water. Sample sizes (in parentheses) indicate numbers of bycatch caught on circle or J-hooks, sample distribution over time shown along x-axes. Note y-axes differ for the two shark species.

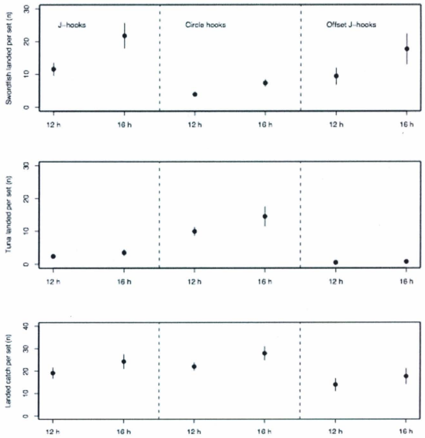

Figure 2.6 Modeled relationship between soak time, hook type and landed catch. Differences in in fishing effort were accounted for by including number of hooks hauled in the negative binomial GLM. Mean number of hooks per set (1115) were used to calculate landed catch. Soak times (x-axis) were calculated as the median time baited hooks were in the water.

CHAPTER 3: OVERLOOKED BYCATCH MITIGATION OPPORTUNITIES IN PELAGIC LONGLINE FISHERIES: SOAK TIME AND TEMPERATURE EFFECTS ON SWORDFISH AND BLUE SHARK CATCH

Chapter 3 builds upon results reported in the previous chapter where I showed that hooking survival levels increased with longer soak times. In Chapter 2 I used the midpoint of total soak time, the average minimum and maximum soak time, to evaluate soak time effects on hooking survival. This metric includes a portion of setting and haulback time. Excluding setting and haulback time would have underestimated the stresses associated with capture and therefore would be an inappropriate metric for hooking survival models. However, in the following chapter I find that the association between target catch and soak time was likely a function of the increased haulback time associated with handling longline catch. Thus, this chapter highlights the importance of understanding the fishing practices that shape fishery-dependent data.

Observations from the field study reported here and observations reported by pelagic longline captains (Chapter 4) led to the hypotheses tested in Chapter 5.

Abstract

Bycatch mitigation approaches aim to either reduce the incidence of unwanted catch or reduce bycatch mortalities. In pelagic longline fisheries incidence of unwanted catch can be reduced by limiting the availability of baited hooks (e.g., within bycatch species' preferred depths and water temperatures), whereas bycatch mortalities can be decreased by gear modifications and changes to fishing practices (e.g., by limiting soak time). To evaluate the effects of temperature, depth, and soak time on catch of target and bycatch species, temperature recorders were set along the length of the longline to characterize the environment at which hooks were fishing. Although few instrumented sets were fished, observations at the within set scale – specifically, that swordfish (*Xiphias gladius*) catch did not increase with longer soak times – led us to re-examine assumptions made in fleet-wide catch models. Swordfish catch did not increase with soak time in generalized linear models based on fisheries observer data collected from swordfish-targeted sets fished by the Canadian pelagic longline fleet in 2008 and 2009 (n=42 and n=78, respectively). Minimum soak time, from end of setting to start of hauling, was used in swordfish catch models. Total soak time is inappropriate for catch models because it includes haulback time, which increases as a function of catch. If landed catch does not increase as a function of soak time, then limiting longline soak time to reduce bycatch mortalities would not cause decreased swordfish catch nor result in economic losses for fishers. While minimum soak time limits would likely decrease bycatch

mortality rates in swordfish longline fisheries, impacts on other aspects of the fishing process would need to be considered, such as negative impacts on fisher safety.

3.1 Introduction

Bycatch mitigation approaches either aim to reduce the incidence of unwanted catch or aim to decrease bycatch mortality rates. For pelagic longline fisheries, methods to reduce the incidence of unwanted catch include setting practices that decrease availability of baited hooks within bycatch species' habitats or foraging areas (e.g., Dietrich et al. 2008; Beverly et al. 2009). Research differentiating species distributions, and inferred foraging areas, has largely focused on depth distributions (Boggs 1992; Bertrand et al. 2002; Bach et al. 2003; Ward and Myers 2005; Beverly et al. 2009). However, higher catch rates of target and non-target species, such as tunas (*Thunnus* spp.), swordfish *(Xiphias gladius),* and loggerhead turtles (*Caretta caretta*), are also associated with particular water temperatures or with thermal fronts (e.g., Podesta et al. 1993; Polovina et al. 2000; Brazner and McMillan 2008). Methods to decrease bycatch mortality or injury rates include changes to hook size and type, reduced time on hooks, and modified handling practices (e.g., Hoey and Moore 1999; Diaz and Serafy 2005; Campana et al. 2009; Carruthers et al. 2009). Thus, depth and temperature fished, as well as soak time affect both catch rates and mortality levels of bycatch.

Because fishers are more likely to adopt mitigation methods that do not decrease landed catch (but see Campbell and Cornwell 2008), effects on target species catch rates are commonly considered in bycatch mitigation research (e.g., Hall et al. 2007; Ward et al. 2008; Wade et al. 2009). For example, Beverly et al. (2009) demonstrated that removing shallow hooks from pelagic longline gear decreased catch rates of epipelagic species, and presumably endangered sea turtles, and maintained catch rates of targeted tunas. In contrast, reduced longline soak times decrease mortality levels of unwanted catch but may also decrease catch rates of targeted and marketable species (Ward et al. 2004; Carruthers et al. 2009). Due to this presumed trade-off between economic benefits for fishers and decreased mortality levels among bycatch species, it has been argued that regulations to decrease soak time would be unacceptable to industry (Diaz and Serafy 2005).

Pelagic longline bycatch research typically uses fishery-dependent observer data to estimate the magnitude of fishing impacts and the importance of different fishing factors on bycatch levels and mortality rates (Bigelow et al. 1999; Lewison et al. 2004; Ward et al. 2004; Campana et al. 2006; Carruthers et al. 2009). Alternatively, longlines instrumented with depth recorders, temperature gauges or hook timers are used to determine how depths, temperatures, and soak times fished affect catch rates and species composition (e.g., Boggs 1992; Bach et al. 2003; Beverly et al. 2009). However, few bycatch mitigation studies use observations from fishing experiments to improve fleet-wide catch models, in order to evaluate how specific fishing practices affect overall fishery impacts (but see Cox et al. 2007; Campana et al. 2009). In this paper, I demonstrate how observations from instrumented longline sets can be used to improve landed catch models and to evaluate mitigation methods in the Canadian pelagic longline fishery.

The Canadian pelagic longline fishery targets swordfish and tunas in the Northwest Atlantic along the continental shelf edge and further offshore in waters north of the Gulf Stream (Figure 3.1). Although the fishery has increasingly targeted bigeye (*T. obesus*), albacore (*T. alalunga*), and yellowfin (*T. albacares*) tunas, swordfish catch still accounts for the majority of landings by this fleet (Paul and Neilson 2010). Fishing practices, catch rates, and species compositions differ for swordfish and tuna-targeted sets (He et al. 1997; Brazner and McMillan 2008). For the purposes of this study, targeted species were determined from catch composition (Rogers and Pikitch 1992; He et al. 1997; Paul and Neilson 2010); swordfish-targeted sets were identified as those where swordfish was the most common species. Here I examine the effects of temperature, depth, and soak time on catch rates of swordfish and the most commonly caught bycatch species (blue shark, *Prionace glauca*). Instrumented longline sets were used to characterize the depth and temperature environment at which the hooks were fishing and to determine if catch rates of swordfish and blue shark were affected by within set temperature or soak time differences. Observations at the within set level, caused us to re-examine assumed relationships between catch, soak time, and temperature used in fleet-wide catch models and used to evaluate bycatch mitigation techniques.

3.2 Methods

3.2.1 Instrumented fishing sets

Within set temperature and depth variability were sampled opportunistically during a charter of a commercial longline vessel with the primary purpose to release swordfish and bluefin tuna (*T. thynnus*) marked with pop-up satellite tags (Neilson et al. 2009). Instrumented longline sets were fished east of the Grand Banks between August 17th and 20th, 2008 (Figure 3.1). Fishing practices were similar to those used by the commercial longline fishery when targeting swordfish (Table 3.1). Gear was set to fish in the upper 20 m, using 4.5 m drop lines and 8 m branch lines (gangions) (Figure 3.2). Three hooks were fished between buoys or within each basket. Circle hooks (size 16/0, 10% offset) were baited with mackerel. Fourteen sections were fished in the first two sets (900 hooks) and 17 sections were fished in the last set (1000 hooks). Each section consisted of approximately 20 baskets (Figure 3.2). Sections were approximately 3 km and total mainline length was between 40 and 50 km. Gear was set in the evening, soaked overnight, and haulback began at 6 am. Instrumented longlines were counter-retrieved; the first hook set was the last retrieved.

Temperature and depth were recorded from the depth at which the gear fished. Temperature recorders (TRs) replaced baited hooks at the end of gangions (Figure 3.2). Eighteen TRs were attached at midpoints of longline sections. A temperature depth recorder (TDR) was attached at the midpoint of the longline set. Therefore, the TDR recorded a range of depths while setting and hauling, but depths were recorded from the deepest point of the longline for the majority of the deployment. TR and TDR resolution was ± 0.4 m and ± 0.2 °C, with stated accuracy ± 2.0 m and ± 0.3 °C (Vemco Division, AMIRIX Systems Inc., NS Canada). Temperature and depth were recorded every 5 minutes. Relative positions (i.e., longline basket or hook number) of species and TRs were recorded during haulback. Before each set water temperature was recorded to 25 m depth using a second TDR. In addition, surface water temperature and time were recorded at four points during the longline sets: start and end of setting, and start and end of hauling.

3.2.2 Fisheries observer data

Data collected from the pelagic longline fishery by at-sea fisheries observers were obtained from the International Observer Program database, created and maintained by the Population Ecology Division of the Canadian Department of Fisheries and Oceans (DFO). Fisheries observer data were used instead of logbook data because catch of bycatch species, such as blue shark, are neither required nor consistently recorded in logbooks. In addition to identifying species caught, fisheries observers recorded information on gear characteristics (i.e., longline length, bait, and hook type), and on the location, timing, and water temperature during setting and hauling. Fisheries observers reported from 11 of 164 trips fished during the 2008 season, accounting for 5% of sea days. Observers reported from longline trips that were fished from late May until mid-October and were distributed from Georges Bank in the south to the eastern Grand Banks in the north (Figure 3.1). Prior to analysis, individual vessel identifiers were replaced with unique identifiers to maintain confidentiality. Swordfish-targeted sets were identified as sets in which the number of swordfish exceeded that of tunas or of other landed species. This approach was validated using a K-means cluster analysis (Xu and Wunsch 2009), which differentiated swordfish and tuna-targeted sets in the first division, and identified the same swordfish-targeted sets as the simpler method. Data from 78 swordfish-targeted sets observed the following fishing season were used to test whether modeled effects of soak time and temperature held across years and data sets.

3.2.3 Statistical analyses

Effects of soak time and water temperature on catch were tested for sections within the three instrumented longline sets. Because TRs were set out along the longline, soak times differed. Soak times were identified by a large temperature change (>2° C) occurring within a 10 minute period (i.e., two recording intervals) within the TR or TDR records. Identified start and end times fell within the setting and hauling periods recorded on deck sheets and were checked against the order in which recorders were set and retrieved (e.g., TR 3 was set before but retrieved after TR 4). Data were imported, compiled, and error checked using custom programs (MATLAB version R2007a). To test for effects of temperature (T) and soak time (duration; D) on swordfish and blue shark catch (number of fish/section between TRs), I used Generalized Linear Models (GLMs) with a Poisson error distribution and log link, appropriate for count data (Maunder and Punt 2004):

$$\text{Catch} = e^{\mu} + \varepsilon. \quad (3.1)$$

Because diagnostic plots showed dispersion of residuals did not increase with fitted values, I considered the Poisson error distribution sufficient for data from instrumented longline sets. Within each set, catch from adjacent sections may be related (Ward et al. 2004), e.g., clustered catches may indicate schooling fish (Rey and Muñoz-Chápuli 1992). Therefore, a categorical variable for fishing set (S) was used to account for differences among sets. Number of hooks between temperature recorders was not included in the model as this variable was not significant nor did it improve explanatory power. The model for swordfish and blue shark catches corresponding to sections associated with each temperature recorder was:

$$\mu = \beta_0 + \beta_T T + \beta_D D + \beta_s S + \beta_{TxS} TxS, \quad (3.2)$$

where μ corresponds to mean catch for each section.

Similarly, I modeled soak time and temperature effects using fisheries observer data collected from swordfish-targeted sets fished during the 2008 fishing season. However, soak time is not recorded for sections within a longline during observed commercial fishing sets. Instead, time is recorded at four points in the longline set. Before using total soak time (start of setting until end of hauling), I first determined if the number of target species caught (i.e., tunas and swordfish) increased haulback time. In the Canadian longline fishery, and in other fresh-chilled swordfish fisheries (P. Ward, pers. comm. July 27, 2010), hauling often stops to bring fish aboard and may take considerable time depending on the size and activity level of fish. Because haulback time increased as a function of the number of target species, I used minimum soak time (duration; D, end of setting until start of hauling) in landed catch models. Minimum soak time is not affected by setting and hauling practices (e.g., number of hooks fished or amount of landed catch). Estimated fishing depth was not included in catch models because it was not clear how such estimates were made. For example, water column depth was reported instead of fishing depth for 6 of the 42 swordfish-targeted sets observed in 2008. Number of hooks hauled (H), an effort measure, and water temperature (T) averaged from four points in the longline set, were included as factors in the catch model:

$$\mu = \beta_0 + \beta_T T + \beta_D D + \beta_H H, \qquad (3.3)$$

where μ corresponds to mean catch for each set. Previous catch rate models for blue shark caught by the Canadian pelagic longline fishery included categorical variables for fishing quarter and region (e.g., Scotian Shelf or Grand Banks; Campana et al., 2006). However, the majority of swordfish-targeted sets observed during 2008 were fished on the Scotian Shelf and in the third quarter. Curvilinear relationships between soak time or temperature and catch levels were not evident in the fisheries observer data. Therefore, I used GLMs that paralleled those used for instrumented sets. Standardized residuals plots were used to evaluate whether underlying error distribution assumptions were met.

Scale parameters and diagnostic plots of initial models revealed variance greater than accounted for by the Poisson error distribution, which assumes variance equal to the mean. Negative binomial error distributions, which include a dispersion parameter to be estimated (k^{-1}), account for greater variance in error calculations and significance tests ($\mathrm{var}(Y) = \mu + \mu^2 \cdot k^{-1}$). While these models produce more conservative significance estimates, negative binomial models cannot account for variance due to missing explanatory variables (McCullagh and Nelder 1989). Negative binomial error distributions, appropriate for overdispersed count data (Maunder and Punt 2004), were used in catch models based on fisheries observer data collected from swordfish-targeted sets fished in 2008 and 2009. To test whether relationships between temperature and catch held and if minimum soak time remained a non-significant predictor of swordfish catch, GLMs were rerun using observer data collected from 78 swordfish-targeted trips the following fishing season (2009). GLMs were run using the open-source statistical program R, with the packages 'MASS' and 'car' (Venables and Ripley 2002; Fox 2007; RTeam 2007).

3.3 Results

3.3.1 Instrumented fishing sets

Blue shark, swordfish, and shortfin mako (*Isurus oxyrinchus*) were the most common catch, accounting for 94% of the number of fish caught in instrumented sets. The remainder of the catch consisted of unidentified sharks, a single thresher shark (*Alopias* sp.), and a single bluefin tuna. The range of surface water temperatures recorded on deck sheets was 14.9 – 17.2 °C. Maximum soak time, from start of setting to end of hauling, ranged from 13 h 30 min to 18 h 45 min. Minimum soak time ranged from 4 h 20 min to 8 h 30 min.

Temperatures recorded at depth were generally within the range reported on deck sheets, except during brief increases in depth (Figure 3.3). Data from instrumented longline sets indicated that swordfish-targeted sets fished at approximately 13.5 m ± 1.8 (mean ± SD), if sounding events were excluded. Sounding behaviour of hooked fish occurred during Sets 1 and 2, lasting 50 to 85 minutes and marked by an up to 20 m difference in depth and a 4 °C change (Figure 3.3). Prior to the use of hook timers, time of capture was inferred from short-term increases in depth or sounding events (Boggs 1992). The sounding event during Set 2 was a result of blue shark captures. All hooks adjacent to the TDR were recovered and blue shark was the only species captured on the snarled hooks. Little temperature difference was recorded in vertical temperature profiles conducted at the beginning and ending of each set. For example, vertical temperature profiles taken during Set 1 ranged from 14.8 to 15.9 °C in the upper 20 m. Little variability in vertical temperature profiles suggests sets were fished within the upper mixed layer. The rapid change in temperature during sounding events suggests the thermocline occurred at approximately 25 m depth in Set 1 (Figure 3.3).

Along the length of the longline temperatures ranged from 14.4 to 16.8 °C (Figure 3.4). Temperature and soak time data from TR 6 and TR 8 were lost because these recorders were not recovered. Soak time decreased along the length of the longline because longlines were counter-retrieved (Figure 3.5).

3.3.2 Fisheries observer data

Blue shark, swordfish, porbeagle, and mako shark accounted for >95% of fish caught in swordfish-targeted sets. Of the 52 sets observed during the 2008 fishing season, 42 were swordfish-targeted, which fished approximately 44,000 hooks. Swordfish-targeted sets fished both circle (size 16/0) and J-hooks (size 8/0 and 9/0, 36 and 41 mm maximum hook widths) and used mackerel, or a combination of mackerel, herring, and squid baits (Table 3.1). Although the range of surface water temperatures among swordfish-targeted sets was 13.8 – 20.1° C (Table 3.1), the maximum temperature range recorded during a single observed set was 3 °C. Swordfish-targeted sets were predominantly fished along the edge of the continental shelf from May 24 until October 17, 2008 (Figure 3.1). Of the 122 sets observed the following year, 78 were swordfish-targeted. Operational and environmental characteristics of swordfish-targeted sets were similar in 2009 but included shorter and shallower longline sets (Table 3.1). Swordfish-targeted sets were generally set at night and haulback began the following morning (Table 3.1).

3.3.3 GLM analyses

Neither temperature nor soak time affected swordfish catch during instrumented sets (Figure 3.5, Table 3.2). Blue shark catch increased with lower temperatures during Set 2, but the relationship did not hold for other instrumented sets (Table 3.2).

Swordfish catch increased with mean water temperature based on fisheries observer data from 2008, but the relationship was reversed when data were used from the 2009 fishing season. Blue shark catch increased with lower water temperatures in models using 2008 data (Table 3.3). However, the relationship between water temperature and blue shark catch was not significant across instrumented longline sets or different fishing seasons. As expected, swordfish catch increased with the effort measure (number of hooks hauled).

Before evaluating effects of increased soak time in the fisheries observer data, I determined if haulback time, and therefore total soak time, was affected by targeted catch. Number of targeted species caught significantly increased haulback time ($F_{3,39} = 5.779$, $p = 0.0023$), based on linear models of haulback time as a function of number of landed species and number of hooks hauled ($p = 0.027$ and $p = 0.008$, respectively). Therefore, minimum soak time was used in landed catch models. Minimum soak time did not significantly increase swordfish catch using either 2008 or 2009 fisheries observer data (Table 3.3). To compare the effects of minimum soak time and haulback time on swordfish and blue shark catch, I modeled soak time effects using data from swordfish-targeted sets fished during the 2009 season. Average number of hooks (847) and water temperature (17.6 °C) were used in Eq. 3.3. Neither swordfish nor blue shark catch increased with minimum soak time, however, catch of both species increased with haulback time (Figure 3.6).

3.4 Discussion

Bycatch mitigation approaches aim to reduce incidence and mortality levels of bycatch without decreasing catch rates of target species. My analysis of soak time and temperature effects indicated shorter soak times, which would decrease hooking mortality levels (Ward et al. 2004; Diaz and Serafy 2005; Campana et al. 2009; Carruthers et al. 2009), would not decrease catch rates of targeted swordfish. Blue shark bycatch increased with cooler water temperatures, but the relationship was not significant across instrumented sets and fishing seasons, which suggests other environmental or behavioural factors are driving blue shark catch rates.

Analysis of fisheries observer data was limited to swordfish-targeted sets to increase comparability with instrumented longlines. Swordfish-targeted sets fished a range of bait types, depths, and temperatures, in addition to the fleet's traditional fishing practices when targeting swordfish: e.g., mackerel baited, shallow-set hooks fished along the continental shelf edge (Stone and Dixon 2001). Swordfish-targeting was simply identified from catch composition, but this method assumes that the most common landed species was, in fact, the intended target (Rogers and Pikitch 1992). For example, the three sets fished further offshore in 2008 (Figure 3.1) caught a combination of swordfish, tunas, and porbeagle in roughly equal numbers, making it difficult to identify a single target species. Alternatively, target species could be inferred from fishing practices. It looks like longliners tried different targeting practices during the 2009 fishing season (i.e., fishing depths, bait types, and longline lengths), but swordfish remained the most commonly caught target species. Mixed-bait, deeper sets caught both yellowfin tuna and swordfish, which may indicate a mixed targeting strategy. Instrumented longline sets were similar to traditional swordfish-targeting practices in the commercial fishery. While total soak time and sea surface temperatures in instrumented sets were within the range recorded in fisheries observer data (Table 3.1), soak times were shorter than average to increase the likelihood that swordfish and bluefin tuna would be available for tagging and live release.

Blue shark catch generally increased with cooler temperatures, but the relationship was not significant across instrumented longline sets or between the two fishing seasons. While there was likely insufficient contrast among instrumented longline sets to determine temperature effects, temperatures reported in Canadian fisheries observer data were similar to those analyzed by Watson et al. (2005), who found blue shark catch increased with cooler sea surface temperatures. However, Watson et al. (2005) were working with more detailed data; onboard fisheries observers in that fleet recorded water temperature and catch for each longline section. Because water temperatures used here were averaged from four points in the longline set, they may not reflect water temperatures at a scale relevant to blue shark. Other studies that reported fleet-wide or large scale associations between blue shark catch and cooler temperatures may instead reflect targeting practices. For example, Walsh and Kleiber (2001) reported higher blue shark catches associated with colder sea surface temperatures; however, this effect may be indirect because their data set included both swordfish and tuna targeted sets. Blue shark bycatch is associated with swordfish targeting (He et al. 1997), which occurs in cooler waters than tuna targeting (Paul and Neilson 2010). Thus, two possible explanations from the difference between my results and previous research are the scale at which temperature is recorded, or the range of targeting practices included in the data set.

Alternatively, the lack of consistent relationship between fishing seasons may simply reflect that I checked whether the relationship between blue shark and water temperature held – few studies retest effects of environmental factors with new data. While focused on a separate aspect of fisheries research, Myers (1998) found correlations between environmental factors and fish recruitment fared poorly when subject to retesting. The notable exception was when sampled populations were at the northern extent of their range (Myers 1998). Associations among species catch rates and water temperature imply temperature preference or limits. Given that blue sharks encounter 10-15 °C temperature differences during daily dives (Carey and Scharold 1990), it is unlikely that temperatures reported from this fishery (Table 3.1) are near the limit of blue shark temperature preferences. Instead, I suggest that temperature and shark associations are indicative of other processes, such as targeting practices (Walsh and Kleiber 2001), or, at a finer scale, short-term changes to the fished environment and to fish behaviour may be driving blue shark catch rates. Comparisons among instrumented sets and nine adjacent observed sets (Figure 1), showed extreme catch rate variability occurred on short time and space scales – within 10 days and 100 km. For both instrumented and the adjacent observed sets, swordfish catch rate remained below 30 fish/1000 hooks, whereas blue shark catch rates ranged from 10 to >150 sharks/1000 hooks. Thus, reported associations between blue shark and temperature may reflect other short-term environmental changes that coincide with decreased temperature, such as wind-induced mixing.

Analysis method was not a common factor among studies which found significant temperature or soak time effects on swordfish or blue shark catch. For example, both Walsh and Kleiber (2001) and Watson et al. (2005) reported blue shark catch increased with cooler water temperatures, using Generalized Additive Models (GAMs, which allow for non-linear relationships) and GLM analyses. Whereas, Vega and Licandeo (2009) found SST was not a significant factor in blue shark GAMs. While the lack of relationship between swordfish and soak time was surprising, I think positive associations found in previous studies had more to do with how soak time was measured than analysis method. Research in which soak time was recorded for each section was equivocal; with both significant (Ward et al. 2004) and insignificant (Watson et al. 2005) soak time effects. By contrast, studies which used median or maximum soak time, report a positive soak time effect, irrespective of the analysis method used (Carruthers et al. 2009; Vega and Licandeo 2009).

From a bycatch mitigation perspective, the observation that swordfish catch did not increase with soak time could have important management implications. Hooking mortality rates, whether individual animals are alive or dead when brought alongside the vessel, generally increase with longer soak times (Ward et al. 2004; Diaz and Serafy 2005; Campana et al. 2009; Carruthers et al. 2009). If landed catch does not increase as a function of soak time, then limiting soak time would not result in an economic loss for longliners. Effectively, there may be no trade-off between lower bycatch mortalities and fishing profitability. However, evaluating this trade-off depends upon appropriate measures of soak time. Total or median soak time is used to estimate hooking mortality levels (Diaz and Serafy 2005; Campana et al. 2009; Carruthers et al. 2009). Both measures include haulback time and, therefore, are not appropriate for landed catch because haulback time is a function of landed catch. Minimum soak time would not, however, be an appropriate measure for hooking mortality models; it would systematically underestimate time on hooks and associated stresses, such as from limited movement ability (Campana et al. 2009).

Swordfish catch did not increase with longer soak times during the instrumented sets even though soak time of longline sections differed by up to 8 h. The number of instrumented longlines fished is clearly insufficient for fleet-wide inferences. However, observations from these sets caused us to re-examine measures used to evaluate soak time effects using fisheries observer data. Because haulback time increased as a function of landed catch, I used minimum soak time in catch models. Minimum soak time did not increase swordfish catch among observed sets fished by the Canadian Atlantic pelagic longline fleet (Figure 3.6). Interestingly, blue shark catch also increased with haulback time (Figure 3.6), which suggests that discarding sharks can also take considerable time. Haulback practices described here are not unique to the Canadian fishery; therefore, bycatch mitigation opportunities in other pelagic longline fisheries may be overlooked. For example, Watson et al. (2005) attributed the positive relationship between swordfish catch and daylight soak time to the increased time needed to process and catch because haulback time increased as a function of landed catch.

Shorter soak times could decrease bycatch hooking mortalities levels in pelagic longline fisheries. However, key questions would need to be addressed prior to implementing minimum soak time limits. Would reductions in minimum soak time (i.e., the time period over which longliners have greater control), markedly decrease bycatch mortality levels? How do minimum soak time limits affect different targeting strategies and how do they compare to other mitigation strategies, such as modified handling practices (e.g., Campana et al. 2009)?

Given that swordfish longline operations are generally completed within 24 h (Ward and Hindmarsh 2007), would limiting minimum soak times negatively impact fisher safety? Minimum soak times in the 2008 and 2009 fishing season were, on average, 7-8 h (Table 3.1). In the Canadian fleet, this is the time period when longline crews are able to sleep and eat. Fatigue is a common factor in fishing accidents (Windle et al. 2008), therefore, minimum soak time regulations could negatively impact fisher health and safety. If fisheries management and the fleet were able to address the safety issues, then any soak time regulations would need to be based on minimum soak times as it is the time period that fishers can control. Total soak time is affected by amount of catch, line breaks, and other factors beyond the fishing crews' control. Rather than advocate for particular mitigation methods, my point here is that simple catch models, and consequent evaluations of bycatch mitigation opportunities, were based on inappropriate soak time measures. Incorporating results from data collected at the within-set level improved fleet-wide catch models and identified overlooked bycatch mitigation opportunities.

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3.5 References

Bach, P., Dagorn, L., Bertrand, A., Josse, E., Misselis, C., 2003. Acoustic telemetry versus monitored longline fishing for studying the vertical distribution of pelagic fish: bigeye tuna (*Thunnus obesus*) in French Polynesia. Fisheries Research 60, 281-292.

Bertrand, A., Josse, E., Bach, P., Gros, P., Dagorn, L., 2002. Hydrological and trophic characteristics of tuna habitat: consequences on tuna distribution and longline catchability. Canadian Journal of Fisheries and Aquatic Sciences 59, 1002-1013.

Beverly, S., Curran, D., Musyl, M., Molony, B., 2009. Effects of eliminating shallow hooks from tuna longline sets on target and non-target species in the Hawaii-based pelagic tuna fishery. Fisheries Research 96, 281-288.

Bigelow, K.A., Boggs, C.H., He, X., 1999. Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery. Fisheries Oceanography 8, 178-198.

Boggs, C.H., 1992. Depth, capture time, and hooked longevity of longline-caught pelagic fish — timing bites of fish with chips. Fishery Bulletin 90, 642-658.

Brazner, J.C., McMillan, J., 2008. Loggerhead turtle (*Caretta caretta*) bycatch in Canadian pelagic longline fisheries: relative importance in the western North Atlantic and opportunities for mitigation. Fisheries Research 91, 310-324.

Campana, S.E., Joyce, W., Manning, M.J., 2009. Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. Marine Ecology Progress Series 387, 241-253.

Campana, S.E., Marks, L., Joyce, W., Kohler, N.E., 2006. Effects of recreational and commercial fishing on blue sharks (*Prionace glauca*) in Atlantic Canada, with inferences on the North Atlantic population. Canadian Journal of Fisheries and Aquatic Sciences 63, 670-682.

Campbell, L.M., Cornwell, M.L., 2008. Human dimensions of bycatch reduction technology: current assumptions and directions for future research. Endangered Species Research 5, 325-334.

Carey, F.G., Scharold, J.V., 1990. Movements of blue sharks (*Prionace glauca*) in depth and course. Marine Biology 106, 329-342.

Carruthers, E.H., Schneider, D.C., Neilson, J.D., 2009. Estimating the odds of survival and identifying mitigation opportunites for common bycatch in pelagic longline fisheries. Biological Conservation 142, 2620-2630.

Cox,T.M., Lewison, R.L., Zydelis, R., Crowder, L.B., Safina, C., Read, A.J., 2007. Comparing effectiveness of experimental and implemented bycatch reduction measures: the ideal and the real. Conservation Biology 21, 1155-1164.

Diaz, G.A., Serafy, J.E., 2005. Longline-caught blue shark (*Prionace glauca*): factors affecting the numbers available for live release. Fishery Bulletin 103, 720-724.

Dietrich, K.S., Melvin, E.F., Conquest, L., 2008. Integrated weight longlines with paired streamer lines — best practice to prevent seabird bycatch in demersal longline fisheries. Biological Conservation 141, 1793-1805.

Fox, J., 2007. car: Companion to Applied Regression R Foundation for Statistical Computing, Vienna, Austria

Hall, M., Nakano H., Clarke, S., Thomas, S., Molloy, J., Peckham, S., Laudino-Santillan, J., Nichols, W., Gilman, E., Cook, J., Martin, S., Croxall, J., Rivera, K., Moreno, C., Hall, S., 2007. Working with fishers to reduce by-catches. in: Kennelly S. (ed) By-catch Reduction in the World's Fisheries. Springer, Dordrecht, p 235-288.

He, X., Bigelow, K.A., Boggs, C.H., 1997. Cluster analysis of longline sets and fishing strategies within the Hawaii-based fishery. Fisheries Research 31, 147-158.

Hoey, J.J., Moore, N., 1999. Captain's Report: Multi-species Catch Characteristics for the US Atlantic Pelagic Longline Fishery. National Marine Fisheries NOAA-NMFS Marfin Grant NA77FF0543, SK Grant NA86FD0113, 78 pp.

Lewison, R.L., Freeman, S.A., Crowder, L.B., 2004. Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. Ecology Letters 7, 221-231.

Maunder, M.N., Punt, A.E., 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research 70, 141-159.

McCullagh, P., Nelder, J.A., 1989. Generalized Linear Models, second ed. Chapman Hall, London.

Myers, R.A., 1998. When do environment-recruitment correlations work? Reviews in Fish Biology and Fisheries. 8, 285-305.

Neilson J.D., Smith S., Royer F., Paul S.D., Porter J.M., Lutcavage M., 2009. Investigations of horizontal movements of Atlantic swordfish using pop-up satellite archival tags. in: Nielson J.L., Arrizabalaga H., Fragoso N., Lutcavage M., Sibert J. (eds) Tagging and Tracking of Marine Animals with Electronic Devices, Vol 9. SpringerLink, p 145-159.

Paul, S.D., Neilson, J.D., 2010. An exploration of targeting variables in the Canadian swordfish longline CPUE. ICCAT Collective Volume of Scientific Papers 65, 124-134.

Podesta, G.P., Browder, J.A., Hoey, J.J., 1993. Exploring the association between swordfish catch rates and thermal fronts on United-States longline grounds in the western North-Atlantic. Continental Shelf Research 13, 253-277.

Polovina, J.J., Kobayashi, D.B., Parker, D.M., Seki, M.P., Balazs, G.H., 2000. Turtles on the edge: movement of loggerhead turtles (*Caretta caretta*) along oceanic fronts, spanning longline fishing grounds in the central North Pacific, 1997-1998. Fisheries Oceanography 9, 71-82.

Rey, J.C., Muñoz-Chápuli, R.,1992. Intra and interspecific association of large pelagic fishes inferred from catch data of surface longline. Environmental Biology of Fishes 35, 95-103.

Rogers, J.B., Pikitch, E.K., 1992. Numerical definition of groundfish assemblages caught off the coasts of Oregon and Washington using commercial fishing strategies. Canadian Journal of Fisheries and Aquatic Sciences 49, 2648-2656.

R Development Core Team, 2007. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Stone, H.H., Dixon, L.K., 2001. A comparison of catches of swordfish, *Xiphias gladius*, and other pelagic species from Canadian longline gear configured with alternating monofilament and multifilament nylon gangions. Fishery Bulletin 99, 210-216.

Vega, R., Licandeo, R., 2009. The effect of American and Spanish longline systems on target and non-target species in the eastern South Pacific swordfish fishery. Fisheries Research 98, 22-32.

Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S. Springer, New York.

Wade, O., Revill, A.S., Grant, A., Sharp, M., 2009. Reducing the discards of finfish and benthic invertebrates of UK beam trawls. Fisheries Research 90, 140-147.

Walsh, W.A., Kleiber, P., 2001. Generalized additive model and regression tree analysis of blue shark (*Prionace glauca*) catch rates by the Hawaii-based commercial longline fishery. Fisheries Research 53, 115-131.

Ward, P., Hindmarsh, S., 2007. An overview of historical changes in the fishing gear and practices of pelagic longliners, with particular reference to Japan's Pacific fleet. Reviews in Fish Biology and Fisheries 17, 501–516

Ward, P., Lawrence, E., Darbyshire, R., Hindmarsh, S., 2008. Large-scale experiment shows that nylon leaders reduce shark bycatch and benefit pelagic longline fishers. Fisheries Research 90, 100-108.

Ward, P., Myers, R.A., 2005. Inferring the depth distribution of catchability for pelagic fishes and correcting for variations in the depth of longline fishing gear. Canadian Journal of Fisheries and Aquatic Sciences 62, 1130-1142.

Ward, P., Myers, R.A., Blanchard, W., 2004. Fish lost at sea: the effect of soak time on pelagic longline catches. Fishery Bulletin 102, 179-195.

Watson, J.W., Epperly, S.P., Shah, A.K., Foster, D.G., 2005. Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Canadian Journal of Fisheries and Aquatic Sciences 62, 965-981.

Windle, M.J.S., Neis, B., Bornstein, S., Binkley, M., Navarro, P., 2008. Fishing occupational health and safety: a comparison of regulatory regimes and safety outcomes in six countries. Marine Policy 32, 701-710.

Xu R., Wunsch D.C., 2009. Clustering. IEEE Press, Hoboken N.J.

Table 3.1 Operational and environmental characteristics of swordfish-targeted pelagic longline sets observed during the 2008 and 2009 fishing seasons (average ± standard deviation and range (shown in parentheses)).

Characteristic	*2008 Swordfish-targeted sets (n=42)*	*2009 Swordfish-targeted sets (n=78)*
Hook type	29.5% J-hook; 70.5% circle hook	17% J-hook; 83% circle hook
Bait type[a]	29.5% mackerel; 70.5% mixed	40% mackerel; 13% squid; 47% mixed
Number of hooks hauled	1041 ± 337 (576 – 1564)	847 ± 249 (210-1377)
Longline length (km)	45 ± 16.2 (18 – 80)	38.3 ± 17.3 (10 – 70)
Number of hooks between buoys	3 (2 - 4)	52% 2 hooks; 48% 3 hooks
Gangion length (m)	6.3 ± 1.2 (3.6 – 7.3)	6.4 ± 1.5 (1.2 – 8.2)
Fishing depth[b] (m)	18 ± 9.1 (9 – 33)	11.9 ± 6.7 (4 – 27)
Surface water temperature (°C)	17.1 ± 1.6 (13.8 – 20.1)	17.6 ± 2.5 (11 – 21.9)
Minimum soak time[c] (h)	8.4 ± 1.1 (4.9 – 10.5)	7.2 ± 1.5 (3 – 11.5)
Total soak time (h)	19.8 ± 2.3 (12.8 – 25.3)	18.5 ± 2.6 (8.3 – 25.0)
Start of setting	9:36 pm ± 76 min (8:00 pm – 2:35 am)	9:40 pm ± 70 min (7:40 pm – 2:00 am)
Start of hauling	9:58 am ± 43 min (9:00 am – 12:04 pm)	9:36 am ± 45 min (8:22 am – 12:52 pm)

[a] Mixed bait refers to a combination of mackerel, squid, and herring.
[b] Estimated by fishing captains and recorded on deck sheets (2008, *n* = 35; 2009, *n* = 39).
[c] Minimum soak time calculated as time from end of setting until start of hauling.

Table 3.2 Modeled coefficients of temperature and soak time effects on swordfish and blue shark catch in instrumented sets. Catch was recorded for each longline section between temperature recorders (n = 51).

	Term	Coefficient	SE	z	Pr(>|z|)
Swordfish	Set 1	-4.138	6.353	-0.650	0.512
(n=57)	Set 2	1.186	0.381	3.114	0.002
	Set 3	0.202	0.699	0.288	0.773
	Soak time	0.053	0.060	0.875	0.382
	Temperature	0.203	0.401	0.505	0.613
Blue shark	Set 1	9.325	5.811	1.605	0.109
(n=197)	Set 2	32.341	11.868	2.725	0.006
	Set 3	-2.963	7.920	-0.374	0.708
	Soak time	-0.033	0.039	-0.847	0.397
	Temperature	-0.545	0.398	-1.371	0.170
	Set 2 x temperature	-2.106	0.795	-2.648	0.008
	Set 3 x temperature	0.244	0.515	0.473	0.636

Table 3.3 Modeled coefficients of temperature and soak time effects on swordfish and blue shark catch. Models are based on fisheries observer data collected from swordfish-targeted sets during the 2008 and 2009 fishing seasons, 42 and 78 sets observed, respectively.

	Term	Coefficient	SE	z	Pr(>|z|)
2008 Fishing season					
Swordfish (n=919)	Intercept	-0.7762	1.6868	-0.460	0.6454
	Soak time[a]	0.0230	0.0943	0.318	0.7507
	Temperature	0.1565	0.0628	2.494	0.0126
	Number of hooks	0.0008	0.0002	2.771	0.0056
Blue shark (n=2159)	Intercept	7.5737	1.6327	4.639	<0.0001
	Soak time	-0.1580	0.0918	-1.721	0.0853
	Temperature	-0.2803	0.0606	-4.624	<0.0001
	Number of hooks	0.0020	0.0002	7.154	<0.0001
2009 Fishing season					
Swordfish (n=1395)	Intercept	3.0999	0.9470	3.273	0.0011
	Soak time	0.0156	0.0572	0.273	0.7852
	Temperature	-0.0954	0.0395	-2.414	0.0158
	Number of hooks	0.0015	0.0004	3.410	0.0007
Blue shark (n=2191)	Intercept	7.8535	1.0317	4.704	<0.0001
	Soak time	-0.1479	0.0620	-2.386	0.0170
	Temperature	-0.0541	0.0433	-1.250	0.2114
	Number of hooks	0.0007	0.0004	1.587	0.1124

[a]Minimum soak time measured from end of setting to start of hauling.

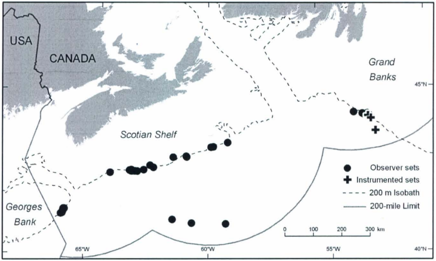

Figure 3.1 Locations of instrumented longline sets, fished between 17-20 August 2008, and swordfish-targeted longline sets observed during the 2008 fishing season. Swordfish-targeted sets were predominantly fished along the continental shelf edge, indicated by the 200 m isobath, and within the Canadian EEZ.

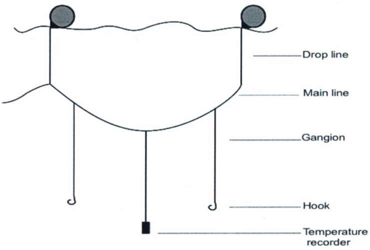

Figure 3.2 Gear configuration of a single longline basket. Twenty baskets were fished per section, and 14 – 17 sections fished in each instrumented longline set. Temperature recorders (TR) and the temperature depth recorder (TDR) replaced a baited hook at the end of a gangion, recording data at the depth of the baited hooks. Data were recorded from 16 TRs and one TDR, which was located at the midpoint of each section.

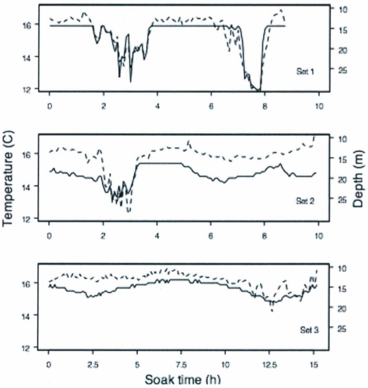

Figure 3.3 Depth (dashed line) and temperature (solid line) recorded by the temperature depth recorder at the mid-point of instrumented longline sets. Data were recorded at five minute intervals. Note soak times differed between the three sets, lasting approximately 15 h during Set 3 as indicated on x-axis.

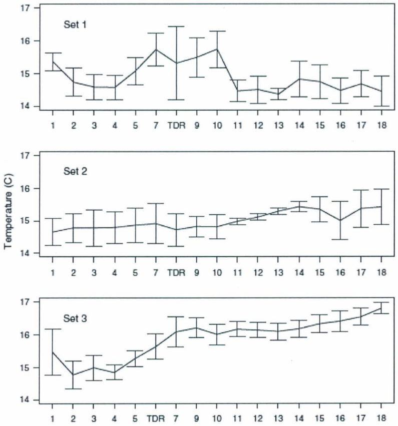

Figure 3.4 Mean temperature (± standard deviation) recorded along the length of the longline. Position of temperature recorders (TR) along the longline shown on x-axis. TR 6 and 8 were not recovered. The temperature depth recorder (TDR) was located at the midpoint of the longline.

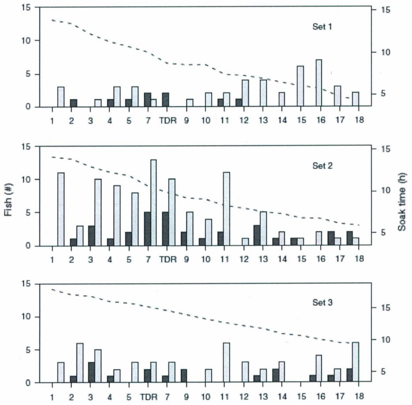

Figure 3.5. Number of swordfish (dark grey) and blue shark (light grey) caught within longline sections between temperature recorders (TRs). Position of TRs along the longline shown on x-axis. Soak time for each section between TRs shown by dashed line.

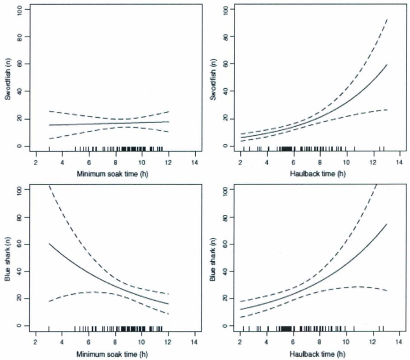

Figure 3.6. Swordfish and blue shark catch per set modeled as a function of minimum soak time or haulback time, and using average number of hooks and temperatures fished during the 2009 fishing season. Dashed lines indicate 95% confidence limits and sample distribution shown along the x-axis.

CHAPTER 4: BYCATCH MITIGATION IN CONTEXT: USING QUALITATIVE INTERVIEW DATA TO IMPROVE ASSESSMENT AND MITIGATION IN A DATA-RICH FISHERY

The following chapter uses qualitative data collected during fishers' knowledge interviews. Because I wanted to identify bycatch mitigation opportunities in the current pelagic longline fishery, I interviewed longline captains who were active in the fleet. Longline captains' descriptions of fishing practices and how these changed in response to management and markets highlighted aspects of the societal context that shape bycatch levels.

Longline captains reported bycatch mitigation approaches that could be used to increase post-release survival of species that survive the capture process (Chapter 2). Qualitative interview data confirmed species associations described in Chapter 3. Longline captains' observations of species distributions and behaviour, and observations made during the field study (Chapter 3) led to the hypotheses tested in Chapter 5.

Abstract

Bycatch from pelagic longline fisheries has contributed to widespread population declines of turtles, sharks, and other pelagic fishes. While large-scale estimates are needed to understand cumulative impacts on these highly migratory species, detailed information on targeting, setting, and discarding practices is needed to develop bycatch mitigation approaches. Data from qualitative fishers' knowledge interviews with Canadian Atlantic pelagic longline captains was used to evaluate current bycatch estimation methods and to identify bycatch mitigation opportunities. Interviewed longline captains reported blue sharks (*Prionace glauca*) were common bycatch during swordfish-targeted sets, but were sometimes absent from tuna-targeted sets. Discrepancies between longline captains' observations and bycatch assessment methods identified needed improvements to data collection methods. Longline captains reported innovative uses of turtle dehooking gear, which two-thirds of interviewed longline captains had used to release other bycatch species in addition to turtles. Longline captains reported techniques for discarding pelagic stingray (*Pteroplatytrygon violacea*), a common bycatch species in Pacific, Atlantic, and Mediterranean pelagic longline fisheries. Therefore, implementation of such techniques could decrease fisheries impacts globally. While there can be major conservation benefits from fishers' knowledge research, one-quarter of the active longline captains I contacted declined interviews because they did not trust the larger research process. I urge conservation biologists to carefully design fishers'

knowledge research, taking into account the often politicized context. Failure to do so may jeopardize future research and conservation efforts.

4.1 Introduction

Pelagic longline fisheries target swordfish (*Xiphias gladius*) and tunas (*Thunnus* spp.) throughout the Atlantic, Pacific, and Indian Oceans, and the Mediterranean Sea. Bycatch from pelagic longline fisheries, defined here as incidental catch that is subsequently discarded dead or released alive, has contributed to widespread population declines of turtles, sharks, and other large pelagic fish (Baum et al. 2003; Lewison et al. 2004; Myers and Worm 2003). Because species caught on pelagic longline gear migrate across ocean basins (Campana et al. 2006; James et al. 2005; Mollet 2002; Neilson et al. 2009), large-scale estimates are needed to understand cumulative impacts from longline fisheries. However, fishing practices and species catch rates differ within fisheries (Baum et al. 2003; Brazner and McMillan 2008; Kerstetter and Graves 2006). Because different targeting, setting, and discarding practices affect bycatch levels and post-release survival (Branch and Hilborn 2008; Campana et al. 2009; Wade et al. 2009), information on the prevalence of different fishing practices is needed to accurately assess overall fishery impacts and to develop effective bycatch mitigation approaches.

Assessments of population or ecosystem level impacts from pelagic longline fisheries are largely based on fishery-dependent data (Maunder and Punt 2004). In data-rich fisheries, impacts are assessed using landings records, logbook data, and data collected by at-sea fisheries observers (McCluskey and Lewison

2008). Because these data are collected during commercial fishing operations and are thus fishery-dependent, additional information on fishing practices is needed to differentiate effects of changing fishing practices from changes in species abundance. Increased fishing power can mask population declines (Bishop 2006), whereas unaccounted for changes in targeting practices has resulted in overestimates of fishery impacts (de Mutsert et al. 2008). Bycatch species are caught incidentally; therefore information on the association between target and bycatch species and on the prevalence of different targeting practices is also needed. Within multispecies fisheries, motivations to switch among target species or fishing regions differ depending on individual captains' skill and experience, fishing preferences, and changing regulations or markets (Béné and Tewfik 2001; Branch and Hilborn 2008; de Mutsert et al. 2008). The efficacy of bycatch mitigation approaches may differ among regions and with targeting practices (e.g., Wade et al. 2009). Therefore, even within data-rich fisheries additional information may be needed to track fishery impacts and to develop bycatch mitigation approaches.

Fishers' knowledge research can contribute important information for assessment, management, and bycatch mitigation even where detailed fisheries science data exist: by identifying needed improvements to the fisheries science data (Saenz-Arroyo et al. 2005); by soliciting feedback on the efficacy of possible mitigation strategies (Santora 2003); and by developing mitigation techniques based on fishers' technical expertise (Hall et al. 2007) and on their observations of bycatch species' behaviour relative to fishing gear and target species (Jenkins 2007). Fishers' knowledge may be particularly important for marine conservation research when population metrics are based on fishery-dependent data and when researchers' observations of species' behaviour or ecology are limited. However, fishers may be unwilling to share their knowledge if research will likely lead to increased regulations, and if fishers' have no control over the use of their knowledge (Hall et al. 2007; Hartley and Robertson 2009; Santora 2003; Silver and Campbell 2005; St. Martin and Hall-Arber 2008). Thus, a core dilemma of fishers' knowledge research is that while there may be an urgent need to access fishers' knowledge, there are potential risks for participants. This research context creates ethical and practical issues for researchers.

Our research objectives were: 1) to use additional information from qualitative interviews to better assess fisheries impacts; 2) to request feedback from longline captains on proposed bycatch mitigation approaches and on existing mitigation tools; and, 3) to identify mitigation opportunities in swordfish and tuna longline fisheries. While fishers' knowledge research can improve assessment and mitigation of pelagic longline bycatch, the process of engaging fishers and their knowledge influences research quality and therefore, future research and mitigation opportunities. Thus, my fourth objective was to design and document a research approach that builds trust and collaborative research opportunities. Using information derived from qualitative fishers' knowledge interviews with members of the Atlantic Canadian longline fishery for swordfish and tunas, I demonstrate that this additional information can be used to improve the accuracy of fishing assessments and the efficacy of bycatch mitigation approaches, even in data-rich fisheries such as this one.

4.1.1 Research context

The Canadian Atlantic pelagic longline fishery targets swordfish, and albacore (*T. alalunga*), bigeye (*T. obesus*), and yellowfin (*T. albacares*) tunas. Quotas for these highly migratory species are set by the International Commission for the Conservation of Atlantic Tunas (ICCAT). Canada's swordfish allocation has been 10% of the North Atlantic quota since 1999, as part of the stock rebuilding program (ICCAT 2006). Within Canada, 90% of the swordfish quota is allocated to the pelagic longline sector and 10% is allocated to the harpoon sector (DFO 2004). The pelagic longline fishery has been fished under an Individual Transferable Quota (ITQ) system since 2002. Previously, swordfish was fished competitively and the Canadian quota was not split between the two sectors. Canada does not have specific quotas for bigeye, yellowfin, and albacore tunas but instead fishes under catch guidelines for these species (DFO 2004). Because most of the Canadian swordfish quota is landed annually (> 97% of annual quota; Lester et al. 2008; Lester et al. 2009), and because individual longliners are limited by ITQ's, swordfish quotas are the key factor limiting fishing levels.

The Canadian longline fishery has increasingly targeted tunas since the mid-1990s (DFO 2004). Swordfish targeting occurs primarily along the continental shelf edge, whereas tuna targeting occurs further offshore and south of the continental shelf (Figure 1; Paul and Neilson 2010). Information on fishing locations and landed catch is collected through logbook and dockside monitoring programs. Additionally, at-sea fisheries observers collect catch composition and fishing effort data from a portion of the fleet; observers typically report from 5% of sea days annually (Lester et al. 2009). Observer data are used to estimate bycatch levels because bycatch is not consistently recorded in logbooks (e.g., Brazner and McMillan 2008; Campana et al. 2006).

Pelagic longline fisheries are facing increased pressures and incentives to decrease both the amount of bycatch and harm to discarded catch. For example, the US pelagic longline fleets were banned from portions of the Northwest Atlantic and Hawaiian waters to protect sea turtles (Hall et al. 2007; Martin and James 2005). Consumer marketing campaigns, which consider both bycatch levels and mitigation approaches when evaluating pelagic longline fisheries (e.g., SeaChoice and Marine Stewardship Council [MSC]), may provide incentives through increased market access or increased prices for sustainably caught fish. Recent conservation status assessments identified pelagic longline bycatch as the primary threat to loggerhead turtle (*Caretta caretta*; COSEWIC 2010) and blue shark (*Prionace glauca*; COSEWIC 2006) populations in Canadian waters. These assessments were based on catch rates recorded by at-sea fisheries observers. Catch ratios between target and bycatch species were then used to estimate total interactions based on effort levels reported in landings and logbook data. Loggerhead turtles were assessed as endangered by the advisory board (COSEWIC 2010). If the species is listed under Canadian endangered species legislation recovery strategies could include limiting fishing levels, modifying fishing and discarding practices, and documentation of decreased harm (DFO 2010). The swordfish and tuna longline fishery was being assessed for MSC certification while I was conducting research on longline bycatch (MSC 2011). As bycatch levels, impacts, and bycatch mitigation strategies are considered during MSC assessments (MSC 2008), certification conditions could include reductions in bycatch levels or harm. Further, if the longline fishery were certified, longline-caught swordfish could access markets and price premiums similar to those for certified harpoon-caught swordfish (Whole Foods Market 2010). Incentives and pressures to decrease longline bycatch in the Canadian pelagic longline fishery will likely increase as the fishery undergoes assessment for MSC certification and as bycatch species are evaluated under Canadian endangered species legislation, but specific guidelines or limits were not known at the time this research was conducted.

4.2. Methods

4.2.1 Research design

Qualitative fishers' knowledge interviews were structured around the fishing process. After initial fishing experience questions, I asked longline captains about their targeting, setting, and discarding practices (Appendix I). Additional interview topics included: associations between target and non-target species, and environmental factors affecting catch and bycatch rates. Images of common bycatch species were used to match local names with species names. Interviews were conducted using a semi-structured guide, meaning longline captains could identify additional topics during the interview (Patton 1990). I also asked longliners to comment on previous bycatch research, which was based on fisheries observer data collected from their fishery, including my own.

Because information requested during interviews was not publicly available and because there were risks associated with participation, this research was considered to be human subjects research (TCP 2005), and thus, national and university research guidelines required ethics review of the proposed research. Although the content and procedures of ethics reviews may differ among universities and jurisdictions (Shackeroff and Campbell 2007), researchers must consider participant risks and benefits, and must provide sufficient information for free and informed consent (TCP 2005). Prior to beginning fishers' knowledge interviews, I detailed the proposed research and how I would address these issues in my ethics review application (ICEHR No. 2006/07-112-SC).

Our goal was to contact and request interviews with all active longline captains in the fishery. Multiple methods were used to contact longliners. Research plans were presented at annual general meetings of the fishing association. A plain language summary of proposed research, which included a request for participants, was sent to all longline license holders along with license information for the 2008 season. A list of license holders was provided by the Department of Fisheries and Oceans (DFO). As the list of license holders did not include contact information, only license holders who were listed in public directories were contacted. Most license holders contacted (27/30) were identified from this list. If contacted license holders indicated that they were not fishing captains, I asked for contact information for the captain who fished the license. Additionally, the first author discussed the research with the fishing association representative, fish buyers, fleet managers, and crew at wharves throughout central and southern Nova Scotia and requested contact information for longline captains.

4.2.2 Fishers' knowledge interviews

Fishers' knowledge interviews were conducted during four trips to Nova Scotia between March 2008 and June 2009, each trip lasting 10 to 15 days. Many pelagic longline fishers are active in other fisheries, such as groundfish, lobster, snow crab, or shark. Therefore, trips were timed to coincide with transitions between the different fishing seasons when fishers were more likely ashore. As required by ethical research guidelines, during initial phone conversations I described my research objectives, detailed possible risks and benefits for the participant, and clearly stated that participation was voluntary (Appendix II). Field notes (FN) were recorded after each contact or interview; these records are denoted in the text (e.g., FN June 18 2008; following Silver and Campbell 2005).

Interviews were audio-recorded, transcribed, and imported into qualitative data analysis software (HyperResearch 2.7, ResearchWare Inc.). Case summaries for each interview detailed their fishing experience, species targeted, and regions fished. Interview guide and additional topics identified by longline captains were coded to allow cross-case comparisons for each topic (Richards and Morse 2007). Common themes were summarized for each topic (e.g., 9/11 longline captains targeted both swordfish and warm-water tunas) and alternative responses were noted (Patton 1990). Interview excerpts are denoted in the text by an interview identifier (e.g., 801). Quotations are used to illustrate common themes or alternative responses. Follow-on phone conversations were used to clarify details from the interview transcripts and to request permission for the use of quotes in publications.

4.3 Results

4.3.1 Research process

Of the 77 longline licenses, 53 licenses were active during the 2008 fishing season (Lester et al. 2009). However, not all active longline licenses were used to fish this gear type: 43% of the active licenses were used to exclusively fish pelagic longline; an additional 33% were used to fish a combination of longline, troll, and harpoon gear; and 24% of the longline licenses were used only to harpoon swordfish or troll for tunas (T. Atkinson, Nova Scotia Swordfishermen's

Association (NSSA) pers. comm. 2010). Thus, approximately 40 licenses were used to fish longline gear, either exclusively or in combination with other gear types. Longline captains who fished these 40 licenses were the target population. I was able to contact 60% of the active longline fishers (24/40). Although research trips were timed to correspond with transitions between fisheries, individual longliners had limited time ashore and had other commitments in their working or personal lives. Up to five phone conversations were required to either arrange interviews or to speak with longline captains and have them decline interviews. I was unable to arrange meetings with seven of the 24 longline captains contacted, an additional six longline captains declined interviews. I audio-recorded interviews with 11 active longline captains, whicch was at least one-quarter of the target population (11/40). These proportions are approximate as the number of active licenses shifts from year to year (Lester et al. 2008).

Six active longline captains declined interviews because they did not trust the larger research and management process. These longliners distinguished between giving information to individual researchers and later public uses of the information. While they wished us well, "I hope you find people who will talk with you, but I'm not one of them" (FN Feb. 26 2009), they declined because the research results would become public knowledge. Before some license holders agreed to interviews or agreed to provide contact information for captains who fished their licenses, they wanted to know who funded the research, what were my motivations and affiliations, how the information would be shared and, more generally, “How do we know this [research] is not going to come back and bite us” (FN Feb. 23 2009). As more bluntly put by a license holder at an association meeting, “You show me yours, I'll show you mine” (FN Jan. 30 2008). Even among fishers who agreed to interviews, some were concerned about possible implications for the fishery. For example, one captain said, “Son, when you want to fish and they say you can't. Blame it on this lady here. She's the one who will shut down the fishery” (FN June 3 2009).

Despite these concerns, captains associated with one-quarter of the active licenses used to fish this gear type agreed to audio-recorded interviews. Longline captains were interviewed from 5 different fishing communities and had between 5 and 45 years of experience as fishing captains. While individual captains had preferred fishing grounds, together they had fished from the Hague Line (US border) to northeast of the Grand Banks, along the continental shelf edge, and offshore into Gulf Stream waters (Figure 1). Most interviewed captains fished both tuna and swordfish, depending on species availability and on individual quota levels. However, two individuals identified themselves as swordfishermen and two indicated that they primarily targeted tunas.

4.3.2 Targeting and setting practices

Interviewed longliners described associations between target and bycatch species, and described changing targeting practices in response to recent management changes. All but one reported an association between swordfish targeting and blue shark (blue dog) bycatch. The one longliner, who did not report an association between swordfish and blue shark, identified himself as a tuna fisherman. Longliners reported which species were commonly caught in swordfish sets:

> You get [blue] shark when you're chasing swordfish on the edge [of the continental shelf] (1101).
>
> Swordfishing along the edge? You know you're going to get your 20, 30 blue sharks a day and you might get one or two scissorfish[1] for the trip (901).
>
> Other than blue dogs? You'll get the odd porbeagle[2], the odd mako[3], the odd scissorfish (401).
>
> If you're in the cool water, blue shark is the main problem (201).

Longliners reported less blue shark bycatch when targeting tunas in warmer water.

> You'll get the odd shark in that warm water but it'll be a tiger shark[4] (901).
>
> If you get 60 or 70 tuna some days, you can get a load of mahi[5], but you very seldom see a swordfish, very seldom see a shark. Like I say, once in a while a turtle (1101).
>
> If you go into the cool water, you're more likely [to] get sharked up. If you go early and you go way offshore, you're not going to have that problem (301).

Another captain illustrated the general pattern by describing an exception:

> Sometimes [it's] tricky, like last year I thought in September all the blue dogs would be in over the edge. And I went outside … the thousand

[1] Lancetfish (*Alepisaurus* sp.)

[2] *Lamna nasus*

[3] *Isurus oxyrinchus*

[4] *Galeocerdo cuvier*

[5] *Coryphaena hippurus*

fathom edge, and quite warm water in September, looking for tuna and we got a load of blue dogs again (801).

Because bycatch species are associated with particular target species, changing fishing practices following the switch to ITQ management in 2002 likely affected bycatch levels. Longliners stated that ITQ's, "made us concentrate on tunas more," (901) and that there was a "big shift from fishing along the edge of the shelf out into deeper waters for tuna" (101). Another longliner said that with the switch to ITQ management, "Now we only have so many fish. Before [when] it was competitive [we] just went wide open for swordfish right until it was caught. Then, if they had enough for a [swordfish] bycatch, they'd go for some tuna" (701). Note he was using the traditional definition of bycatch, which is landed species with limiting quotas or bycatch caps (e.g., Benoît and Allard 2009). Seven longliners reported increased tuna targeting under ITQ management. If few blue sharks are caught in tuna-targeted sets, then blue shark catch rates reported in the fisheries observer data would decline. In response to interviewer comments on declining blue shark populations (e.g., Baum et al. 2003; Campana et al. 2006), one longliner replied, "The only reason it looks like that is because we're not fishing like we used to fish. Earlier, in on the Bank, that's when we got our big pile of sharks" (301). Because his observations did not match with declining blue shark population estimates, he asked, "When they're talking about no sharks, are they talking about when we're way off the 200 mile limit?" (301).

In addition to seasonal and regional blue shark catch distributions; longline captains reported within trip differences in blue shark catch which they attributed to environmental factors, such as water temperature. Further, some reported difficulties setting longline gear in such a way that cooler water temperatures, and consequently blue shark, could be avoided. When asked if there were ways to avoid blue shark, this longliner responded, "Not necessarily. If you can get your gear to stay where you put it, instead of [it] going cold" (901), then you could avoid blue shark. Other longline captains explained difficulties when setting gear on the warm side of an edge (temperature front), "If you get too much gear in the cold water – even if sometimes you get too close to the actual edge – your gear will get pulled into the cold water and you've got a lot of sharks" (1001). Both over the fishing season and within trips, longline captains reported expected blue shark catch patterns, but also described limits of their ability to predict and control pelagic fishing gear, as summarized in this quote:

> Fishermen realize that blue shark inhabit certain waters. They try their damnedest to keep their gear out of that water temperature. If it gets in there, it will typically be [by] accident not by design (101).

Longline captains also reported water temperature effects in tuna-targeted sets, which have implications for proposed bycatch mitigation methods. Because loggerhead turtle catch rates were highest at water temperatures >20 °C in this fishery, Brazner and McMillan (2008) recommended fishing on the cool side of oceanic fronts. Some longliners agreed such setting practices would decrease loggerhead bycatch, "Yes, on the cold side of the water, you won't get so many loggerhead" (801). However, fishing on the cool side would affect tuna catch, "You'd get no amount of fish. No fish" (501). Others said, "You'd get no tuna. You've got to stay on the hot side of it" (1101) and explained why, "Because the yellowfin, they like the warmer water. Think everybody knows that" (301). Thus, longline captains reported that targeting practices, such as deciding where and when to fish, and setting practices relative to thermal fronts affected target catch and bycatch rates whether targeting tunas or swordfish.

4.3.3 Discarding practices

Longline captains reported different discarding practices depending upon the type of bycatch being released, fish condition, hook location, and crew safety. They considered management regulations, landed values, and the long-term health of the fishery when discarding small, commercially valuable species. Longline captains also volunteered feedback on current bycatch mitigation tools and reported innovative uses of turtle dehooking gear.

All Canadian longline vessels carry turtle dehooking gear (NSSA 2002), which includes pig-tailed and J-style dehookers (ARC Dehooker Inc., Bunnell FL, USA). Captains referred to the gear as "some slick rig", saying:

> Yeah, they're good. The people [who made them] put some thought into them and they actually work. I was surprised ... the traditional way of longline and groundfishing, and that's what people learn, you just ripped the hooks out. It's definitely a better, safer way of not harming the animals (601).

Longliners described how to use the gear, but mentioned you needed to learn how to use it:

> These things work pretty slick once you learn how to use it. It's all in the [demonstrates flip] with your wrist (701).
>
> That's the little twirly rig [pig-tailed dehooker]. You just shove it down like that and give it a snap with your wrist and [it] pops the hook right out (501).

Longliners were using the dehooking gear to release other bycatch species, in addition to turtles. Turtle dehooking gear was used to release small tunas, blue shark, and pelagic stingray (*Pteroplatytrygon violacea*). While describing how he releases small tunas, this longliner volunteered information on the dehooking gear, "If they're real live, we take the hook out. We pop the hook out with the kit. The rig we got, that's a slick rig, by the way (501)." Few longliners were using dehooking gear to release blue shark, but those that did said,

> These things work pretty slick, once you learn how to use it. I'm getting my hooks back out of those sharks that I used to lose my hooks in every time. So that's 60 cents to a dollar I'm saving for every one of those things that swims off (101).

Although two-thirds of those interviewed reported that turtle dehooking gear was easier to use and likely increased post-release survival, two longliners preferred their own methods for releasing unwanted catch.

Pelagic stingray (black skate) are common bycatch in the Canadian pelagic longline fishery (Carruthers et al. 2009). Further, because of venomous tail spikes, which are "razor sharp and poisonous" (601), discarding the fish can be hazardous. As one longliner said, "You don't want to get too close to them …

their tail is going pretty fast[6] (301)." One longline captain reported using dehooking gear on all bycatch, but most used long-handled gaffs to release pelagic stingray:

> Some of the experienced fishermen, the deckhands I should say, will do teamwork. One hauls on the gangion [or leader line]. The other takes the unhooking gaff, the long-handled gaff so he doesn't put himself in danger, and leans over broad side and trips them off. No harm, no fuss (601).
>
> We haul them up and we take the hook. Take an unhooking gaff and unhook (1001).
>
> We've got a gaff, same as [what] you use for gaffing a haddock[7]. You just take that gaff put it around the hook and anybody who knows how to do it just one little turn …just a twist of the wrist. Bang. Gone (301).
>
> Sometimes [with] the black skates, we'll haul the gangion up and we'll try to slide the gaff down the hook and unhook them. But the sharks are too big for that (701).

Similarly, crew safety and ease of discarding were key considerations when discarding blue shark. Most longliners reported simply cutting the line, either near the hook or where the gangion attaches to the main line, to release blue shark bycatch:

> See with the [blue] sharks, they chew up the gangion anyway. You're just losing the hook, more or less. So we just cut them off (701).
>
> If you get into a lot of blue dogs, you wouldn't know it if you weren't looking over the rail because we just cut them away. We'll have what we call a shark line. If I say shark before it comes [up], and he's standing there with a shark knife and [he] nicks [the gangion] (201).

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[6] Field guides contain similar warnings for handling whip-tail stingrays, including pelagic stingray (e.g., Robins et al. 1986).

[7] *Melanogramus aeglefinus*

> We just haul the gangion up and cut it off close to the hook. We've got long knife gaff, just cut it off close to the hook. I'm not hauling sharks aboard the boat to take hooks out and take the chance of one of my men [will] get chewed up (901).

Small commercial species were discarded because of minimum size regulations, low market price, or because individual longliners were thinking of the long-term health of the fishery. When describing why he releases small live tuna, this longline captain explained, "I'm only young; if I'm going to do well in the fishery I've got to think of the next 30 years" (601). Due to minimum size regulations that limit the proportion of swordfish landings consisting of fish less than 125 cm in length (DFO 2004), small swordfish are considered bycatch in this fishery. Longline captains considered swordfish health when discarding small live swordfish bycatch:

> We see where it's hooked first of all. If it's not in a vital spot, we'll haul him up and grab his sword [as] best we can and cut it or trip the hook out. ...If it's in a vital spot, we'll snip the line down as short as we can so it doesn't mess him up (601).

> If you got a pretty blue fish, and he's kicking alive, well my crew would get mad at me if I kept him, and I wouldn't blame them (401).

They reported using hook location, activity level, and coloration (swordfish lose their bright colors as they die) to evaluate swordfish condition.

Longliners acknowledged that there are economic incentives to discard small swordfish under current ITQ management and minimum size regulations, and that some discarding happens. However, some also reported that they kept or landed small dead swordfish. Further, they told us how to find evidence of such practices in the logbook data.

> The only swordfish I ever throw back is anything that's small and alive. Get the hook out of the swordfish and let him swim away, "We'll get you another day when you grow up" ... If he's small and he's dead, we keep him (801).
>
> In my own opinion, there's not a whole lot of guys that do it [discard small swordfish]. OK, do some math here. You're buying quota, and a hundred pound fish and up is three-fifty a pound and a little tiny fish is a dollar-fifty a pound. The guy that paid a dollar-fifty for quota, he's in a bad spot isn't he? So number one, you got to be where the big fish are — and you can do that (401).
>
> I mean there's limited markets [for small swordfish]. For the guys who make the moral judgment, if it's dead then I'll bring it in and maybe I'll take it home and eat it… you know, 'crew fish' in the logbooks … And then the others [say] … I can't sell it, I'm not going to get anything for it, and it's coming off my quota, so it's going back (101).

These quotes illustrate that there are different discarding practices for small swordfish within the fleet. While some longline captains did not discard small dead swordfish for ethical reasons, they acknowledged discarding of dead small swordfish occurs and that there are economic incentives to do so under the current management system.

4.4 Discussion

Interviews with pelagic longline captains and the process of conducting research on fishers' knowledge provided information which could be used to increase the accuracy of bycatch assessments and the efficacy of bycatch mitigation approaches. Needed changes to the documentation and analysis of observer data – particularly, documentation of evolving observer protocols – were highlighted by the discrepancy between longline captains observations' and current assessment methods. Longline captains' described operational difficulties with proposed bycatch mitigation approaches and reported innovative uses of turtle dehooking gear that could decrease post-release mortality levels of common bycatch species worldwide. Future research to examine ecological relationships or to develop bycatch mitigation opportunities identified here would need to address the trust issues highlighted by longline captains who declined interviews.

4.4.1 Research process

The process of doing fishers' knowledge research revealed basic information about the structure of the Canadian pelagic longline fishery. During conversations with the industry representative and with fleet managers, I learned that the longline fishery was more complex than reported in fisheries management and assessment documents, which report the number of active longline licenses and total landings (Lester et al. 2008; Lester et al. 2009). The national fishery report indicated that swordfish harpooned by longline license holders were included in total harpoon landings, but detailed neither the proportion of harpoon landings nor the number of longline licenses involved (Lester et al. 2009). The Canadian Atlantic longline fishery is data-rich; the fishery is subject to 100% dockside monitoring, logbook reporting requirements have been enforced since 1998, and at-sea fisheries observers report from approximately 5% of sea days each year (DFO 2004; Lester et al. 2009). Despite this, the process of trying to recruit fishers to this study revealed new and management relevant information, such as the prevalence of different gear types using longline licenses. This information was needed to define the target population – the approximately 40 active longline licenses used to fish this gear type.

Our goal was to contact and interview all active longline captains in the fleet. I was able to contact captains associated with 60% of the active licenses used to fish this gear type. Eleven interviews were recorded, representing 25% of the target population in 2008. Sample size and participation rates vary widely within fishers' knowledge research, from single in-depth ecological descriptions (e.g., Johannes 1981) to rapid surveys of global fisheries impacts where thousands of fishers were interviewed representing <3% of the sample population (e.g., Moore et al. 2010). While low, the sample represented approximately one-quarter of the active licenses used to fish this gear type, which is comparable to participation rates reported in other qualitative fishers' knowledge research (e.g., Silver and Campbell 2005; Hartley and Robinson 2009).

Low sample sizes do, however, raise the concern that interviewed longline captains were not representative of the fleet, or that the sample was biased towards longline captains interested in bycatch mitigation. Characteristics of the sample relative to the inferred population can be used to evaluate whether a sample is representative (Patton 1990). Interviewed longline captains were from five of the six key Nova Scotia ports listed in the management plan (DFO 2004) and among them had experience fishing the entire region. Longline captains were contacted as a result of a systematic sampling process – I contacted all license holders for whom I had information. Had convenience sampling been used (e.g., captains from the nearest port or captains who participate in fisheries research), the sample would more likely be biased towards particular regions or fishing practices (Patton 1990; Schumann 2010). Most of the active longline captains were not interviewed simply because contact information was not available in public directories nor supplied by fish buyers (17/40 active licenses used to fish this gear type). I do not know the characteristics of this group (e.g., experience, targeting practices, or preferred fishing grounds) or their interest in bycatch mitigation. Similarly, I do not know the fishing practices of the seven longline captains with whom I was unable to meet, or of the six longline captains who declined interviews. In future research, such information could be collected during initial contacts, which would allow better evaluation of sample representativeness. Because the recruitment process did not favour particular regions or targeting practices and because approximately one-quarter of active longline captains were interviewed, I consider the sample representative. I cannot assume that interviewed longline captains were more interested in bycatch mitigation, as this was not the explanation provided by longline captains who declined interviews. I do, however, discuss implications of possible sample bias for my research objectives and for my findings on targeting, setting, and discarding practices.

My bycatch mitigation research objectives were: 1) to use information from qualitative interviews (in addition to existing quantitative fishery-dependent data) to better assess fisheries impacts; 2) to solicit feedback on proposed bycatch mitigation approaches and existing mitigation tools; and, 3) to identify bycatch mitigation opportunities in the Canadian pelagic longline fishery. Qualitative research methods are most appropriate when research goals include understanding processes from participants' points of view and uncovering new ways of looking at complex situations (Richards and Morse 2007). Thus, qualitative interviews were used to uncover alternate ways of interpreting existing quantitative data and to consider the efficacy of bycatch mitigation approaches and tools from the longline captains' point of view. Had my first two research objectives been to estimate overall fishing impacts or to determine the extent of particular targeting, setting or discarding practices; then quantitative survey data would have been more appropriate – provided that sample representation and bias were adequately addressed (e.g., Benoît and Allard 2009). The third objective – to identify bycatch mitigation opportunities – would not be negatively affected if interviewed longline captains were more interested in bycatch mitigation than the rest of the fleet. Individual captains have developed widely-used bycatch mitigation techniques such as the Medina panel, which allows live release dolphins from tuna seines (Jenkins 2007), and tori poles, which deter seabirds from taking longline baits (Hall et al. 2007). These innovations were based upon individual captains' exemplary knowledge of fishing practices and of target and bycatch species' interactions with fishing gear (Jenkins 2007). There are, however, important limits to the use of the qualitative data reported here. I did not ask longline captains to estimate bycatch levels nor likely impacts on bycatch populations. I chose not to ask these questions because such data already exist and, given the research context, I expected such questions would increase antagonism towards my research and would increase the number of refusals. Instead, I focused on improving current assessments, evaluating proposed bycatch mitigation approaches, and developing possible solutions. These objectives were better matched to the research method (in-depth qualitative interviews) and would not jeopardize my fourth objective – to design and document a research process with the potential to build, rather than erode, trust even within a politicized research context.

Given the research context – bycatch levels were being evaluated during the MSC assessment (MSC 2008), were central to arguments made through international media to increase harpoon quota (Rigney 2008), and were the basis of environmental organizations' recommended changes to fishery management (DSF 2009) – some longliners decided the risks from participation were too high. Moore et al. (2010) stated that research with high refusal rates can yield biased information and, thus, suggested minimizing refusal rates by making the research relevant to fishers' interest and by assuring fishers that risks from participation are low. My focus on problem-solving and bycatch mitigation opportunities addressed the first suggestion. However, when asked if the research would "come back and bite us", I could not honestly assure them it would not. Voluntary participation and informed consent are key aspects of ethical research guidelines (TCP 2005) and failure to disclose research aims and possible risks can lead to decreased participation in subsequent research (Maurstad 2002). Finally, focus on minimizing refusal rates may overlook the crucial information contained in interview refusals. During my research, six longline captains declined interviews because they did not trust the larger research and management process, specifically mentioning publication and subsequent uses of information in their refusals. While information from interviewed longline captains identified bycatch mitigation opportunities, information contained in interview refusals identified trust issues that need to be addressed to develop these mitigation opportunities.

4.4.2 Fisheries assessment

In general, longline captains reported bycatch levels and species associations, which were consistent with fisheries observer data. For example, loggerhead turtles and yellowfin tuna were caught in warm water (Brazner and McMillan 2008); blue, porbeagle, and mako sharks were associated with swordfish catch (Carruthers et al. 2011); and, reports of tiger shark catch coincided with locations where this species has been tagged (Kohler et al. 1998). Longline captains agreed that blue sharks were the most common bycatch during swordfish-targeted sets fished along the continental shelf edge; however, they reported few blue sharks when targeting tunas further offshore. Although there are obvious pragmatic and political motivations to underestimate bycatch levels (Palmer and Wadley 2007), there are a number of reasons why I think longliners were accurately representing the incidence of blue shark bycatch in tuna-targeted sets. First, the observation was consistent among interviewed longline captains, who identified limits to this general pattern (e.g., when neither fish nor gear behaved as expected). More importantly, when longline captains provided example numbers of blue shark bycatch caught in swordfish-targeted sets, these matched average blue shark catch rates (Campana et al. 2006). Finally, research from other pelagic longline fisheries suggests that blue shark bycatch is both less common and more variable in tuna-targeted sets (He et al. 1997; Walsh et al. 2002). While estimates of total blue shark bycatch for this fishery are premised on catch and distribution patterns that largely agree with longline captains' observations, differing interpretations of sets that reported no blue shark catch have important implications for overall impact assessments.

Fisheries observer data are used to estimate total blue shark bycatch. Bycatch ratios, based on the summed weight of blue shark relative to target species among observed sets, are then multiplied by unobserved target species weight taken from the landings records (Fowler and Campana 2009). These bycatch estimates are considered a minimum because of anecdotal reports of observer underreporting (Fowler and Campana 2009). For example, when longline crew release shark bycatch by simply cutting the gangion, fisheries observers may not be able to observe and record all discards (Campana et al. 2009; Fowler and Campana 2009). Assessments include an upper limit or maximum estimate, in which bycatch ratios are based only on those sets that reported at least one blue shark — assuming blue shark were caught (but not recorded) in all sets (Fowler and Campana 2009). The maximum estimate is used as an upper limit and annual estimates are calculated as the midpoint of these upper and lower limits. Separate bycatch ratios are calculated for different fishing seasons and targeting practices, with bycatch ratios considerably higher for swordfish-targeted sets. However, bycatch ratios are based on fisheries observer data collected before 2004 (Fowler and Campana 2009). Longline captains would likely dispute the assumption that blue sharks were caught in all sets; particularly those fished early in the season, further offshore, or with high tuna catch rates.

To evaluate how conflicting interpretations of zero blue shark sets influence overall bycatch assessments, I examined fisheries observer data from 2007 (fisheries observer data described in Carruthers et al. 2009), the last year used in the recent blue shark assessment. Only one swordfish-targeted set reported zero blue shark bycatch. Further, the onboard observer reported up to 93 blue shark from other sets during that trip. However, because bycatch ratios reflect fishing and observer practices from earlier in the program, bycatch estimates for 2007 were considerably higher. The bycatch estimate based on observed blue shark bycatch was 1339 mt, whereas the averaged estimate was 1827 mt (Fowler and Campana 2009) – amounting to an increase equal to one-third of the initial estimate.

Differentiating between zero catch (i.e., no blue shark were caught), uncertain catch (i.e., bycatch was released before identified to species) and underreporting (i.e., observers did not record all bycatch) could be done within the existing observer program and would greatly reduce the uncertainty of blue shark bycatch estimates. Although information volunteered during a fishers' knowledge interview corroborated the difficulty of observing shark bycatch that was cut off before being brought alongside the vessel (201), fisheries observers would know when such discarding practices occurred. Gangions are slack and hooks are recovered when neither target nor bycatch species are hooked (pers. obs.). Thus, uncertainty resulting from this discarding practice could be quantified. Like other fisheries observer programs (Cotter and Pilling 2007), pelagic longline observer protocols have evolved in response to changing management and science priorities (Javitech 2002; Porter et al. 2000). For example, before 1998 at-sea observers did not consistently record length and weight estimates of bycatch discarded by cutting the gangion (Porter et al. 2000); however, program staff indicated this problem was addressed during the 1999 fishing season and during the subsequent period of high observer levels (G. Croft pers. comm.). Thus, the interpretation of sets that reported no blue shark bycatch reflects observer protocols early in the time series. Cotter and Pilling (2007) recommend creating a working document, detailing changes to observer program objectives and protocols, and making it available to all researchers using such data. This relatively simple recommendation could be used to resolve differing interpretations and improve the accuracy of current bycatch estimates.

4.4.3 Bycatch mitigation opportunities

Longline captains' descriptions of setting practices and of species' distributions highlighted likely problems with proposed bycatch mitigation approaches, such as setting gear on the cool side of thermal fronts (Brazner and McMillan 2008). Longline captains' observations that yellowfin and bigeye tuna catch, and loggerhead turtle bycatch were associated with warmer water temperatures were consistent with fisheries observer data. Brazner and McMillan (2008) suggested longliners shift in targeting, from tuna to swordfish, to decrease loggerhead turtle bycatch levels. However, the longline fleet increased targeting of warm-water tunas, in part to offset swordfish quota limits, and Canadian landings are well below current catch guidelines for warm-water tunas (DFO 2004, Lester 2009). A shift in targeting may not be possible under current swordfish quota limits. Decreased tuna targeting would likely be achieved by decreased effort, or by a shift in fishing gear used (DFO 2010). Longline captains identified likely problems with fishing on the cool side in addition to decreased tuna catch: increased blue shark bycatch and operational difficulties of keeping the gear on the warm side of thermal fronts. Thus, the proposed conservation initiative of fishing on the cool side of thermal fronts could have unintended impacts on other bycatch species.

Longline captains set their gear on the warm side of thermal fronts, particularly when targeting warm-water tunas, and reported an increase in blue shark bycatch when gear was pulled onto the colder side of the front. Pelagic longline gear is neither anchored nor attached to the vessel while fishing. Accidental shifts in longline location arise when setting gear close to a thermal front, "where the bait is held," but not setting gear too close so that it "breaks through the hot edge and into the cold edge" (601). Currents differ on either side of thermal fronts. For example, captains reported that the currents in the Gulf Stream were 2-3 knots but that adjacent cold water may be flowing at less than 1 knot. These current speeds are consistent with those reported from drifter buoys (Reverdin et al. 2003). Longline captains' comments on the American captain fined for fishing 10 km inside Canadian waters (CBC 2009), illustrated the difficulties of fishing pelagic gear along fronts. Interviewed captains reported longline gear could drift that far; one captain referred to his logbook and showed his gear had drifted >70 km in one night (801). These setting difficulties affect current bycatch levels and could impact the efficacy of proposed bycatch mitigation approaches. Linking information on local current speeds or vertical ocean structure with longline fishing practices may help identify conditions under which gear is pulled across thermal fronts. In the meantime, methods to further reduce bycatch injuries and mortalities could be developed based on the information provided by interviewed longline captains.

Longline captains used different discarding practices depending on the species captured, how animals were hooked, crew safety, and their familiarity with different discarding methods. They volunteered information on turtle dehooking gear, which two-thirds of the interviewed captains had used to release other bycatch species in addition to loggerhead and leatherback turtles. I recognize there are limitations to voluntarily reported discarding practices. For example, longline captains did not report harsh discarding practices observed in swordfish and blue shark longline fisheries (Campana et al. 2009). Longline captains did, however, identify key considerations in their discarding decisions (e.g., crew safety and ease of discarding). By addressing longliners' key considerations, future researchers could increase the likelihood that longliners would adopt modified discarding practices. Given current incentives to decrease fishery impacts, the fleet may choose to decrease post-release mortality levels by standardizing and documenting best discarding practices, such as use of turtle dehooking gear. Recent turtle dehooking protocols mention that the gear can be used to release other bycatch species, but best practices have not been developed (NMFS 2008). Further, because pelagic species caught by the Canadian longline fleet are highly migratory, mitigation methods developed here could benefit bycatch species' populations globally if widely implemented.

Pelagic stingray are common bycatch in longline fisheries throughout the Pacific (Mollet 2002; Ward et al. 2004), the Atlantic (Carruthers et al. 2009; Domingo et al. 2005; Kerstetter and Graves 2006), and the Mediterranean (Piovano et al. 2010). In their review of the global conservation status of sharks and rays, Dulvy et al. (2008) stated the likelihood of post-release survival was low based on discarding practices reported for the Uruguay pelagic longline fishery (Domingo et al. 2005). It is not known, however, whether discarding practices reported in that fishery (smashing rays against the rail to remove hooks) are common or represent a worst-case scenario. Fisheries observer data from the US Atlantic and Canadian fisheries report over 90% of pelagic stingray were alive at haulback (Kerstetter and Graves 2006) or when released (Carruthers et al. 2009). Given the diversity of discarding practices described within a single fleet, I caution against extrapolating discarding practices from a single fleet to global pelagic longline fisheries (e.g., Dulvy et al. 2008). Domingo et al. (2005) stated the purpose of the reported discarding methods was to recover hooks without injuring fishing crew. Safety was a consideration among interviewed longline captains, who stated using long-handled gaffs or dehookers allowed crew to safely discard pelagic stingray and recover hooks. Where discarding practices described by Domingo et al. (2005) are common, adopting discarding practices reported by Canadian longline captains would improve pelagic stingray survival, would likely increase crew safety and hook recovery.

Discarding practices described by interviewed Canadian longline captains could decrease post-release mortality levels both within the fleet and worldwide. Given the range of within-fleet experience, best discarding practices could be developed through within-fleet consultations, which have led to improved mitigation techniques for other bycatch species (e.g., Hall et al. 2007). Bycatch species caught in swordfish and tuna gear fisheries travel through several jurisdictions and may encounter multiple longline fisheries. As a result, conservation efforts need to cross international borders; otherwise, "it's like putting a speed limit on three cars" (401). Conservation efforts such as fisher-exchange programs have introduced effective bycatch mitigation techniques to other fleets (Hall et al. 2007). Interestingly, a fisher-exchange program would parallel the historical development of the Canadian longline fishery for tunas. An American tuna fisherman was hired on as crew for the summer "to show us what to do" (501).

4.4.4 Summary

Our research demonstrates that information from fishers' knowledge interviews can improve both the accuracy of bycatch assessments and the efficacy of mitigation, but that there are practical and ethical issues to including fishers and their knowledge in research on contentious conservation issues. The key issue is one of trust. Concerns about negative consequences of research are common among fishers who participate in research (Hall et al. 2007; Hartley and Robertson 2009; St. Martin and Hall-Arber 2008), particularly in politicized conservation contexts where research may lead to increased regulation (e.g., Silver and Campbell 2005). Nor are these concerns limited to fisheries like the Canadian pelagic longline fishery; Silver and Campbell (2005) reported similar concerns among turtle fishers who either fished for personal consumption or sold turtle meat in local markets.

While approaches to engage fishers and their knowledge differ among research contexts, there are common themes. The process of engaging fishers in research can take considerable time (Hall et al. 2007; Martin and James 2005). Face-to-face interactions between researchers and fishers are preferable to presentations at industry meetings, phone interviews, or mail surveys for building trust (Martin and James 2005; Neis et al. 1999). My research questions were limited to those appropriate to the research context and approach; I did not ask longline captains to self-report bycatch levels, but instead focused on the capture process and on bycatch mitigation opportunities. By contrast, Moore et al.'s (2010) recommendations to evaluate reliability of fishers' bycatch estimates – by asking fishers to report others' bycatch levels – would have increased antagonism towards my research and, likely, further jeopardized future conservation opportunities (Shackeroff and Campbell 2007). Ideally, the research process involves two-way communication, neither limited to scientists educating fishers (Campbell and Cornwell 2008) nor simply extracting knowledge (Martin and James 2005). Possible management outcomes were included in research summaries sent out to the fleet and discussed with captains, acknowledging likely uses of my results (Appendix III). This feedback process is ongoing. My research was designed with the overall goal of reducing bycatch in the Canadian pelagic longline fishery for swordfish and tunas. Therefore, I drew on existing fishers' knowledge research to design an approach that would not jeopardize future research.

Fishers' knowledge research provided feedback on current bycatch mitigation gear and identified opportunities to further reduce bycatch mortalities which would have been missed had I limited my research to the available fishery-dependent data. Fishers' knowledge research is often motivated by a lack of fisheries data, which is not the case in the Canadian Atlantic pelagic longline fishery. Instead, discrepancies between longline captains' observations and bycatch estimation methods identified needed improvements to existing fisheries science data. I recognize that improvements to the observer program, such as quantifying deployment effects (e.g., Benoît and Allard) or resolving differences between observers' and scientists' assessment of injury rates and therefore post-release survival rates (Campana et al. 2009), would also increase the accuracy of bycatch assessments. However, addressing the issue identified here, namely documentation of current observer practices, would not only improve the accuracy of current bycatch estimates but would provide a stronger base for any subsequent improvements to the program. Specific management recommendations following from my work include: develop a working document that details evolving observer protocols, and document current handling and discarding practices. These recommendations could be implemented within the existing research and management framework. Subsequent conservation and research initiatives, such as developing best discarding practices or tracking effects of changing targeting practices, would be better addressed by including fishers and their knowledge in the research process.

Our research approach was chosen with the overall goal of reducing bycatch in the Canadian pelagic longline fishery for swordfish and tunas. To meet this goal, ongoing research on bycatch mitigation opportunities (i.e., developing best discarding practices) and ecological interactions (i.e., disentangling the relationships between target species and thermal fronts) is needed. Such research would be better addressed through systematic records of discarding practices and post-release survival, and ecological field experiments rather than in-depth qualitative interviews. However, qualitative research methods provided information on the catch and discard process from the point of view of active longline captains, which highlighted problems with existing data and with proposed mitigation approaches. Thus, my research has laid the groundwork for future bycatch mitigation research and for building collaborative relationships to solve these conservation issues. Given longline captains' enthusiasm for dehooking gear, their interest in avoiding blue sharks, and the ongoing conservation assessments and fisheries certification; there are clearly incentives to do so – provided that the research context is taken into account.

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4.5 References

Baum, J.K., Myers, R.A., Kehler, D.G., Worm, B., Harley, S.J., Doherty, P.A., 2003. Collapse and conservation of shark populations in the Northwest Atlantic. Science 299, 389-392.

Béné, C., Tewfik, A., 2001. Fishing effort allocation and fishermen's decision making process in a multi-species small-scale fishery: analysis of the conch and lobster fishery in Turks and Caicos Islands. Human Ecology 29, 157-186.

Benoît, H.P., Allard, J., 2009. Can the data from at-sea observer surveys be used to make general inferences about catch composition and discards? Canadian Journal of Fisheries and Aquatic Sciences 66, 2025-2039.

Bishop, J., 2006. Standardizing fishery-dependent catch and effort data in complex fisheries with technology change. Reviews in Fish Biology and Fisheries 16, 21-38.

Branch, T.A., Hilborn, R., 2008. Matching catches to quotas in a multispecies trawl fishery: targeting and avoidance behaviour under individual transferable quotas. Canadian Journal of Fisheries and Aquatic Sciences 65, 1435-1446.

Brazner, J.C., McMillan, J., 2008. Loggerhead turtle (*Caretta caretta*) bycatch in Canadian pelagic longline fisheries: relative importance in the western North Atlantic and opportunities for mitigation. Fisheries Research 91, 310-324.

Campana, S.E., Joyce, W., Manning, M.J., 2009. Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. Marine Ecology Progress Series 387, 241-253.

Campana, S.E., Marks, L., Joyce, W., Kohler, N.E., 2006. Effects of recreational and commercial fishing on blue sharks (*Prionace glauca*) in Atlantic Canada, with inferences on the North Atlantic population. Canadian Journal of Fisheries and Aquatic Sciences 63, 670-682.

Campbell, L.M., Cornwell, M.L., 2008. Human dimensions of bycatch reduction technology: current assumptions and directions for future research. Endangered Species Research 5, 325-334.

Carruthers, E.H., Neilson, J.D., Smith, S.C., 2011. Overlooked bycatch mitigation opportunities in pelagic longline fisheries: soak time and temperature effects on swordfish (*Xiphias gladius*) and blue shark (*Prionace glauca*). Fisheries Research 108, 112-120.

Carruthers, E.H., Schneider, D.C., Neilson, J.D., 2009. Estimating the odds of survival and identifying mitigation opportunites for common bycatch in pelagic longline fisheries. Biological Conservation 142, 2620-2630.

CBC, 2009. Perfect storm skipper fined $35,000 for illegal fishing. <http://www.cbc.ca/news/canada/newfoundland-labrador/story/2009/06/09/perfect-storm-fine-609.html>

COSEWIC, 2006. COSEWIC assessment and status report on the blue shark *Prionace glauca* (Atlantic and Pacific populations) in Canada, In

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Ottawa.

COSEWIC, 2010. Assessment and status report on the loggerhead sea turtle (*Caretta caretta*), In Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Ottawa.

Cotter, A.J.R., Pilling, G.M., 2007. Landings, logbooks and observer surveys: improving protocols for sampling commercial fisheries. Fish and Fisheries 8, 123-152.

David Suzuki Foundation (DSF), 2009. Canada must protect Atlantic sharks, turtles. http://www.davidsuzuki.org/media/news/2009/canada-must-protect-atlantic-sharks-turtles/.

de Mutsert, K., Cowan Jr., J.H., Essington, T.E., Hilborn, R., 2008. Reanalyses of Gulf of Mexico fisheries data: Landings can be misleading in assessments of fisheries and fisheries ecosystems. Proceedings of the National Academy of Sciences 105, 2740-2744.

DFO, 2010. Recovery Potential Assessment for Loggerhead Turtles (*Caretta caretta*) in Atlantic Canada, In DFO Canadian Science Advisory Secretariate Science Advisory Report 2010/042.

DFO, Fisheries and Aquatic Management, 2004. Canadian Atlantic Swordfish and Other Tunas 2004-2006 Integrated Management Plan. <http://www.dfo-mpo.gc.ca/communic/fish_man/ifmp/swordfish/index_e.htm>.

Domingo, A., Menni, R., Forselledo, R., 2005. Bycatch of the pelagic ray *Dasyatis violacea* in Uruguayan longline fisheries and aspects of distribution in the southwestern Atlantic. Scientia Marina 69, 161-166.

Dulvy, N.K., Baum, J.K., Clarke, S., Compagno, L.J.V., Cortes, E., Domingo, A., Fordham, S., Fowler, S., Francis, M.P., Gibson, C., Martinez, J., Musick, J.A., Soldo, A., Stevens, J.D., Valenti, S., 2008. You can swim but you can't hide: the global status and conservation of oceanic sharks and rays. Aquatic Conservation: Marine and Freshwater Ecosystems 18, 459-482.

Fowler, G.M., Campana, S.E., 2009. Commercial by-catch rates of blue shark (*Prionace glauca*) from longline fisheries in the Canadian Atlantic. Collected Volume of Scientific Papers ICCAT 64, 1650-1667.

Hall, M., Nakano, H., Clarke, S., Thomas, S., Molloy, J., Peckham, S., Laudino-Santillan, J., Nichols, W., Gilman, E., Cook, J., Martin, S., Croxall, J., Rivera, K., Moreno, C., Hall, S., 2007. Working with fishers to reduce by-catches, In By-catch Reduction in the World's Fisheries. ed. S. Kennelly, pp. 235-288. Springer, Dordrecht.

Hartley, T.W., Robertson, R.A., 2009. Stakeholder collaboration in fisheries research: integrating knowledge among fishing leaders and science partners in northern New England. Society and Natural Resources 22, 42-55.

He, X., Bigelow, K.A., Boggs, C.H., 1997. Cluster analysis of longline sets and fishing strategies within the Hawaii-based fishery. Fisheries Research 31, 147-158.

ICCAT, 2006. Supplemental Reccommendations by ICCAT to Amend the Rebuilding Program of North Atlantic Swordfish (2006-02). Available from http://www.iccat.int/en/RecsRegs.asp.

James, M.C., Ottensmeyer, C.A., Myers, R.A., 2005. Identification of high-use habitat and threats to leatherback sea turtles in northern waters: new directions for conservation. Ecology Letters 8, 195-201.

Javitech, 2002. Report on Sea Turtle Interactions in the 2001 Pelagic Longline Fishery. Dartmouth, Nova Scotia.

Jenkins, L., 2007. Bycatch: interactional expertise, dolphins and the US tuna fishery. Studies in History and Philosophy of Science 38, 698-712.

Johannes, R.E., 1981. Words of the Lagoon: Fishing and Marine Lore in the Palau District of Micronesia. University of California Press, Berkeley.

Kerstetter, D.W., Graves, J.E., 2006. Effects of circle versus J-style hooks on target and non-target species in a pelagic longline fishery. Fisheries Research 80, 239-250.

Kohler, N., Casey, J.G., Turner, P.A., 1998. NMFS cooperative shark tagging program, 1962-93: an atlas of shark tag and recapture data. Marine Fisheries Review 60, 1-87.

Lester, B., Paul, S., Neilson, J., Campana, S., Hunt, L., 2008. Annual Report of Canada, In Report for biennial period 2006-07, Part II (2008) - Vol. 3 Annual Reports, ICCAT, 19-27.

Lester, B., Paul, S., Neilson, J., Campana, S., Hussey, L., 2009. Annual Report of Canada, In Report for biennial period 2008-09, Part II (2009) - Vol. 3 Annual Reports, ICCAT, 25-35.

Lewison, R.L., Freeman, S.A., Crowder, L.B., 2004. Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. Ecology Letters 7, 221-231.

Martin, K., James, M.C., 2005. Conserving sea turtles in Canada: successful community-based collaboration between fishers and scientists. Chelonian Conservation and Biology 4, 899-907.

Maunder, M.N., Punt, A.E., 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research 70, 141-159.

Maurstad, A., 2002. Fishing in murky waters - ethics and politics of research on fisher knowledge. Marine Policy 26, 159-166.

McCluskey, S.M., Lewison, R.L., 2008. Quantifying fishing effort: a synthesis of current methods and their applications. Fish and Fisheries 9, 188-200.

Mollet, H.F., 2002. Distribution of the pelagic stingray, *Dasyatis violacea* (Bonaparte, 1832), off California, Central America, and worldwide. Marine Freshwater Review 53, 525-530.

Moore, J.E., Cox, T.M., Lewison, R.L., Read, A.J., Bjorkland, R., McDonald, S.L., Crowder, L.B., Aruna, E., Ayissi, I., Espeut, P., Joynson-Hicks, C., Pilcher, N., Poonian, C.N.S., Solarin, B., Kiszka, J., 2010. An interview-based approach to assess marine mammal and sea turtle captures in artisanal fisheries. Biological Conservation 143, 795-805.

MSC, 2008. Marine Stewardship Council Fisheries Assessment and Methodology and Guidance to Certification Bodies: Default Assessment Tree, Performance Indicators and Scoring Guideposts. Available from <http://www.msc.org>.

MSC, 2011. North West Atlantic Canada longline swordfish. <http://www.msc.org/track-a-fishery/in-assessment>.

Myers, R.A., Worm, B., 2003. Rapid worldwide depletion of predatory fish communities. Nature 423, 280-283.

Neilson, J.D., Smith, S., Royer, F., Paul, S.D., Porter, J.M., Lutcavage, M., 2009. Investigations of horizontal movements of Atlantic swordfish using pop-up satellite archival tags, In Tagging and Tracking of Marine Animals with Electronic Devices. eds J.L. Nielson, H. Arrizabalaga, N. Fragoso, M. Lutcavage, J. Sibert, pp. 145-159. SpringerLink.

Neis, B., Schneider, D.C., Felt, L., Haedrich, R.L., Fischer, J., Hutchings, J.A., 1999. Fisheries assessment: what can be learned from interviewing resource users? Canadian Journal of Fisheries and Aquatic Sciences 56, 1949-1963.

NMFS, National Marine Fisheries Service Southeast Fisheries Science Centre 2008. Careful release protocols for sea turtle release with minimal injury. NOAA Technical Memorandum NMFS-SEFSC-580. <http://sero.nmfs.noaa.gov/sf/pdfs/Sea_Turtle_Release_Protocols_April2011.pdf>

NSSA, 2002. Code of Conduct for Responsible Sea Turtle Handling and Mitigative Measures. Nova Scotia Swordfishermen's Association.

Palmer, C.T., Wadley, R.L., 2007. Local ecological knowledge, talk, and scepticism: Using 'LES' to distinguish "LEK' from LET in Newfoundland Human Ecology 35, 749-760.

Patton, M.Q., 1990. Qualitative Evaluation and Research Methods, 2nd edn. Sage Publications, Newbury Park.

Paul, S.D., Neilson, J.D., 2010. An exploration of targeting variables in the Canadian swordfish longline CPUE. Collected Volume of Scientific Papers ICCAT 65, 124-134.

Piovano, S., Clò, S., Giacoma, C., 2010. Reducing longline bycatch: the larger the hook, the fewer the stingrays. Biological Conservation 143, 261-264.

Porter, J.M., Wood, B.M., Stone, H.H., 2000. Preliminary estimation of the tonnage of dead swordfish and bluefin tuna discards from the 1998 Canadian swordfish longline fishery Collected Volume of Scientific Papers ICCAT 51, 1460-1468.

Reverdin, G., Niiler, P.P., Valdimarsson, H., 2003. North Atlantic Ocean surface currents. Journal of Geophysical Research 108, 3002.

Richards, L., Morse, J.M., 2007. Readme First for a User's Guide to Qualitative Methods, 2nd edn. Sage Publications, Thousand Oaks.

Rigney, M., 2008. Harpooners seek bigger cut of swordfish market, In The Boston Globe.

<http://www.boston.com/news/science/articles/2008/12/08/harpooners_seek_bigger_cut_of_swordfish_market/>.

Robins, C.R., Ray, G.C., Douglass, J. 1986. A Field Guide to Atlantic Coast Fishes of North America. The Peterson Field Guide Series. Houghton Mifflin, Boston.

Saenz-Arroyo, A., Roberts, C.M., Torre, J., Carino-Olvera, M., 2005. Using fishers' anecdotes, naturalists' observations and grey literature to reassess marine species at risk: the case of the Gulf grouper in the Gulf of California, Mexico. Fish and Fisheries 6, 121-133.

Santora, C., 2003. Management of turtle bycatch: Can endangered species be protected while minimizing socioeconomic impacts? Coastal Management 31, 423-434.

Schumann, S., 2010. Application of participatory principles to investigation of the natural world: an example from Chile. Marine Policy 34, 1196-1202.

Shackeroff, J.M., Campbell, L.M., 2007. Traditional ecological knowledge in conservation research: problems and prospects for their constructive engagement. Conservation and Society 5, 343-360.

Silver, J.J., Campbell, L.M., 2005. Fisher participation in research: dilemmas with the use of fisher knowledge. Ocean & Coastal Management 48, 721-741.

St. Martin, K., Hall-Arber, M., 2008. Creating a place for "community" in New England fisheries. Human Ecology Review 15, 161-170.

TCP, Canadian Institutes of Health Research, Natural Sciences and Engineering Research Council of Canada, Social Sciences and Humanities Research

Council of Canada 2005. Tri-Council Policy (TCP) Statement: Ethical Conduct for Research Involving Humans.

Wade, O., Revill, A.S., Grant, A., Sharp, M., 2009. Reducing the discards of finfish and benthic invertebrates of UK beam trawls. Fisheries Research 90, 140-147.

Walsh, W.A., Kleiber, P., McCracken, M., 2002. Comparison of incidental blue shark catch rates by Hawaii-based longline vessels to fishery observer data by application of a generalized additive model. Fisheries Research 58, 79-94.

Ward, P., Myers, R.A., Blanchard, W., 2004. Fish lost at sea: the effect of soak time on pelagic longline catches. Fishery Bulletin 102, 179-195.

Whole Foods Market. 2010. Whole Foods Market: Only major grocer to offer sustainable MSC-certified, harpoon-caught swordfish. <http://wholefoodsmarket.com>.

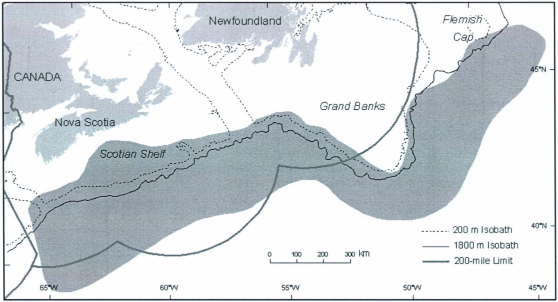

Figure 4.1 Fishing grounds of the Canadian Atlantic pelagic longline fishery for swordfish and tunas extend from the US border in the southwest to northeast of the Grand Banks. The boundary of Canada's Exclusive Economic Zone is shown by the 200-mile limit. Swordfish targeting occurs along the continental shelf edge, indicated by the 200 m and 1800 m (1000 fathom) isobaths. Tuna targeting occurs further offshore in waters warmed by the Gulf Stream.

CHAPTER 5: IDENTIFYING OPPORTUNITIES TO REDUCE BLUE SHARK BYCATCH: USING FISHERIES OBSERVER DATA AND FISHERS' KNOWLEDGE TO DIFFERENTIATE FISHING DECISIONS FROM FISH BEHAVIOUR

This chapter builds upon observations made during the field study reported in Chapter 3 and upon longline captains' observations reported in Chapter 4. Data from the fisheries observer program, from qualitative fishers' knowledge interviews, and from moored weather buoys were used to test hypotheses on catch rates and hunting behaviour of blue shark and swordfish – the most common bycatch and landed species respectively in the Canadian pelagic longline fishery.

Abstract

Catch rates reflect fish behaviour, fishing decisions, and interactions between these two processes. For pelagic longline and other fisheries that use baited gear, catch rates depend upon feeding behaviour. Therefore, differences in the distributions and feeding behaviours of target and bycatch species may be used to identify opportunities to decrease bycatch without decreasing target species catch. I used fisheries observer and concurrent environmental data to determine how fishing decisions and environmental variables affect catch rates of the most common bycatch (blue shark, *Prionace glauca*) and landed species (swordfish, *Xiphias gladius*) in the Canadian pelagic longline fishery. Qualitative interview data were used to identify fishing decisions and to describe pelagic species distributions and feeding behaviour. Sets with high blue shark catch rates accounted for most of the bycatch – 10% of the observed sets accounted for close to half of the observed blue shark bycatch. Fishing decisions, such as fishing season, region, or bait type, had little effect on blue shark catch rates but did affect target species catch rates. Expected associations between blue shark catch rates and wind stress, and between swordfish catch rates and lunar cycles were not significant in the generalized linear model analyses. Instead, water temperature was identified as the key environmental variable affecting blue shark catch rates. Further, interviewed longline captains' observations identified

possible ecological mechanisms for this relationship and, therefore, ways to better focus future blue shark bycatch mitigation research.

5. 1 Introduction

Catch rates reflect fish behaviour, fishing decisions, and interactions between these two processes. For example, seasonal migrations affect regional abundances; lunar or diel cycles affect movement patterns; and feeding or predator avoidance affect activity levels, and therefore vulnerability to fishing gear (e.g., Bertrand et al. 2002; James et al. 2005; Poisson et al. 2010). Expected distribution, abundance, and behaviour of target species are factored into fishing decisions, such as choice of fishing grounds, timing of fishing trips, and setting location relative to local physical features or processes (e.g., Branch and Hilborn 2008; Grant and Berkes 2007; Hobday and Campbell 2009; Podesta et al. 1993). For longline or other baited gear fisheries, catch rates depend on feeding behaviour; fish must detect, locate, and prey upon baited hooks. Expected differences among species' distributions, movement patterns, and feeding behaviour may be exploited to decrease bycatch without decreasing targeted species catch.

Pelagic longline fisheries capture highly migratory target species, such as swordfish (*Xiphias gladius*) and tunas (*Thunnus* spp.), as well as unwanted and protected species, such as sharks and turtles. In many pelagic longline fisheries, blue shark (*Prionace glauca*) is the most common shark species (e.g., Campana et al. 2006; Francis et al. 2001; Gilman et al. 2008), and may account for up to 90% of the shark catch in these fisheries (Gilman et al. 2008). For pelagic longline fisheries with shark-finning regulations, limited markets for shark, and high catch rates (Gilman et al. 2008), there are incentives to reduce blue shark catch levels (i.e., reduced risks to fisher safety, gear damage, and time spent discarding sharks). Further, increased conservation and consumer pressure to reduce impacts on vulnerable populations, such as sharks, may lead to market advantages for fisheries that demonstrate decreased bycatch levels (Chapter 4). Where incentives to reduce the incidence of blue shark bycatch exist, research on distribution and feeding behaviour differences among blue shark and target species might identify bycatch mitigation opportunities for these fisheries.

Blue shark bycatch is generally more common among swordfish-targeted sets than among sets targeting albacore (*T. alalunga*), bigeye (*T. obsesus*), and yellowfin (*T. albacares*) tunas or mahi-mahi (*Coryphaena hippurus*) (Campana et al. 2006; He et al. 1997; Ward et al. 2004). Within mixed-species fisheries, blue shark bycatch levels differ among regions or seasons fished (Campana et al. 2006; He et al. 1997; Kerstetter and Graves 2006). For example, in the Canadian Atlantic swordfish and tuna longline fishery few blue shark were caught early in the season and at the southern extent of the fishing grounds (Campana et al. 2006), which is associated with tuna-targeting (Chapter 4). However, large differences in blue shark catch rates also occur within limited areas or fishing periods.

Carruthers et al. (2011) reported extreme blue shark catch rate variability (ranging from 10 to over 150 blue sharks per 1000 hooks) among longline sets fished within 100 km and within a 10 day time period. This high variability at small scales suggests local behavioural responses are an important driver of blue shark catch rates.

While general distribution patterns and diel migrations of swordfish and blue shark overlap, local abundance patterns may differ in response to oceanographic features such as thermal fronts. Both species migrate throughout the North Atlantic (Kohler et al. 2002; ICCAT 2006), with seasonal latitudinal migrations reported for blue shark and swordfish (Neilson et al. 2009; Queiroz et al. 2005). Acoustic tracking data indicate similar diel movement patterns. Off the continental shelf, swordfish and blue shark generally remain at or above the thermocline at night and dive deeper during the day (Carey and Robinson 1981; Carey and Scharold 1990). However, fisheries catch data indicate differing responses to water temperature within some fishing regions, with blue shark catch rates increasing with cooler water temperatures (e.g., Bigelow et al. 1999; Carruthers et al. 2011; Watson et al. 2005). Temperature associations likely do not reflect temperature preferences or limits, as both blue shark and swordfish encounter temperature changes of 10-15 °C during diel vertical migrations (Carey and Robinson 1981; Carey and Scharold 1990). Instead, temperature associations may reflect differences in blue shark and swordfish local abundance relative to oceanographic features, such as thermal fronts or water masses (Chapter 4; Walsh and Kleiber 2001).

Blue shark and swordfish diets overlap, but there may be differences in hunting tactics and how these species detect and locate prey – or baited longline gear. Blue shark and swordfish are opportunistic predators. Stomach contents of both species were dominated by fish (e.g., mackerel, *Scomber scombrus;* and herring, *Clupea harengus*) or squid prey (e.g., short-finned squid, *Illex illecebrosus*), with differences among regions and seasons likely reflecting local prey availability (Henderson et al. 2001; McCord and Campana 2003; Stevens 1973; Stillwell and Kohler 1985). Longline catch rates, acoustic tracking data, experimental feeding trials, and differences in brain morphology suggest that blue shark and swordfish differ in their abilities to detect and locate baited longline gear. Catch data from the Hawaiian pelagic longline fishery indicated swordfish catch increased during the full moon, whereas blue shark catch increased with wind speed (Bigelow et al. 1999). Bigelow et al. (1999) suggested that blue shark were less affected by changes to longline gear configuration during high winds. Tracking data was used to infer how swordfish behaviour may have contributed to these catch rates (Bigelow et al. 1999): that swordfish respond to light levels and swam deeper during periods of high winds (Carey and Robinson 1981). More generally, experimental research has demonstrated that sharks require both odour and turbulence cues to efficiently locate odour sources, such as baits or prey (Gardiner and Atema 2007). Finally, based on differences in brain morphology, Lisney and Collin (2006) suggest vision is dominant sensory modality among swordfish, whereas smell is likely the dominant sense blue shark use to detect prey. Environmental variables that affect prey detection, such as lunar illumination levels or wind induced mixing, likely impact catch rates of baited fishing gear (Stoner 2004). Thus, I expect blue shark catch rates will increase when wind-induced mixing disperses bait odours as blue shark are better able to detect odor cues. Similarly, blue shark catch rates should increase with steady winds, which would produce more coherent wind induced turbulence flows (Gill 1982), and, consequently, odour plumes from baited longline gear. Swordfish catch rates should increase during the full moon period, as swordfish longline gear is fished at night (Bigelow et al. 1999) and this species is thought to rely on visual cues (Carey and Robinson 1981; Lisney and Collin 2006).

Inferring fish abundance, distribution, or behaviour from commercial fisheries catch data can be problematic. Catch rates are influenced by changes in fishing power, regulations, and individual fisher's targeting practices (e.g., Béné and Tewfik 2001; Bishop 2006; de Mutsert et al. 2008). Therefore, detailed information on targeting practices and fishing decisions is needed to differentiate fishing effects from fish behaviour. Commercial fisheries data provide an overview of the fishery – necessary for overall estimates of fishing impacts – but do not provide information on fishing decisions or on target and bycatch species behaviour. The latter two types of information are needed to develop bycatch mitigation strategies (e.g., Hall et al. 2007; Jenkins 2007).

Our overall objective was to identify fishing decisions, environmental factors, and possibly fish behaviour that decreased blue shark bycatch levels in the Canadian Atlantic pelagic longline fishery, and thereby identify bycatch mitigation opportunities. As mitigation efforts that do not decrease target catch are more readily adopted (for additional factors, see Campbell and Cornwell 2008), my second objective was to determine how these fishing and environmental factors affected catch rates of targeted swordfish, tunas, and mahi-mahi. Fisheries data, collected by at-sea observers in the commercial fleet, were used to evaluate fishing and environmental variables. As I was inferring ecological processes from commercial fishing data, information on fishing decisions was needed. Therefore, I interviewed active pelagic longline captains, who detailed their observations of environmental factors and fish behaviour, in addition to information on fishing practices associated with high blue shark catch rates.

The Canadian Atlantic pelagic longline fishery targets swordfish, albacore, yellowfin and bigeye tunas, and mahi-mahi. Blue shark is the most common bycatch species discarded from the Canadian pelagic longline fishery (Carruthers et al. 2009). The Canadian Atlantic swordfish and tuna longline fishery has high levels of blue shark bycatch, has limited markets for landed blue shark, and has had finning regulations since 1994 (Campana et al. 2006); thus, there are incentives to reduce the costs and risks associated with blue shark bycatch (Gilman et al. 2008). The fishery is active from May through October and the fishing region extends from Georges Bank in the south to northeast of the Flemish Cap, but individual longline captains have preferred fishing grounds and target species (Chapter 4). Bycatch levels may differ among fishing vessels due to targeting practices, preferred fishing regions, and setting practices (e.g., Branch and Hilborn 2008; Hall et al. 2007; Wade et al. 2009). From a conservation perspective, if factors associated with high blue shark catch rates were identified and avoidance strategies developed from that information, overall levels of blue shark bycatch could be greatly reduced. Further, such information would benefit longliners who wish to avoid getting “sharked up” (sets full of unwanted sharks).

5.2 Methods

5.2.1 Fishers’ knowledge interviews

Fishers’ knowledge interviews were conducted with 11 longline captains from the Canadian pelagic longline fishery for swordfish and tunas, accounting for approximately one-quarter of the active fishing licences using longline gear (Chapter 4). Interviewed captains had among them experience longlining the entire fishing grounds from the US border in the south to northeast of the Grand Banks (Figure 5.1). Interview topics included targeting practices, associations among target and bycatch species, and environmental and operational factors that may affect catch rates of target and bycatch species (Appendix I). Interviews were semi-structured, meaning longline captains could identify additional topics during the interview. Because this information was not publicly available and because there are risks to the interviewees associated with participating in fishers' knowledge interviews, national and university guidelines require ethics review of the proposed research (ICEHR No. 2006/07-112-SC). In compliance with ethical research guidelines, I clearly detailed the possible risks and benefits of participation and indicated that participation was voluntary (Appendix II, Chapter 4).

Fishers' knowledge interviews were conducted between March 2008 and June 2009. Interviews were audio-recorded, transcribed, and imported into qualitative data analysis software (HyperResearch 2.7, ResearchWare Inc.). Information on targeting practices, species associations, and environmental and operational factors were coded to allow cross-comparison among interviews (Richards and Morse 2007). Further, case summaries for each interview detailed the context of their fishing knowledge (e.g., fishing experience, species targeted, and regions fished). Quotes from interviews are denoted in the text by an interview identifier (e.g., 301). Follow-on phone conversations were used to clarify details from the interview transcripts and to request permission for the use of quotes.

5.2.2 Fisheries observer data

Data collected by fisheries observers onboard pelagic longline vessels were obtained from the International Observer Program database, created and maintained by the Population Ecology Division of the Canadian Department of Fisheries and Oceans (DFO). Individual vessel identifiers were replaced with unique identifiers to maintain confidentiality. Fisheries observers identify species caught, record catch composition, and detail environmental and operational factors for each set. For example, sea surface temperature is recorded at four points during the set (start and end of setting and hauling). Information recorded includes gear characteristics (such as total number of hooks hauled, number of hooks between buoys, and gangion or leader line length). Surface water temperature, timing, and location information is recorded during setting and hauling. Fisheries observer data from the 2002 to 2009 fishing seasons were used in these analyses. Observers reported from approximately 5 to 18% of sea days during these years (Javitech 2002; Lester et al. 2009). Observer data were used to determine catch composition and bycatch levels because bycatch data are not routinely recorded in logbooks.

Observed sets were ordered by blue shark catch rates (number of fish per 1000 hooks). To identify sets dominated by blue shark catch, I selected 10% of sets from each fishing season with the highest blue shark catch rates, which I considered "sharked-up sets". These sets accounted for 48% of all blue shark observed and had catch rates >55 sharks per 1000 hooks (Figure 5.2). Because the number of observed sets differed among years, the number of sharked-up sets ranged from 3 sets in 2008 to 36 sets in 2002. These sets accounted for between 30 and 55% of all blue shark observed in each fishing season. For the purposes of determining if short-term, local scale environmental variability contributed to high blue shark catch, I selected all sets from trips that contained sharked-up sets. The initial data set contained 349 sets, however corresponding wind data were not of sufficient quality for 44 sets (detailed below). Water temperature was not recorded during 12 sets, which were also removed from the data set. The data set was further limited to those trips where catch composition, gear characteristics, and setting and hauling times were recorded for at least 5 sets. Fisheries observer data from 263 sets fished during 28 longline trips were used to evaluate the effects of environmental variability on catch of blue shark and target species. Three additional sets, with abnormal soak times, were removed after being identified as outliers during data analysis.

5.2.3 Environmental data

Water temperature data were recorded by fisheries observers, whereas lunar and wind data were obtained from online databases. Percent lunar illumination data, ranging from 0 (dark moon) to 1 (full moon), were downloaded from the US Naval observatory website (http://www.usno.navy.mil/USNO/). These illumination percentages were converted to lunar day and lunar quarter. Archived wind data recorded by moored weather buoys were accessed from the DFO Integrated Science Data Management website (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/waves-vagues/index-eng.htm). Distances between longline set locations and weather buoys were calculated using the proximity toolbox in ArcMap (version 10). Wind speed and direction data were downloaded from moored weather buoys nearest to longline set locations (Figure 5.1) and corresponding to total longline soak time for each set. Further, wind data were extracted for 24 h prior to each longline set because longline captains indicated prior storm events affected catch rates. Fisheries observer, lunar cycle and wind data were imported, compiled and error checked using custom programs (MATLAB version R2007a).

I compared three methods of representing lunar effects: percent lunar illumination, periodic regression, and lunar quarter. Increased swordfish catch rates with lunar illumination levels would be consistent with the hypothesis that, as visual predators, swordfish were responding to increased light levels (Bigelow et al. 1999; Carey and Robinson 1981; Ortega-Garcia et al. 2008). Periodic regression allows for evaluation of other aspects of the lunar cycle, such as tidal currents (deBruyn and Meeuwig 2001; Poisson et al. 2010). Previous researchers have used Generalized Additive Models (GAMs) to account for non-linear lunar effects (e.g., Bigelow et al. 1999; Ortega-Garcia et al. 2008). I used periodic regression instead of GAMs because I wanted to evaluate a semi-lunar cycle with expected peaks corresponding to tidal amplitudes at full and new moon. Lunar quarter roughly corresponded to the time periods discussed during fishers' knowledge interviews where longline captains differentiated between waxing and waning periods of the lunar cycle. Thus, the three methods of representing lunar cycles corresponded to a single maxima associated with the full moon, a semi-lunar cycle, or a four-level categorical variable.

Prior to using downloaded wind data, quality codes and archived plots of wind speed and direction were examined. Although available quality codes are based on significant wave height and peak period data, they may also indicate problems with the associated wind speed and direction data. If visual inspection of archived plots indicated gaps or missing data from one or both anemometers, I either selected data from the second anemometer or downloaded data from an adjacent weather buoy. Corresponding wind data were not available for some sets. For example, trips fished during July 2006 were removed from the data set because there were gaps in the records from anemometers on four separate weather buoys during that two week time period.

Wind speed and direction data were available for the majority of time periods corresponding to longline sets or to periods 24 h prior. Hourly wind data were used to calculate mean wind speed, and standard deviation of wind speed and direction for the total soak time for each set from the start of setting to the end of hauling, which may be up to 25 h (Carruthers et al. 2011). Calculations of average wind direction and variability were based on the circular statistics toolbox for MATLAB (Berens 2009). Wind stress, which is an estimate of the force or energy of the wind, was calculated from hourly wind speed and direction data. Wind stress (τ) for the east/west (*u*) and north/south (*v*) vectors was calculated using the equation:

$$\tau = \rho C_D W^2;$$

where ρ is the density of air (1.3 kg m^{-3}), W is the wind speed vector calculated from moored buoy measurements (m s^{-1}), and drag coefficients (C_D) were based on the bulk parameters suggested by Large and Pond (1981). Drag coefficients differed for decreasing (e.g., 4 m s^{-1} lower than 6 h earlier), changing direction (e.g., direction change >60° within a 2 h time period), or rising winds and for wind speeds greater than 11 m s^{-1} (Large and Pond 1981).

5.2.4 Catch models

Catch models were built to evaluate whether blue shark or swordfish catch were affected by changing wind, lunar cycles, or water temperature. My hypotheses were: 1) blue shark catch would increase in strong steady wind conditions, which would create coherent odour plumes; and 2) swordfish catch would increase with lunar illumination levels. However, I considered alternate methods of representing wind and lunar effects because there were alternate explanations of the relationship between catch and environmental factors. Fishing region, month, bait type and water temperature were included in the catch models to account for differences in targeting practices and local abundance. Numbers of blue shark or swordfish caught per set were response variables and an effort measure (Nhh; number of hooks fished per set) was included as an offset. Including an offset term allowed modeling of individuals (count data) as the response variable (Maunder and Punt, 2004).

Six candidate models were evaluated based on three methods of representing lunar effects and two methods of representing wind effects. These short-term environmental variables were evaluated in addition to key seasonal, regional and operational factors known to affect catch rates in this fishery (Campana et al. 2006; Paul and Neilson 2010), such as region (Rgn), month (Mn) and bait type (Bt). For example, mean blue shark catch modeled as a function of number of hooks hauled (Nhh), water temperature (Tmp), wind stress in the *u* and *v* directions (Wstu and Wstv), and lunar illumination (Li) was:

$$\text{Catch} = e^{\mu} + \varepsilon, \tag{1}$$

$$\mu = \log(\text{offset}(\text{Nhh})\text{-}1) + \beta_{Tmp}\text{Tmp} + \beta_{Wstu}\text{Wstu} + \beta_{Wstv}\text{Wstv} + \beta_{Li}\text{Li} + \beta_{Bt}\text{Bt} + \beta_{Rgn}\text{Rgn} + \beta_{Mn}\text{Mn} + \beta_{RgnxMn}\text{Rgn x Mn} \tag{2}$$

where μ corresponds to the mean catch in each set. Bait type was included as a 3-level categorical variable (fish, squid, or mixed bait). The fishing ground was divided into four regions, which corresponded to Georges Bank, Scotian Shelf, Grand Banks and Flemish Cap (Figure 5.1). Month was considered a continuous variable. Lunar effects were alternatively modeled using a periodic regression term or using a 4-level categorical variable for lunar quarter (Lqt). Lunar quarter was modeled as a categorical variable – and not an ordinal variable – because lunar illumination levels during the second and fourth quarters were similar and because longline captains differentiated between the different quarters. Because I was interested in modeling a semi-lunar cycle, the periodic regression term was cos(2θ), where θ is the angular equivalent of lunar day (e.g., 1/29.5 of 360; deBruyn and Meeuwig 2001). Wind effects were also modeled as mean wind speed (Wspd, m/s), the standard deviation of the wind speed (Wstd, which is proportional to the energy imparted by the wind), and wind direction variability (standard deviation of wind direction; Dstd). Wind stress includes directional information and is the measure of the energy imparted by the wind used to calculate wind induced flows, whereas the second method of representing wind effects described the overall magnitude and variability. Thus, alternative catch models based on a semi-lunar cycle, wind speed, and wind direction variability were:

$$\mu = \log(\text{offset}(Nhh)-1) + \beta_{Tmp}Tmp + \beta_{Wspd}Wspd + \beta_{Dstd}Dstd + \beta_{\cos 2\theta}\cos 2\theta + \beta_{Bt}Bt + \beta_{Rgn}Rgn + \beta_{Mn}Mn + \beta_{RgnxMn}Rgn \times Mn \qquad (3)$$

Diagnostic plots indicated greater variance than accounted for by the Poisson error distribution because residuals increased with fitted values. A single outlier was identified in diagnostic plots of blue shark catch models. Because the outlier was associated with a longline set that had a minimum soak time (time between setting and hauling) of less than 1 h, it was removed from the data set. Minimum soak times averaged 7.9 h (± 1.4 h SD), therefore soak times < 1 h indicate abnormal sets. To be consistent, two additional sets were removed from the data set. One had a minimum soak time of <1 h and the other fished >18 h between setting and hauling. Consequently, the data set used to evaluate environmental effects on blue shark and swordfish catch consisted of 260 sets fished during 28 longline trips.

The Poisson error distribution assumes variance equal to the mean, which was not the case in the blue shark and swordfish catch models. The ratio of residual deviance to degrees of freedom indicated substantial overdispersion, which is common in ecological and fisheries count data (Maunder and Punt 2004; Richards 2008; Venables and Dichmont 2004). The best way to address overdispersion is to incorporate missing explanatory variables or otherwise address the ecological reason for overdispersion (McCullagh and Nelder 1989). Where this is not possible, a practical approach is to include a dispersion parameter in the error distribution and thereby, produce more conservative error estimates. Diagnostic plots for models using negative-binomial error distributions indicated residuals no longer increased with fitted values and this model assumption was met. Model selection was based on the likelihood of the model and Akaike's information criterion (AIC), which includes a penalty term to limit overly complex models. When models were equally likely given the data, I chose the simpler model to communicate with fisheries managers and fishing captains. GLMs were run using the open source program R, with the 'MASS', and 'car' packages (Venables and Ripley, 2002; Fox, 2007; RTeam, 2007).

5.3 Results

5.3.1 Longline captains' observations and interpretations

In general, longline captains reported higher blue shark catch during swordfish-targeted sets (Chapter 4). They distinguished between swordfish and tuna targeted trips based on timing (10 responses), location (11 responses), and bait type (9 responses). Tuna (primarily yellowfin and bigeye) sets were fished early in the season, were further offshore, and were baited with squid. These fishing decisions were based on expected migration patterns, "Tuna are here first. You don't go swordfishing until the middle of July - at the earliest" (1101). Fishing decisions were also based on expected distributions, "Swordfish tend to come in to the hundred fathom edge, the edge of the continental shelf. You wouldn't get many tuna in that depth, you'd get [tuna] more at the 500 to 1000 fathom." (1001); and were based on expected feeding preferences, "If you don't have squid, you're not going to get any tuna (well, maybe the odd bigeye). But squid's the thing, it's their feed" (601). One longline captain reported that feeding behaviour of swordfish caught by the harpoon and by longline fisheries differed, "When the sticking [harpoon] boats can stick them, we can't catch them. When we can catch [swordfish], they can't stick them" (1101). Even when longline and harpoon vessels were fishing in the same region, he reported that swordfish were not biting longline gear when harpoon fishermen were able to catch basking swordfish.

Bycatch avoidance and the current management system were also factored into choice of fishing regions and seasons. Longline captains chose fishing regions, in part, to avoid blue shark, "If you go early swordfishing early in on the Bank, you're going to get sharked to death" (301); or that, "There's swordfish in there [southern Scotian Shelf] right now, but you wouldn't dare fish it because [your gear would] get chewed up by the sharks" (901). The second quote was from an interview in early June. Finally, longline captains mentioned that the current management system, with individual swordfish quotas which differ among license holders based on swordfish landings history, affected seasonal targeting practices (Chapter 4). Longline captains were fishing swordfish later in the season because they either had to buy more quota or stop longlining once their individual swordfish quota had been caught. In addition to expected seasonal, regional, and targeting associations, longline captains described how local environmental variability might affect catch rates of blue shark and of target species.

Longline captains indicated that environmental factors, such as lunar cycles and weather, affected catch rates of blue shark and target species. Most captains considered lunar cycles when planning longline trips because higher catch rates of target species were expected during the full moon or during the waxing period prior to the full moon, "on the making of the moon" (901). However, the relationship between lunar cycles and target species catch rates was not simple. For example, longline captains indicated that lunar effects had a greater influence on tuna catch than on swordfish catch (5 responses); that other factors (such as location relative to thermal fronts or edges, or fishing practices of adjacent longline vessels) were more important (3 responses); or that although the best fishing was associated with a full or waxing moon, you could catch swordfish throughout the fishing season (2 responses). One longline captain indicated that, in his experience, catch rates did not increase with the full moon (301). Longline trips may last up to 19 days in the Canadian pelagic longline fishery. Therefore, longline captains planned trips so that the few days ashore were not during the making of the moon or during the full moon period (1001). The captain who did not find an association between lunar cycles explained that when they fished without breaks between trips, there was little difference in catch rates.

When asked for their interpretations or possible explanations for the association between increased catch rates and lunar cycles, longline captains described how water, particularly thermal fronts, changed during the full moon. Further, when I described research that suggests that swordfish were responding to higher light levels as visual predators (e.g., Carey and Robinson 1981), longline captains responded:

> Maybe, but it's got a lot to do with the tides and the water. I don't know why but [the warmer water] doesn't move around so much (201).

> It could be that it [lunar illumination] brings the fish up to the surface to look for their prey, but even the water changes. It edges up better (701).
>
> It's both, in my opinion. The water edges up better, which pulls the bait in, which pulls the fish in. (401)

Only one longline captain mentioned the possible effects of lunar illumination on tuna catch rates, "It seems when the moon's bright, [tunas] come to the top of the water" (501).

Although wind effects were not in the original interview schedule, several captains mentioned that blue shark catch rates increased during stormy nights or shortly thereafter. Longline captains described how multiple environmental factors affect blue shark catch rates:

> Sloppy sou'westers, [when it's] moon-black and overcast, make them [blue shark] right ugly. When the moon is full, you don't seem to get too many (801).
>
> There's a tonne of [blue] sharks, but if it's a full moon and if you can find a piece of water, you can keep clear of them. The stormy nights are the nights you load up on them. After a big nor'wester, you're hammered with sharks, then the next night you'll get the swordfish (401).

These longline captains agreed on the combined effects of lunar cycles and wind but gave different example wind directions, which may be related to topographic effects associated with their different fishing grounds. The first captain fished the southern portion of the longline fishing grounds near the US border, whereas the second captain fished from the Eastern Scotian Shelf to the Flemish Cap (Figure 5.1). During follow-on phone conversations, three other captains agreed blue shark catch rates increase with wind speed. They pointed out, however, that longlines are generally fished deeper during bad weather and that, "We go for 15 to 20 days so you have no choice but to be there when it blows" (1101). Longline captains also indicated that tuna catch increased during calm days (2 responses) or that, "You could be fishing a perfect piece of water, catching tuna every day. One little puff of wind [will] come along and bust it up" (601).

Whether discussing tuna, swordfish or blue shark catch rates, longline captains described the combined effects of different environmental factors. For example, water temperature was discussed relative to thermal fronts and water colour, which captains used to distinguish between shelf, and slope or Gulf Stream water. When fishing along thermal fronts, longline captains reported that if opposing currents pulled the longline into the cooler side, you'd get more sharks (Chapter 4). When discussing the association between blue shark and temperature, this longline captain mentioned how temperature effects interacted with water colour, "[Blue shark] seem to like the colder part of the water, but the colour of the water makes a difference. I've fished 57 [°F or 14 °C] but it was dark water and there were no sharks" (901). When asked about water temperature longline captains described the importance of water temperature in relation to fronts (9 responses), water colour (5 responses), or currents (6 responses). No longline captains described water temperature as an important factor by itself.

5.3.2 Fisheries observer data

Trips that included sharked-up sets were fished from Georges Bank to the east of the Flemish Cap (Figure 5.1), and throughout the fishing season during the second (16%), third (62%) and fourth (22%) fishing quarters (Table 5.1). Among sharked-up sets, the majority appeared to be targeting swordfish, meaning the number of swordfish caught exceeded the total of warm-water tunas (albacore, bigeye, and yellowfin tunas) and mahi-mahi in the set. Porbeagle and shortfin mako were not considered targeted species because not all of these sharks were landed (Carruthers et al. 2009). Bluefin tuna were not included in tuna catch estimates. They are not considered a target species of the longline fishery eventhough regulations that permit landing bluefin tuna caught incidentally were introduced in 2004 (DFO 2004). Swordfish accounted for over 60% of the landed catch in 57 of the 83 sharked-up sets, whereas warm-water tunas and mahi-mahi accounted for >60% of the landed catch in only 13 of the sets. In the remaining sets, catch was either a mix of swordfish, warm-water tunas, and mako (8 sets), a mix of porbeagle and bluefin (3 sets), or only caught shark (2 sets). Mean blue shark CPUE was 101 ± 69 among sharked-up sets, whereas mean CPUE among sets which were not associated with high blue shark trips was 11 ± 12 blue sharks per 1000 hooks (Table 5.1).

Although there was little difference in the targeting practices of sharked-up sets and sets from the same trips that had lower blue shark catch rates, blue shark catch rates differed (Table 5.1). The difference in fishing quarter between these two groups can be attributed to seven trips, which were fished at the end of September and into October with blue shark sets occurring later in the longline trips. Bait and hook type did not differ between sharked-up sets and other sets fished during those trips. Similarly, neither estimated fishing depth nor fishing characteristics associated with depth (gangion length and number of hooks between floats) differed among sharked-up sets and other sets from the same trip. Even though bait types differed within one-third of these trips, particular bait types were not associated with sharked-up sets. Among the remaining observed sets there was a higher proportion of sets that caught warm-water tunas and mahi-mahi. The remaining observed sets also had a higher proportion of operational characteristics associated with tuna-targeting in this fishery, such as squid bait (Table 5.1). Almost all observed sets (96%), including those with high blue shark catch rates, were fished at night.

5.3.3 Environmental data

There was little difference in the distribution of fishing sets throughout the lunar cycle, whether sets were associated with high blue shark catch, were from the same trips, or were from the remainder of the database. One quarter of high blue shark sets (83 sets) were fished during the new moon period. The proportion was the same for sets fished during those trips (260 sets) or for the remainder of the data set (679 sets). Similarly, 32 to 38% of longline sets were fished during the full moon period, with more sets fished during the full moon among high blue shark sets and those fished during the same trips.

Hourly wind records indicated that wind speed varied from no wind to wind speeds of 20 m s^{-1} (~40 kn) during the period that corresponded to a longline fishing trip (Figure 5.3). Among the 260 longline sets, mean wind speed was 5.8 ± 2.4 m s^{-1} (range: 0.3 – 12.2 m s^{-1}) based on wind speeds averaged over total soak time for each set. The range of directions from which the wind blew varied within the soaking period of each longline set (Figure 5.3), with change in wind direction exceeding 60° during 133 of the 263 sets considered. Ninety-four of these sets met Large and Pond's (1981) criteria for variable wind (a greater than 60° shift in wind direction within a 2 h time period).

Surface water temperatures, recorded by at-sea fisheries observers during setting and hauling, did not differ among high blue shark sets and other sets fished during the same trips (Table 5.1). Low water temperatures (<12 °C) were generally reported from late in the fishing season and caught swordfish, porbeagle and bluefin tuna. Although the range in water temperatures recorded from all observed sets fished between 2002 and 2009 was >20 °C (Table 5.1), the temperature range within longline trips was less than 3 °C for two-thirds of the observed trips.

5.3.4 Catch models

Catch models that included short-term environmental factors, in addition to regional, seasonal, and operational factors, explained 18% of the variability in blue shark catch models and one-third of the variability in swordfish catch models (Table 5.2). The interaction term representing combined regional and seasonal effects was not significant, and was therefore removed from final models. There was little difference in overall model fit or AIC values among models which included different methods of representing wind or lunar effects (Table 5.2). When differences among AIC values are less than or equal to four, as was shown here, models are considered equally likely (Burnham and Anderson 1998). I chose to focus on the model that included wind stress factors and lunar illumination, which retained directional information on wind stress and which represented the expected ecological mechanism for increased swordfish catch rates (Table 5.3).

While bait type or month did not affect blue shark catch, catch levels were lower in sets fished in the Flemish Cap region (Figure 5.4). These 19 sets were fished during three separate trips and the fisheries observers onboard differed, therefore lower blue shark sets in this region were not the result of a single trip nor associated with a particular fisheries observer. Swordfish catch levels were not associated with specific regions (Table 5.3) but did increase over the fishing season (Figure 5.4). Further, bait type was a significant factor in swordfish catch models (Table 5.3), with higher swordfish catch during sets that used fish bait than on sets that used squid bait or a mixture of fish and squid baits (Figure 5.5). The opposite pattern was evident for tuna catch, which was higher during sets baited with squid (Figure 5.5).

Blue shark catch declined with lunar illumination levels (β_{Li} = -0.28, z value = -1.692, p =0.047). No relationship between swordfish catch and lunar illumination levels was evident in this data set. Further, there was little difference in the explanatory power of lunar and semi-lunar cycles in swordfish catch models (β_{Li} =0.235, z value =1.571, p =0.058; β_{2s} =0.010, z-value =1.380, p =0.167). Catch rate effects from lunar illumination levels, wind stress, and the effort offset (number of hooks hauled) were evaluated using one-tailed tested as there was anexpected direction to the relationship.

Contrary to expectations blue shark catch did not increase with wind stress, based either on wind stress levels calculated for the time period fished (Table 5.3) or calculated for the time period 24 h prior to each longline set (Table 5.4). There was, however, a significant negative relationship between swordfish catch and east/west wind stress calculated for the duration of the fishing set (β_{Wstu} = -3.79, z value = -2.409, *p* =0.008; Figure 5.6). Because longline captains reported decreased tuna catch during windy conditions, I ran comparable GLMs with the sum of warm-water tunas and mahi-mahi as the response variable. These models did not converge to a maximum likelihood estimate as >40% of the sets in the data set did not catch any warm-water tunas or mahi-mahi. However, almost no tuna were caught during sets fished at wind stress levels corresponding to average wind speeds > 7 m s^{-1} (~14 kn; Figure 5.6).

Surface water temperature was the most important environmental factor in blue shark models (Table 5.3). As expected, blue shark catch decreased with warmer water temperatures (β_{Tmp} = -0.165, z value = -5.105, *p* <0.001; Figure 5.7). However, the association between blue shark catch and water temperature was not simply a result of surface water temperatures warming over the fishing season. Some of the warmest sea surface temperatures reported were fished in October in waters warmed by the Gulf Stream (Figure 5.8). Interviewed longline captains reported the importance of water temperature only in association with other physical factors, such as the presences of particular water masses or thermal fronts.

To examine within trip temperature effects, I considered water temperature, targeting strategies, set location, and wind speed effects on blue shark catch within trips that contained extreme blue shark catch rates (>150 blue shark per 1000 hooks). The six trips with extreme blue shark catch rates were fished from July through October in the Scotian Shelf, Grand Banks, and Flemish Cap regions. One trip fished in October contained both tuna and mixed targeting strategies. During this trip blue shark catch rates were below average in tuna targeted sets, which were identified by the bait type (squid) and by surface water temperatures (>17 °C). Extreme blue shark catch rates were associated with mixed baits and surface water temperatures <14 °C. Four of the six sets fished in these water temperatures had catch rates in excess of 300 sharks. During another trip fished in October, none of the 6 sets fished in temperatures >17 °C had blue shark catch rates greater than 24 shark/ 1000 hooks, whereas 6/7 sets that were fished in cooler water temperatures did. Eight sets fished during an August tuna-targeted trip were fished in surface water temperatures of 16.5-19.1 °C, but the single extreme blue shark set was fished in the coolest water. No sets were made during the two days following this set, although the vessel remained in the same area. During the remaining three trips that contained blue shark catch rates in excess of

> 150 sharks/ 1000 hooks, surface water temperature did not seem to be a factor. During one of these trips, blue shark catch rates halved following a decrease in wind speed from 8 to 4 m s^{-1}. There were no obvious within trip differences in location, targeting, or environmental factors during two of the trips that contained extreme blue shark catch rates.

5.4 Discussion

Analysis of qualitative interview data, fisheries observer data, and concurrent environmental data suggested that local distribution patterns had a greater effect on blue shark catch rates than fishing decisions or hunting behaviour. Water temperature had a greater effect on blue shark catch rates than bait type, region or month fished, or than wind-induced mixing, which I hypothesized would give blue shark a behavioural advantage in detecting and locating baited longline gear. Sharked-up sets accounted for most of the blue shark bycatch observed during each fishing season; each year 10% of the observed sets accounted for between 30 and 55% of all blue shark caught on observed sets in the swordfish and tuna longline fishery. Thus, fishing practices that decrease sharked-up sets could greatly decrease overall blue shark bycatch levels.

In the Canadian pelagic longline fishery, targeting practices had little effect on blue shark catch, but did affect target species catch rates. My results did not support the hypothesis that short-term environmental variability increased species' ability to detect and locate baited hooks. Blue shark catch did not increase when wind stress increased the distribution of bait odour and the strength of turbulent odour plumes. Similarly, swordfish catch did not increase with lunar illumination levels as expected, given that vision is likely the dominant sense in this species (Lisney and Collin 2006). Instead, water temperature was identified as the key environmental variable affecting blue shark catch rates. Longline captains' observations identified possible ecological mechanisms for this relationship and, therefore, ways to better focus blue shark bycatch mitigation research.

5.4.1 Targeting practices

Fishing decisions, such as where and when to fish, had little effect on blue shark catch. With the exception of low blue shark catch levels in the Flemish Cap region, there was no regional or seasonal pattern to high blue shark sets. Because I was interested in the fishing and environmental factors associated with sharked-up sets, particularly at the within trip level, I limited the data set to those trips that contained these high blue shark sets. This data analysis decision may have affected my results that showed limited regional or seasonal effects on blue shark catch. However, analyses of regional and seasonal effects using the complete observer data set should also evaluate the influence of sharked-up sets, given the distribution of blue shark catch rates (Figure 5.2). To resolve differing results on seasonal and regional patterns – and therefore the likely efficacy of closures in reducing blue shark bycatch – subsequent analyses would need to evaluate how the focus on trips containing sharked-up sets affected my results and how extreme blue shark sets affected reported relationships between catch rates and seasons or regions (Campana et al. 2006).

Fishing decisions, such as the choice of bait type, also had little effect on blue shark catch rates. Blue shark catch was not associated with squid, mackerel or mixed baits. Although Watson et al. (2005) reported higher blue shark catch rates on squid-baited hooks than on those baited with mackerel, Mejuto et al. (2008) did not. Given that mackerel and squid are both commonly found in blue shark stomach contents (Henderson et al. 2001; McCord and Campana 2003; Stevens 1973), I expect changing bait type would have little impact on blue shark catch. From a management perspective, the lack of significance in the blue shark models suggests that regional or seasonal closures or shifts in bait type would not affect blue shark catch, but would impact catch levels of targeted swordfish and tunas.

Swordfish catch rates were low during the first three months of the fishing season (April, May, and June; Figure 5.4) and increased throughout the year. Longline captains reported this pattern was a result of both targeting practices and fish behaviour. Longline captains were targeting swordfish later in the season because individual licenses are limited by swordfish quota (Chapter 4). Captains also described migratory and feeding behaviour that likely affected swordfish catchability, stating that swordfish arrived later and that swordfish feeding behaviour affected catchability by longline and harpoon fisheries. Tagging research supports their observations of swordfish migration; satellite tagging data show swordfish return to temperate waters (40° N) in June (Neilson et al. 2009). The second observation, that swordfish feeding behaviour shifts over the fishing season, has not been investigated. However, pelagic predators' vertical and horizontal movements suggest feeding behaviour shifts within seasons and among regions in response to local environmental variability (e.g., Queiroz et al. 2010; Shepard et al. 2006; Takahashi et al. 2003)

Both targeting practices and fish feeding behaviour affect the relationship between target catch and bait type. Above average swordfish catch was associated with mackerel baited sets, whereas tuna catch was associated with squid baits. Comparable results were found using logbook data from all sets fished between 1998 and 2008. Most albacore, yellowfin, and bigeye tunas were caught using squid bait, whereas the majority of swordfish were caught on mackerel baits (Paul and Neilson 2010). However, swordfish catch rates were comparable on mixed bait sets (Paul and Neilson 2010). Mixed bait sets likely represent an intermediate targeting strategy. Given that squid is common in swordfish stomach contents (Stillwell and Kohler 1985), low swordfish catch rates using this bait type may reflect other tuna-targeting practices, and not swordfish bait preference. Exclusive use of mackerel baits would likely decrease catch rates of bigeye (Watson et al. 2005) and other warm-water tunas, but would likely not affect catch rates of swordfish or blue shark.

5.4.2 Lunar, wind, and temperature effects

Contrary to expectations, blue shark catch did not increase with strong steady winds and swordfish catch did not increase with lunar illumination levels. Instead model results showed a negative correlation between swordfish catch and wind stress and a negative correlation between blue shark and lunar illumination levels. My hypothesis that blue shark catch rates would increase with wind speed was based on an expected behavioural advantage for olfactory detection of prey by blue shark. Lower swordfish catch rates may reflect avoidance or a hunting disadvantage for this species. Carey and Robinson (1981) suggested that swordfish may increase swimming depth in response to increased light levels or to increased winds, based on the three tracked swordfish that swam at greater depths during windy and full moon periods. Longline captains' observations and fisheries observer data agreed that few warm-water tunas were caught during windy conditions. However, my data set was limited to longline trips that contained high blue shark sets. Relationships between target species and wind conditions would be better investigated using the wider set of fisheries observer or logbook data.

Previous researchers reported blue shark catch increased with wind speed and swordfish catch increased with lunar illumination levels (e.g., Bigelow et al. 1999; Damalas et al. 2007). However wind speed and lunar illumination levels were minor explanatory variables, accounting for less than 2% of overall deviance explained (Bigelow et al. 1999; Damalas et al. 2007). Other researchers have found no association between lunar cycles and swordfish or report the inverse relationship. Podesta et al. (1993) found no association between swordfish catch and lunar phase despite increased longline fishing effort during the full moon period. Poisson et al. (2010) reported lower swordfish catch during the full moon and suggested swordfish catch levels corresponded with low tidal phase and currents. A common theme within this research – shared with my own – is that swordfish or blue shark behaviour was inferred from fisheries catch data. Instead of inferring behavioural responses from fishery dependent data, behavioural hypotheses would be better evaluated using swordfish or blue shark dive profiles from acoustic (e.g., Carey and Robinson 1981; Carey and Scharold 1990), archival (Takahashi et al. 2003), or satellite tags (e.g., Campana et al. 2009; Neilson et al. 2009), with wind, lunar, and oceanographic data obtained for corresponding time periods and regions.

Among the environmental factors tested that could influence short-term variability in blue shark catch rates, only water temperature was significantly associated with higher blue shark catch. Neither tagging data nor longline captains' observations suggest that this relationship simply reflects temperature preference. Blue shark experience 10-15 °C temperature changes during diel vertical migrations (Campana et al. 2009; Carey and Scharold 1990; Queiroz et al. 2010), therefore it is unlikely that blue shark are limited by temperatures fished by this fleet. Longline captains reported blue shark catch rates increased with cooler water temperature but all captains linked water temperature to local oceanographic features, such as thermal fronts or water masses. The fleet fishes along the continental shelf edge and further offshore into slope waters, north of the Gulf Stream. The fishing ground is influenced by the Labrador Current, meanders and rings originating from the Gulf Stream, and freshwater from the Gulf of St. Lawrence which is a component of shelf water flowing south over the Scotian Shelf and Georges Bank regions (Loder et al. 1998). Interviewed longline captains described these features, with "green water" associated with the Scotian Shelf and containing freshwater from the Gulf of St. Lawrence, in relation to targeting decisions and blue shark catch rates. While analysis of fisheries observer data identified water temperature as the key environmental factor, interviewed longline captains described possible ecological mechanisms for this relationship.

In their analysis of blue shark catch rates in the Hawaiian longline fishery, Walsh and Kleiber (2001) reported temperature was a key variable at multiple points in their regression tree, indicating multiple ways in which temperature could influence blue shark behaviour and catch rates. At a broad scale the association between blue shark bycatch and cooler water temperatures may reflect targeting practices or associations with water masses (Carruthers et al. 2011; He et al. 1997), whereas at a finer scale blue shark behaviour has been correlated with thermal structure of the water column (Queiroz et al. 2010). I briefly considered the relationship between fishing and environmental factors, and blue shark catch within trips that contained extreme blue shark catch rates (e.g., >150 sharks/ 1000 hooks). While changes in temperature appeared to be the primary factor in three of the six trips, these short-term variations in catch rate would be better investigated using detailed gear configuration and oceanographic data (e.g., depth and location of the main line relative to thermal fronts). Further research on blue shark distribution and catchability in the Canadian pelagic longline fishery will require understanding local ocean dynamics at the scale of a longline trip and of sets within trips.

5.4.3 Summary

Reducing the incidence of high blue shark sets would greatly decrease the overall bycatch levels in the Canadian pelagic longline fishery. Interviewed longline captains were interested in avoiding sharked-up sets (Chapter 4) and described two ecological mechanisms possibly driving the association between water temperature and blue shark catch rates: 1) blue shark were associated with shelf water; and 2), blue shark were found on the cold side of thermal fronts. Subsequent blue shark bycatch mitigation research could investigate these hypotheses. Because longline captains expressed interest in avoiding high blue shark sets, there may be opportunities for collaborative bycatch mitigation research, particularly focused on ocean dynamics at the scale of a longline set. Pelagic longline captains reported difficulties in keeping longline gear on the warm side of thermal fronts (Chapter 4), therefore such fine-scale research may provide useful information for blue shark avoidance. However, fishing on the warm side of thermal fronts would likely increase of bycatch of vulnerable loggerhead sea turtles (*Caretta caretta*, Brazner and McMillan 2008; Chapter 4).

I demonstrated that fishing decisions, such as where and when to fish and choice of bait type, did not affect blue shark catch rates in the Canadian pelagic longline fishery. Given that catch rates reflect fishing practices, fish behaviour, and the interaction between the two processes, future bycatch mitigation research should focus on blue shark behaviour, particularly relative to water temperature – the key environmental variable identified here. From a fisheries management or conservation biology perspective, identifying opportunities to reduce the incidence of sharked-up sets would limit mortalities, stresses, and injuries to sharks associated with the capture process (Campana et al. 2009), and would limit cost and safety issues of longline fishers discarding these fish (Gilman et al. 2008).

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5.5 References

Béné, C., Tewfik, A., 2001. Fishing effort allocation and fishermen's decision making process in a multi-species small-scale fishery: analysis of the conch and lobster fishery in Turks and Caicos Islands. Human Ecology 29, 157-186.

Berens, P., 2009. CircStat: A MATLAB Toolbox for Circular Statistics. Journal of Statistical Software 31, 1-21.

Bertrand, A., Josse, E., Bach, P., Gros, P., Dagorn, L., 2002. Hydrological and trophic characteristics of tuna habitat: consequences on tuna distribution and longline catchability. Canadian Journal of Fisheries and Aquatic Sciences 59, 1002-1013.

Bigelow, K.A., Boggs, C.H., He, X., 1999. Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery. Fisheries Oceanography 8, 178-198.

Bishop, J., 2006. Standardizing fishery-dependent catch and effort data in complex fisheries with technology change. Reviews in Fish Biology and Fisheries 16, 21-38.

Branch, T.A., Hilborn, R., 2008. Matching catches to quotas in a multispecies trawl fishery: targeting and avoidance behavior under individual transferable quotas. Canadian Journal of Fisheries and Aquatic Sciences 65, 1435-1446.

Brazner, J.C., McMillan, J., 2008. Loggerhead turtle (*Caretta caretta*) bycatch in Canadian pelagic longline fisheries: relative importance in the western North Atlantic and opportunities for mitigation. Fisheries Research 91, 310-324.

Burnham, K.P., Anderson, D.R., 1998. Model-selection and inference: a practical information-theoretic approach. Springer-Verlag, New York.

Campbell, L.M., Cornwell, M.L. 2008. Human dimensions of bycatch reduction technology: current assumptions and directions for future research. Endangered Species Research 5, 325-334.

Campana, S.E., Joyce, W., Manning, M.J., 2009. Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. Marine Ecology Progress Series 387, 241-253.

Campana, S.E., Marks, L., Joyce, W., Kohler, N.E., 2006. Effects of recreational and commercial fishing on blue sharks (*Prionace glauca*) in Atlantic Canada, with inferences on the North Atlantic population. Canadian Journal of Fisheries and Aquatic Sciences 63, 670-682.

Carey, F.G., Robinson, B.H., 1981. Daily patterns in the actvities of swordfish, *Xiphias gladius,* observed by acoustic telemetry. Fishery Bulletin 79, 277-292.

Carey, F.G., Scharold, J.V., 1990. Movements of blue sharks (*Prionace glauca*) in depth and course. Marine Biology 106, 329-342.

Carruthers, E.H., Neilson, J.D., Smith, S.C., 2011. Overlooked bycatch mitigation opportunities in pelagic longline fisheries: soak time and temperature effects on swordfish (*Xiphias gladius*) and blue shark (*Prionace glauca*). Fisheries Research 108, 112-120.

Carruthers, E.H., Schneider, D.C., Neilson, J.D., 2009. Estimating the odds of survival and identifying mitigation opportunites for common bycatch in pelagic longline fisheries. Biological Conservation 142, 2620-2630.

Damalas, D., Megalofonou, P., Apostolopoulou, M., 2007. Environmental, spatial, temporal and operational effects on swordfish (*Xiphias gladius*) catch rates of eastern Mediterrean Sea longline fisheries. Fisheries Research 84, 233-246.

de Mutsert, K., Cowan Jr., J.H., Essington, T.E., Hilborn, R., 2008. Reanalyses of Gulf of Mexico fisheries data: Landings can be misleading in assessments of fisheries and fisheries ecosystems. Proceedings of the National Academy of Sciences 105, 2740-2744.

deBruyn, A.M.H., Meeuwig, J.J., 2001. Detecting lunar cycles in marine ecology: periodic regression versus categorical ANOVA. Marine Ecology Progress Series 214, 307-310.

DFO Fisheries and Aquatic Management, 2004. Canadian Atlantic Swordfish and Other Tunas 2004-2006 Integrated Management Plan. <http://www.dfo-mpo.gc.ca/communic/fish_man/ifmp/swordfish/index_ehtm>.

Fox, J., 2007. car: Companion to Applied Regression R Foundation for Statistical Computing, Vienna, Austria.

Francis, M.P., Griggs, L.H., Baird, S.J., 2001. Pelagic shark bycatch in the New Zealand tuna longline fishery. Marine and Freshwater Research 52, 165-178.

Gardiner, J.M., Atema, J., 2007. Sharks need the lateral line to locate odour sources: rheotaxis and eddy chemotaxis. The Journal of Experimental Biology 210, 1925-1934.

Gill, A.E., 1982. Atmosphere-Ocean Dynamics. Academic Press, Inc., San Diego.

Gilman, E., Clarke, S., Brothers, N., Alfaro-Shigueto, J., Mandelman, J., Mangel, J., Petersen, S., Piovano, S., Thomson, N., Dalzell, P., Donoso, M., Goren, M., Werner, T., 2008. Shark interactions in pelagic longline fisheries. Marine Policy 32, 1-18.

Grant, S., Berkes, F., 2007. Fisher knowledge as expert system: a case from the longline fishery of Grenada, the Eastern Caribbean. Fisheries Research 84, 162-170.

Hall, M., Nakano, H., Clarke, S., Thomas, S., Molloy, J., Peckham, S., Laudino-Santillan, J., Nichols, W., Gilman, E., Cook, J., Martin, S., Croxall, J., Rivera, K., Moreno, C., Hall, S., 2007. Working with fishers to reduce by-catches, In By-catch Reduction in the World's Fisheries. ed. S. Kennelly, pp. 235-288. Springer, Dordrecht.

He, X., Bigelow, K.A., Boggs, C.H., 1997. Cluster analysis of longline sets and fishing strategies within the Hawaii-based fishery. Fisheries Research 31, 147-158.

Henderson, A.C., Flannery, K., Dunne, J., 2001. Observations on the biology and ecology of the blue shark in the Northeast Atlantic. Journal of Fish Biology 58, 1347-1358.

Hobday, A.J., Campbell, G., 2009. Topographic preferences and habitat partitioning by pelagic fishes off southern Western Australia Fisheries Research 95, 332-340.

ICCAT. 2006. Report of the 2006 Atlantic swordfish stock assessment session. Collected Volume of Scientific Papers ICCAT 60, 1787-1896.

James, M.C., Ottensmeyer, C.A., Myers, R.A., 2005. Identification of high-use habitat and threats to leatherback sea turtles in northern waters: new directions for conservation. Ecology Letters 8, 195-201.

Javitech, 2002. Report on Sea Turtle Interactions in the 2001 Pelagic Longline Fishery. Dartmouth, Nova Scotia.

Jenkins, L., 2007. Bycatch: interactional expertise, dolphins and the US tuna fishery. Studies in History and Philosophy of Science 38, 698-712.

Kerstetter, D.W., Graves, J.E., 2006. Effects of circle versus J-style hooks on target and non-target species in a pelagic longline fishery. Fisheries Research 80, 239-250.

Large, W.G., Pond, S., 1981. Open ocean momentum flux measurements in moderate to strong winds. Journal of Physical Oceanography 11, 324-336.

Lester, B., Paul, S., Neilson, J., Campana, S., Hussey, L., 2009. Annual Report of Canada, In Report for biennial period 2008-09, Part II (2009) - Vol. 3 Annual Reports, ICCAT, 25-35.

Lisney, T.J., Collin, S.P., 2006. Brain morphology in large pelagic fishes: a comparison between sharks and teleosts. Journal of Fish Biology 68, 532-554.

Loder, J.W., Petrie, B., Gawarkiewicz, G., 1998. The coastal ocean off northeastern North America: a large scale view. The Sea 11, 105-133.

Maunder, M.N., Punt, A.E., 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research 70, 141-159.

McCord, M.E., Campana, S.E., 2003. A quantitative assessment of the diet of blue shark (*Prionace glauca*) off Nova Scotia Canada. Journal of Northwest Atlantic Fisheries Science 32, 57-63.

McCullagh, P., Nelder, J.A., 1989. Generalized Linear Models, Second ed. edn. Chapman Hall, London.

Mejuto, J., Garcia-Cortés, B., Ramos-Cartelle, A., 2008. Trials using different hook and bait types in the configurations of the surface longline gear used by the Spanish swordfish (*Xiphias gladius*) fishery in the Atlantic Ocean. Collected Volume of Scientific Papers ICCAT 62, 1793-1830.

Neilson, J.D., Smith, S., Royer, F., Paul, S.D., Porter, J.M., Lutcavage, M., 2009. Investigations of horizontal movements of Atlantic swordfish using pop-up satellite archival tags, In Tagging and Tracking of Marine Animals with Electronic Devices. eds J.L. Nielson, H. Arrizabalaga, N. Fragoso, M. Lutcavage, J. Sibert, pp. 145-159. SpringerLink.

Ortega-Garcia, S., Ponce-Diaz, G., Merila, J., 2008. The relative importance of lunar phase and environmental conditions on striped marlin (*Tetrepturus audax*) catches in sport fishing. Fisheries Research 93, 190-194.

Paul, S.D., Neilson, J.D., 2010. An exploration of targeting variables in the Canadian swordfish longline CPUE. Collected Volume of Scientific Papers ICCAT 65, 124-134.

Podesta, G.P., Browder, J.A., Hoey, J.J., 1993. Exploring the association between swordfish catch rates and thermal fronts on United States longline grounds in the western North Atlantic. Continental Shelf Research 13, 253-&.

Poisson, F., Gaertner, J.-C., Taquet, M., Durbec, J.-P., Bigelow, K., 2010. Effects of lunar cycle and fishing operations on longline-caught pelagic fish: fishing performance, capture time, and survival of fish. Fishery Bulletin 108, 268-281.

Queiroz, N., Humphries, N.E., Noble, L.R., Santos, A.M., Sims, D.W., 2010. Short-term movements and diving behaviour of satellite-tracked blue shark *Prionace glauca* in the northeastern Atlantic Ocean. Marine Ecology Progress Series 406, 265-279.

Queiroz, N., Lima, F.P., Maia, A., Ribeiro, P.A., Correia, J.P., Santos, A.M., 2005. Movement of blue shark, *Prionace glauca*, in the north-east Atlantic based on mark-recapture data. Journal of the Marine Biological Association of the United Kingdom 85, 1107-1112.

R Development Core Team, 2007. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Richards, L., Morse, J.M., 2007. Readme First for a User's Guide to Qualitative Methods, 2nd edn. Sage Publications, Thousand Oaks.

Richards, S.A., 2008. Dealing with overdispersed count data in applied ecology. Journal of Applied Ecology 45, 218-227.

Shepard, E.L.C., Ahmed, M.Z., Southall, E.J., Witt, M.J., Metcalfe, J.D., Sims.D.W., 2006. Diel and tidal rhythms in diving behaviour of pelagic sharks identified by signal processing of archival tagging data. Marine Ecology Progress Series 328, 205-213.

Stevens, J.D., 1973. Stomach contents of the blue shark (*Prionace glauca L.*) off south-west England. Journal of the Marine Biological Association of the United Kingdom 53, 357-361.

Stillwell, C.E., Kohler, N.E., 1985. Food and feeding ecology of the swordfish *Xiphias gladius* in the western North Atlantic Ocean with estimates of daily ration. Marine Ecology Progress Series 22, 239-247.

Stoner, A.W., 2004. Effects of environmental variables on fish feeding ecology: implications for the performance of baited fishing gear and stock assessment. Journal of Fish Biology 65, 1445-1471.

Takahashi, M., Okamura, H., Yokawa, K., Okazaki, M., 2003. Swimming behaviour and migration of a swordfish recorded by an archival tag. Marine and Freshwater Research 54, 527-534.

Venables, W.N., Dichmont, C.M., 2004. GLMs, GAMs and GLMMs: an overview of theory for applications in fisheries research. Fisheries Research 70, 319-337.

Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S. Springer, New York.

Wade, O., Revill, A.S., Grant, A., Sharp, M., 2009. Reducing the discards of finfish and benthic invertebrates of UK beam trawls. Fisheries Research 90, 140-147.

Walsh, W.A., Kleiber, P., 2001. Generalized additive model and regression tree analyses of blue shark (*Prionace glauca*) catch rates in the Hawaii-based commercial longline fishery. Fisheries Research 53, 115-131.

Ward, P., Myers, R.A., Blanchard, W., 2004. Fish lost at sea: the effect of soak time on pelagic longline catches. Fishery Bulletin 102, 179-195.

Watson, J.W., Epperly, S.P., Shah, A.K., Foster, D.G., 2005. Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Canadian Journal of Fisheries and Aquatic Sciences 62, 965-981.

Table 5.1 Fishing and environmental characteristics of pelagic longline sets which contained the highest blue shark catch rates in each year, compared with sets fished during the same trips and with all other sets observed by at-sea fisheries observers during the 2002 to 2009 fishing seasons (average ± standard deviation and range (shown in parentheses)).

Characteristic	Blue shark sets (n = 83)	Same trip sets (n =177)	Remaining sets (n = 679)
Target species[a]	69% swordfish; 16% tunas	67% swordfish; 20% tunas	46% swordfish; 44% tunas
Blue shark CPUE (/1000 hk)	100 ± 69 (29 – 380)	24±20 (0 –124)	10 ±11 (0 – 86)
Swordfish CPUE (/1000 hk)	11± 13 (0 – 74)	15±13 (0 – 63)	11±12 (0 – 83)
Environmental variables			
Fishing quarter	0; 23%; 40%;37%	0; 16%; 62%; 22%	0; 12%; 77%; 11%
Water temperature (*C)	16.9 ± 2.1 (12.4 – 20.0)	18.1 ± 1.9 (12.6 – 23.9)	20±3 (7 – 27)
Fishing depth (m)[b]	15.7 ± 4.9 (10 – 33)	16.8 ± 6.1 (7 – 36)	12.4 ± 3.8 (4 – 34)
Operational variables			
Longline length (km)	48.4 ± 17.1 (15 – 78)	50.5 ± 14.0 (14 – 79)	44.9 ± 20 (2 – 92)
Number of hooks hauled	1113 ± 348 (480 – 1700)	1213 ± 304 (408 –1800)	1062 ± 311 (210 –1900)
Hook type	22% J-hooks; 78% circle hooks	23% J-hooks; 77% circle hooks	30% J-hooks; 69% circle hooks
Bait type[c]	17% fish; 37% squid; 46% mix	21% fish; 33% squid; 46% mix	18% fish; 48% squid; 23% mix
Hooks between floats	10% 2 hooks; 34% 3 hooks; 56% 4 hooks	8% 2 hooks; 34% 3 hooks; 58% 4 hooks	26% 2 hooks; 44% 3 hooks, 29% 4 hooks
Gangion length (m)	8.1 ± 2.3 (5.5 – 14.6)	7.6 ± 2.2 (5.5 – 29)	7.0 ± 2.0 (1.2 – 20)

[a] Reported as the percentage of sets where swordfish or warm-water tunas (albacore, bigeye, yellowfin plus mahi-mahi) and account for over 60% on the landed species.
[b] Fishing depth estimates are based on 72, 199 and 554 sets because some observers reported water column depth.
[c]Fish bait is primarily mackerel. Herring is used as bait in less than 10% of the mixed bait sets.

Table 5.2 Model selection table for blue shark and swordfish catch. Complete models included an offset term to account for differences in fishing effort (Nhh; number of hooks hauled).

Model terms[a]	Residual deviance	Residual df	AIC
Blue shark			
Tmp + Wstu + Wstv + Li + Bt + Mn + Rgn	291.22	248	2582.5
Tmp + Wstu + Wstv + cos2θ + Bt + Mn + Rgn	291.41	248	2585.1
Tmp + Wstu + Wstv + Lqt + Bt + Mn + Rgn	290.92	246	2580.6
Tmp + Wspd + Wstd + Dstd + Li + Bt + Mn + Rgn	291.27	247	2584.9
Tmp + Wspd + Wstd + Dstd + cos2θ + Bt + Mn + Rgn	291.58	247	2588.6
Tmp + Wspd + Wstd + Dstd + Lqt + Bt + Mn + Rgn	290.93	248	2582.6
Swordfish			
Tmp + Wstu + Wstv + Li + Bt + Mn + Rgn	301.05	248	1873.5
Tmp + Wstu + Wstv + cos2θ + Bt + Mn + Rgn	301.25	248	1873.9
Tmp + Wstu + Wstv + Lqt + Bt + Mn + Rgn	301.36	246	1875.0
Tmp + Wspd + Wstd + Dstd + Li + Bt + Mn + Rgn	301.26	247	1875.4
Tmp + Wspd + Wstd + Dstd + cos2θ + Bt + Mn + Rgn	301.62	247	1875.9
Tmp + Wspd + Wstd + Dstd + Lqt + Bt + Mn + Rgn	301.70	245	1875.4

Model terms for wind effects are wind stress in the east/west (u; Wstu) and north/south (v; Wstv) directions, average and standard deviation of wind speed (Wspd, Wstd) and standard deviation of wind direction (Dstd) calculated for the duration of the longline set.

Lunar effects were represented as percent lunar illumination (Li), as a function of the semi-lunar cycle (cos2θ), or as lunar quarter (Lqt). Surface water temperature (Tmp) was recorded during setting and hauling. Month (Mn) and region (Rgn) represented seasonal and regional effects. Interaction terms between the last two terms were not significant and were removed from final models.

Table 5.3 Modeled effects of environmental factors, in addition to seasonal, regional and bait type effects, on blue shark and swordfish catch among sets fished during 28 trips that included high blue shark sets.

Factor	Likelihood Ratio	Df	Pr(>Chisq)
Blue shark			
Effort offset[a]	15.593	1	0.001
Wind stress (east/west)[a]	0.828	1	0.182
Wind stress (north/south)[a]	0.358	1	0.275
Lunar illumination[a]	2.825	3	0.047
Surface temperature[a]	23.886	1	<0.001
Bait type	3.154	2	0.207
Month	0.408	1	0.523
Region	6.731	3	0.081
Swordfish			
Effort offset[a]	33.865	1	<0.001
Wind stress (east/west)[a]	5.649	1	0.008
Wind stress (north/south)[a]	0.256	1	0.306
Lunar illumination[a]	2.273	1	0.058
Surface temperature[a]	6.268	1	0.007
Bait type	69.511	2	<0.001
Region	4.510	3	0.211
Month	8.876	1	0.003

[a]Effort, wind stress, and lunar illumination variables were tested using one-tailed p-values as there was an expected direction of the relationship.

Table 5.4 Modeled effects of previous wind conditions on blue shark catch in addition to environmental, seasonal, regional and bait type among sets fished during trips that included high blue shark sets. Wind stress levels were calculated from wind speed and direction recorded 24 h prior to the longline set.

Factor	Likelihood Ratio	Df	Pr(>Chisq)
Blue shark			
Effort offset[a]	11.815	1	0.001
Wind stress (east/west)[a]	0.008	1	0.464
Wind stress (north/south)[a]	1.0817	1	0.149
Lunar illumination[a]	2.528	3	0.056
Surface temperature[a]	24.081	1	<0.001
Bait type	3.281	2	0.194
Month	0.394	1	0.530
Region	7.003	3	0.082

[a]Effort, wind stress, and lunar illumination variables were tested using one-tailed p-values as there was an expected direction of the relationship.

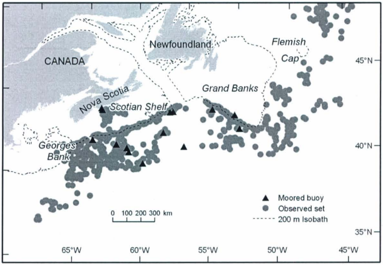

Figure 5.1 Distribution of observed pelagic longline sets from trips that contained high blue shark sets fished between 2002 and 2009. Locations of moored weather buoys indicated along the continental shelf, shelf edge, and further offshore.

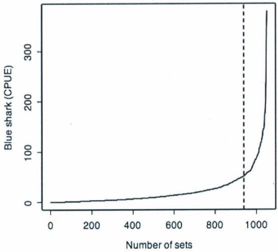

Figure 5.2 Sets with high blue shark catch were defined as the upper 10% of catch rates (indicated by dashed line). Blue shark catch rates (CPUE) calculated as the number of sharks caught per 1000 hooks. These sharked-up sets accounted for 48% of all blue shark observer records from the swordfish and tuna longline fishery between 2002 and 2009.

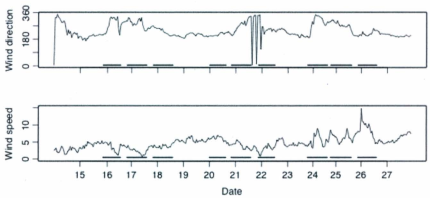

Figure 5.3 Example wind direction and wind speed (m s^{-1}) data from a moored weather buoy located off the central Scotian Shelf in July 2005. Duration of longline sets indicated by horizontal lines.

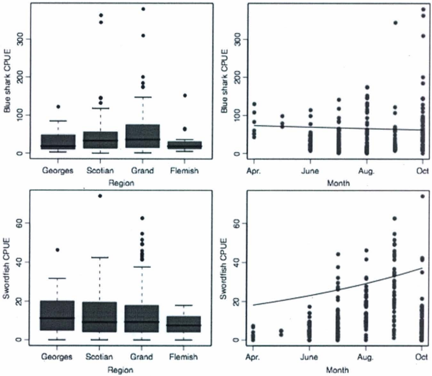

Figure 5.4 Regional and monthly effects on blue shark and swordfish catch rates (CPUE: number per 1000 hooks) based on the 260 longline sets that either had high blue shark catch rates or were fished during the same trips. Box and whisker plots represent the median catch rate, 25% and 75% quartile, and two standard deviations for each region (Georges Bank, Scotian Shelf, Grand Banks, and Flemish Cap). Modeled blue shark and swordfish catch rates were based on mackerel baited sets fished during August on the Scotian Shelf.

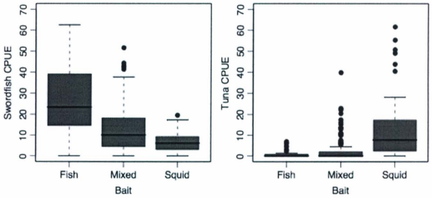

Figure 5.5 Bait type effects on catch rates of swordfish and warm-water tunas (CPUE: number per 1000 hooks). Tuna catch rates were based on the total of albacore, yellowfin and bigeye tunas, and mahi-mahi per set. Box and whisker plots represent the median catch rate, 25% and 75% quartile, and two standard deviations for each bait type.

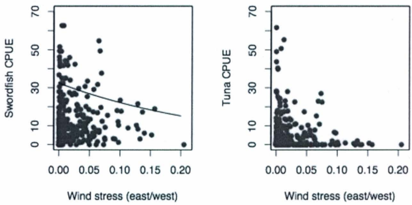

Figure 5.6. Target species rates (CPUE: number per 1000 hooks) from all sets fished during trips that contained high blue shark sets (260 sets). Relationship between swordfish CPUE and wind stress was modeled for sets baited with mackerel and fished during August within the Scotian Shelf region. Tuna catch rates are based on the summed total of albacore, yellowfin and bigeye tunas, and mahi-mahi per set. The relationship between wind stress and tuna CPUE was not modeled due to the high number of sets that did not catch these species.

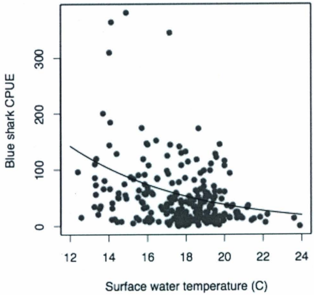

Figure 5.7 Blue shark catch rates (CPUE: number of fish per 1000 hooks) from all sets fished during trips that contained high blue shark sets (260 sets). Relationship between blue shark CPUE and surface water temperature was modeled for mixed bait sets fished during October within the Grand Banks region.

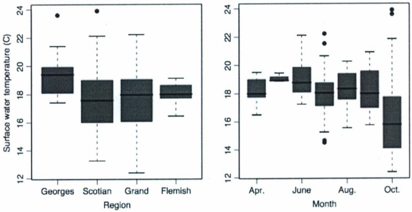

Figure 5.8 Surface water temperature (°C) recorded by fisheries observers from each region (Georges Bank, Scotian Shelf, Grand Banks, and Flemish Cap) and month fished during trips that contained high blue shark sets (260 sets). Box and whisker plots represent the median surface temperature, 25% and 75% quartile, and two standard deviations.

CHAPTER 6: ECOLOGICAL AND SOCIETAL CONTEXT OF CATCH AND DISCARDS: SUMMARY AND NEXT STEPS

6.1 Bycatch mitigation opportunities

The overall objective of this dissertation was to identify bycatch mitigation opportunities within the Canadian pelagic longline fishery for swordfish and tunas. Fishing decisions made throughout the fishing process could be used to reduce bycatch and harm, from choice of gear and setting locations to improved handling and discarding practices. Bycatch mortality levels and injury severity could be reduced for common bycatch species by increased use of circle hooks (Chapter 2) and by increased use of turtle dehooking devices and long-handled gaffs when discarding (Chapter 4). Limited soak time (Chapter 3) would likely decrease catch rates of the most common bycatch species (blue shark, *Prionace glauca*) without decreasing catch rates of targeted swordfish (*Xiphias gladius*). Limited fishing in cooler water temperatures would likely decrease blue shark catch rates but not catch rates of targeted warm-water tunas (*Thunnus obesus, T. albacares, T. alalunga*) and mahi-mahi (*Coryphaena hippurus*) or of loggerhead bycatch (*Caretta caretta)* (Chapter 4). Catch rates of targeted tuna decreased during above average wind conditions but blue shark catch rates did not – indicating little incentive to continue fishing tunas when average wind speeds exceeded 7 m s^{-1} or 14 kn (Chapter 5).

These results provided much needed detail on the efficacy of existing bycatch mitigation approaches. Increased circle hook use, reduced soak times, and better handling practices are bycatch mitigation approaches which have been previously recommended for pelagic longline fisheries (e.g., Watson et al. 2005; Campana et al. 2009; Diaz and Serafy 2005). However, this dissertation research detailed impacts for a suite of common bycatch species and challenged expected trade-offs between conservation and fishing profitability. Circle hooks have been proposed as a bycatch mitigation tool to decrease the severity of hooking injuries among sea turtles (Watson et al. 2005). My results showed that benefits of circle hook use were negligible for loggerhead turtles in this fishery. Importantly, my results demonstrated conservation benefits of circle hook use for porbeagle (*Lamna nasus*), blue shark, and pelagic stingray (*Pteroplatytrygon violacea*) (Chapter 2). Like other researchers (Diaz and Serafy 2005; Ward et al. 2004), I found shorter soak times increased the proportion of bycatch that was alive when brought alongside the vessel (hooking survival). However, the assumed relationship between soak time and target catch was not supported by the data when handling and haulback time were taken into account (Chapter 3). Careful handling and discarding practices are known to improve the condition and likelihood of post-release survival of bycatch (e.g., Campana et al. 2009; Epperly and Boggs 2004; Casale et al. 2008). Longline captains described innovative uses of turtle dehooking gear and long-handled gaffs that likely increased post-release survival and that had not been previously documented (Chapter 4), thereby providing a specific example of improved handling and discarding practices that could benefit pelagic longline bycatch species worldwide.

Multiple data sources were necessary to identify these bycatch mitigation opportunities. Fisheries observer data were the primary data source used in this dissertation. These data constitute the largest data set on bycatch in the Canadian pelagic longline fishery. However, had analyses been limited to these data, key bycatch mitigation opportunities would have been missed or would have been misinterpreted. Detailed within set observations of soak time effects led to a re-evaluation of the assumed trade-off between fishing profitability and bycatch release condition (Chapter 3). Similarly, longline captains' observations of species associations and of local ocean conditions identified likely problems with proposed bycatch mitigation approaches: unintended negative impacts for other bycatch species and operational difficulties of keeping gear on the cool side of thermal fronts (Chapter 4). Fisheries observer data contains detailed quantitative information on bycatch in the Canadian pelagic longline fishery but, as fishery-dependent data, catch and bycatch composition reflect the combined effects of fishing decisions and fish behaviour. By using multiple data sources, I was better able to determine how fishing decisions affected catch and bycatch, and thereby identify key research priorities on the behaviour of open-ocean predators (Chapter 5).

There are, however, important limits to the scope of research based on fisheries observer data. I did not estimate overall bycatch levels for the entire fishery. Such fishery-level estimates are based upon overall landings or effort, and on the assumption that observed and unobserved fishing practices are similar (Benoît and Allard 2009). While aspects of this assumption can be accounted for using factors such as target species, water temperature, region, or season in bycatch models (e.g., Campana et al. 2006; Brazner and McMillan 2008), estimating from a subset of observed trips to the fishery or from a fishery to the population is not a trivial problem (e.g., Benoît and Allard 2009; Baum et al. 2003; Burgess et al. 2005). Thus, an important limitation of this research is that overall bycatch levels were not estimated, neither were reductions in bycatch levels or mortalities from mitigation approaches. Given the current fishing, conservation, and management incentives to decrease bycatch, such quantification may be needed to satisfy reporting requirements for fishery assessment (MSC 2011) and for endangered species recovery plans (DFO 2010a).

6.2 Societal and ecological context

The efficacy of bycatch mitigation efforts depends upon the societal and ecological context. At a broad scale, the efficacy of bycatch mitigation undertaken within the Canadian fishery will be influenced by both the international management context and the migratory nature of target and bycatch species. Because pelagic longline bycatch species migrate across national and international boundaries, mitigation approaches that cross international boundaries would likely have greater conservation benefits. However, the importance of international conservation measures will depend upon fishing practices and effort levels among fisheries and upon bycatch species' biology. If reproductively important life stages are associated with a particular fishery, then within-fishery mitigation can have population-level conservation benefits (e.g., Brazner and McMillan 2008). Within fisheries, differences in targeting practices and in the distribution and vulnerability of bycatch species, will also affect mitigation efficacy. In the Canadian fleet, loggerhead turtle bycatch appears to be associated with tuna-targeted trips (Chapter 4; Brazner and McMillan 2008). Thus, increased targeting of warm-water tunas likely affected loggerhead bycatch levels. Mitigation efforts appropriate for swordfish-targeted sets (e.g., Chapter 2 and Chapter 5) may be less effective or even counter-productive for tuna-targeted sets, given the different species associations and fished environments. Interestingly, the shift to ITQ management may have affected hooking survival as well (Chapter 2); the interactive effects of management system and hook type and of management system and fish length on hooking survival were significant for bycatch associated with swordfish targeting. I did not, however, explore the direction of the effect nor likely underlying mechanisms in that chapter. Effects from the shift to ITQ management will differ within the fleet because ITQ levels were based, in part, on swordfish landings history and because individual longline captains have preferred fishing regions and targeting practices (Chapter 4). As Wade et al. (2008) demonstrated with their research on trawl gear modifications, voluntary uptake of bycatch mitigation gear depended upon preferred fishing regions, species landed, and expected bycatch levels within a multispecies fishery. Some captains found the modified trawl gear beneficial – others did not (Wade et al. 2008).

The efficacy of future bycatch mitigation research will be affected by another important aspect of the societal context: the relationship between fishers and researchers, and between fishers and management (Hall et al. 2007; Campbell and Cornwell 2008). The process of interviewing pelagic longline captains revealed both interest and willingness to reduce bycatch, but also wariness and suspicion of research efforts (Chapter 4). These differing responses are not unique to the Canadian pelagic longline fishery (e.g., Hartley and Robinson 2009; Martin and James 2005; Silver and Campbell 2005). Similarly, efforts to build research collaborations to document bycatch levels or to develop solutions have common themes, including respect for the fishing profession and clear statements of research goals and affiliations (e.g., Hall et al. 2007; Martin and James 2005). Hall et al. (2007) described how external pressure from environmental groups and from consumer campaigns helped generate interest in developing bycatch solutions, although they specified that litigious and antagonistic environments did not foster the development of bycatch mitigation.

Within this fishery, there is documented interest in reducing bycatch and harm (DFO 2010b) and in developing practices that could reduce fishery impacts (Chapter 4). Currently, there are both external pressures and internal incentives to develop bycatch solutions for the Canadian pelagic longline fishery (Chapter 4).

6.3 Next steps

This dissertation research identified bycatch mitigation opportunities that could be developed within the current fishery, and identified improvements to research and management that could be implemented immediately. Hooking mortality was lower and hooking injuries were less severe on circle hooks than on J-hooks for most common bycatch species (Chapter 2). Circle hook use has increased in recent years coinciding with increased targeting of warm-water tunas and mandatory use of circle hooks will start in the 2012 fishing season (DFO 2010b). Improvements to current research and management include developing a working document detailing priorities and protocols of the fisheries observer program (Chapter 4). Like other observer programs, the observer program for the Canadian pelagic longline fishery has evolved to reflect changing research, management, and conservation priorities – and will continue to do so. Documentation of current and past observer practices would provide information needed to avoid a mismatch between observer practices and analysis of the resulting data. This simple change would increase the accuracy of bycatch assessments. Further, it would lay the foundation for subsequent improvements to the program, such as resolving the discrepancy between researchers' and observers' assessments of discarding practices and release condition (Campana et al. 2009). My research identified discarding and handling practices that could increase post-release survival, such as use of turtle dehooking gear (Chapter 4). The documentation of such practices could benefit species discarded from the Canadian fishery and from other pelagic longline fisheries worldwide (Domingo et al. 2005). Thus, developing, documenting, and evaluating best discarding practices will likely become a research priority.

Through the combined use of fisheries observer data, qualitative data from fishers' knowledge interviews, and concurrent environmental data, I developed hypotheses to explain high blue shark catch rates (Chapter 5). As blue shark is the most common bycatch species in the fishery and as there are conservation, management, and fishing incentives to avoid sharked-up sets (Chapter 4; Chapter 5; Burgess et al. 2005; Gilman et al. 2008); reducing the incidence of blue shark bycatch will likely become a research priority. Reducing the incidence of high blue shark sets or sharked-up sets would greatly reduce overall fishery impacts. The ecological hypotheses developed here, as well as addressing the data limitations described in Chapter 5, could be further developed in future bycatch mitigation research. While such research to develop blue shark avoidance strategies is ongoing, methods to reduce blue shark injuries and mortalities could be implemented (Campana et al. 2009; Carruthers et al 2009; Godin and Worm 2010).

In summary, the approach taken here of considering bycatch mitigation opportunities at multiple stages throughout the fishing process, of considering effects on multiple bycatch species, and of considering the societal and ecological context of catch and bycatch, allows for a more comprehensive and effective approach of bycatch management. As detailed above, I identified bycatch mitigation opportunities that could be implemented immediately or that will likely become bycatch research priorities. I do not however recommend focussing research and management attention on a particular stage of the fishing process. Like other multispecies fisheries, targeting practices shift within the Canadian pelagic longline fishery. The migratory behaviour and population status of many bycatch species are poorly known, as are the conservation benefits (e.g., post-release survival) of particular interventions. Given these uncertainties, a multi-faceted approach to mitigation that consider both the societal and ecological context will likely have greater overall conservation and fishing benefits.

Clearly, there are opportunities for bycatch mitigation in the Canadian pelagic longline fishery for swordfish and tunas but how such research is conducted matters. Thus, subsequent research will need to consider the management and fishing context, as these affect the efficacy of mitigation efforts (Campbell and Cornwell 2008). Currently, there are opportunities to work together to solve bycatch issues in the Canadian pelagic longline fishery for swordfish and tunas. Knowledge of current fishing practices, detailed oceanographic data, post-release survival studies, practical fishing knowledge, and on-the-water observations will be needed to do so.

6.4 References

Baum, J.K., Myers, R..A., Kehler, D.G., Worm, B., Harley, S.J., Doherty, P.A., 2003. Collapse and conservation of shark populations in the Northwest Atlantic. Science 299,

Benoît, H.P., Allard, J., 2009. Can the data from at-sea observer surveys be used to make general inferences about catch composition and discards? Canadian Journal of Fisheries and Aquatic Sciences 66, 2025-2039.

Brazner, J.C., McMillan, J., 2008. Loggerhead turtle (*Caretta caretta*) bycatch in Canadian pelagic longline fisheries: relative importance in the western North Atlantic and opportunities for mitigation. Fisheries Research 91, 310-324.

Burgess, G. H., Beerkircher, L.R., Cailliet, G.M., Carlson, J.K., Cortes, E., Goldman, K. J., Grubbs, R. D., Musick, J.A., Musyl, M.K., Simpfendorfer, C.A., 2005. Is the collapse of shark populations in the northwest Atlantic Ocean and Gulf of Mexico real? Fisheries 30, 20-26.

Campana, S.E., Joyce, W., Manning, M.J., 2009. Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. Marine Ecology Progress Series 387, 241-253.

Campana, S.E., Marks, L., Joyce, W., Kohler, N.E., 2006. Effects of recreational and commercial fishing on blue sharks (*Prionace glauca*) in Atlantic

Canada, with inferences on the North Atlantic population. Canadian Journal of Fisheries and Aquatic Sciences 63, 670-682.

Campbell, L.M., Cornwell, M.L., 2008. Human dimensions of bycatch reduction technology: current assumptions and directions for future research. Endangered Species Research 5, 325-334.

Carruthers, E.H., Schneider, D.C., Neilson, J.D., 2009. Estimating the odds of survival and identifying mitigation opportunites for common bycatch in pelagic longline fisheries. Biological Conservation 142, 2620-2630.

Casale, P., Freggi, D., Rocco, M., 2008. Mortality induced by drifting longline hooks and branchlines in loggerhead sea turtles, estimated through observation in captivity. Aquatic Conservation Marine and Freshwater Ecosystems 18, 945-954.

DFO, 2010a. Recovery Potential Assessment for Loggerhead Turtles (*Caretta caretta*) in Atlantic Canada, In DFO Canadian Science Advisory Secretariate Science Advisory Report 2010/042.

DFO. 2010b. Atlantic Canadian Loggerhead Turtle Conservation Action Plan. Fisheries and Oceans Canada – Maritimes Region <http://www.dfo-mpo.gc.ca/fm-gp/policies-politiques/log-turtle-tortue-caouane/index-eng.htm#n1>.

Diaz, G.A., Serafy, J.E., 2005. Longline-caught blue shark (*Prionace glauca*): factors affecting the numbers available for live release. Fishery Bulletin 103, 720-724.

Domingo, A., Menni, R. Forselledo, R., 2005. Bycatch of the pelagic ray *Dasyatis violacea* in Uruguayan longline fisheries and aspects of distribution in the southwestern Atlantic. Scientia Marina 69, 161-166.

Epperly S.P., Boggs, C., 2004. Post-hooking mortality in pelagic longline fisheries using "J" hooks and circle hooks. Application of new draft criteria to data from the Northeast Distant Experiments in the Atlantic. Contribution #PRD-03/04-04 of National Marine Fisheries Service, Miami FL, USA <http://www.sefsc.noaa.gov/PDFdocs/UPR_Epperly_Boggs_2004.pdf>.

Gilman, E., Clarke, S., Brothers, N., Alfaro-Shigueto, J., Mandelman, J., Mangel, J., Petersen, S., Piovano, S., Thomson, N., Dalzell, P., Donoso, M., Goren, M., Werner, T., 2008. Shark interactions in pelagic longline fisheries. Marine Policy 32, 1-18.

Godin, A.C., Worm, B., 2010. Keeping the lead: How to strengthen shark conservation and management policies in Canada. Marine Policy 34, 995-1001.

Hartley, T.W., Robertson, R.A., 2009. Stakeholder collaboration in fisheries research: integrating knowledge among fishing leaders and science partners in northern New England. Society and Natural Resources 22, 42-55.

Lewison, R.L., Freeman, S.A., Crowder, L.B., 2004. Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. Ecology Letters 7, 221-231.

Martin, K., James, M.C., 2005. Conserving sea turtles in Canada: successful community-based collaboration between fishers and scientists. Chelonian Conservation and Biology 4, 899-907.

MSC, 2011. North West Atlantic Canada longline swordfish. <http://www.msc.org/track-a-fishery/in-assessment>.

Silver, J.J., Campbell, L.M., 2005. Fisher participation in research: dilemmas with the use of fisher knowledge. Ocean & Coastal Management 48, 721-741.

Ward, P., Myers, R.A., Blanchard, W., 2004. Fish lost at sea: the effect of soak time on pelagic longline catches. Fishery Bulletin 102, 179-195.

Watson, J.W., Epperly, S.P., Shah, A.K., Foster, D.G., 2005. Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Canadian Journal of Fisheries and Aquatic Sciences 62, 965-981.

APPENDIX I: GUIDE FOR FISHERS' KNOWLEDGE INTERVIEWS

General Background Information

- For how many years have you been a longline captain?

- Before you became a longline captain, did you work in the fleet?
    - As crew? In other sectors?

- Are swordfish and tuna targeted trips different?
    - What do you currently target?

- Has your targeted catch changed over your career?
    - How so? Why?

- Where do you generally fish?

- Do you fish other types of licenses?
    - Which ones?

Fishing decisions, where and when

- When do you start longlining for swordfish and tuna? What is the start of the season?
    - Why do you start longlining for swordfish or tunas then?

- For a particular trip, how do you choose when and where to fish?
    - timing (e.g., markets, moon cycle, ...)
    - location (e.g., target fish, fuel, ...)
    - Where others are fishing? Where you fished in the past?
    - Temperature charts?

- What clues do you look for when setting your gear?
    - E.g., water temperature, water colour, presence of birds or prey?
    - Are you looking for different clues when fishing for swordfish? Or for tunas?

- Can you talk about the how currents and temperature affect how you set your gear?

- How does how other people fish, or where other boats are affect where/when/how you fish?
    - Does the berth system affect how you set?

- Has how you set your gear changed over your career – if so – how and why?
- Could you tell me about the shift from competitive to individual quotas? How did it affect your fishery?
    - Did it affect where and when you fish?
    - How did the shift to ITQs affect bycatch?

Ecology/distributions

- When do swordfish and other tunas come up to Canadian waters?

- Have you noticed a change in when and where different fish are caught since you started fishing?
    - Why do you think that is?

- What fish would you expect to catch when going for Bigeye?
    - What about for yellowfin or swordfish?

- What does it mean to get all sharked up? When would you expect to get sharked up?
    - Do you ever get no blue dogs at all, why do you think that is?

Hauling back

- Can you see the line when it's coming out of the water?

- Where do the observers stand?

- For catch like tunas or swordfish, where some are landed and some are not, can you tell me how you decide which to keep and which to throw back?

Handling/ Release

- Can you describe how you let unwanted catch go?
    - small tunas or swordfish?
    - black skate?
    - blue shark?

- What is your experience with circle and J-hooks? What about offset J's?
    - Which do you use, when, for what species?
    - Which hook type works best to catch tunas? What about swordfish?

- How de-hooking is done?

- When do you think it is better to leave the hooks in?
  - Which animals are difficult to remove hooks from?
  - Are circle-hooks or J-hooks harder to remove?

- Do you think catch rates or where an animal is hooked is more related to hook type or to bait type?

Research priorities and management options

- What are approaches you or the fleet have already done to decrease bycatch harm?

- For each of these, what impact do you think the change has had on your landed catch?
  - Has it changed the amount or type of bycatch?

- Are there any past changes you think didn't work and should be abandoned – why?

- A recent paper on loggerheads caught by your fishery suggested that fishing on the cool side of a front would decrease the number of loggerheads caught.
  - Could you keep the longline gear on one side of a front?
  - How would that affect target catch?

- One of the things I expect conservation groups to focus on is blue shark bycatch.
  - Do you think there are ways to avoid blue shark?
  - How might this affect landings?

End of Interview Questions

- What research is needed for the pelagic longline fishery?

- Is there anything else you'd like to add?

APPENDIX II: CONSENT FORMS FOR PARTICIPATION, RECORDING, AND DATA STORAGE FOR QUALITATIVE INTERVIEWS

MEMORIAL
UNIVERSITY

CONSENT FORM FOR PARTICIPANTS

These interviews are part of my PhD research in Biology at Memorial University in Newfoundland. The research is on the Canadian Atlantic longline fishery for swordfish and tunas. I will use information from fisheries observers and from interviews with longline captains to understand how fishing decisions and fish behaviour affect catch and bycatch in this fishery. I hope to identify opportunities to reduce the numbers of dead and injured discards from a strong Canadian fishery.

You are being asked to participate in one of the interviews for this research. I will ask about how you decide where and when to set your gear. I will ask about what fish you see together and why you think that is. This is an opportunity for you to comment on bycatch and management issues. I would be happy to discuss the research we've done using the observer data and what we plan to do next. I requested observer data from DFO and worked through it with the help of DFO in St. Andrews. Vessel names and CFVs were removed from that data. I cannot link what you say in this interview with information found in the observer data.

Participation in this interview is voluntary – you are free to choose to participate or not, to answer all questions, a few or none. If you decide to stop participating in this project, I will either destroy my records of the information you provided or will return them to you. Your choice. If you agree to be interviewed, you decide how I report that information. You may choose to be quoted, to report your comments only if others report similar information, or to simply have your comments be used as general background information. If you don't want to be known, I will remove any identifying information. But because there are few vessels in the fleet, someone familiar with the fishery might guess what information you provided.

There are potential risks with this project, such as increased fishing regulations related to COSEWIC or other conservation measures. I believe there is little increased risk. Information, like catch rates of protected turtles, is in the observer data and can be requested by the public. If you choose to participate in the research your understanding of catch and bycatch gets recorded and counted. You get to shape research in the fleet. You get to comment on research and management and you have control over what happens with information from your interview.

I would be very grateful if you would agree to be interviewed. In signing this consent form, you are indicating that you are aware of the potential risks and benefits associated with your participation. You are also indicating that you have been given the opportunity to ask questions about and to offer opinions about those risks and benefits. My signature means I will respect your decisions about this interview.

I agree to participate in an interview with the researcher named below, and understand my rights as a participant and the potential risks and benefits of participating.

Name ____________________________

Signature____________________________ Date ________

I agree to maintain the confidentiality of information gathered from this interview and to respect the choices of those interviewed.

Researchers' Name ____________________________

Signature____________________________ Date ________

Contact Information:
Erin Carruthers
cell:(902) 433- 5743
work: (709) 737-3068
email: ehcarrut@mun.ca

Supervisors:
Dr. Dave Schneider and Dr. Barb Neis
work: (709) 737-8841 and (709) 737-7244
email:a84dcs@mun.ca and bneis@mun.ca

The proposal for this research has been approved by the Interdisciplinary Committee for Ethics in Human Research at Memorial University of Newfoundland. If you have ethical concerns about the research (such as the way you have been treated or your rights as a participant), you may contact the Chairperson of the ICEHR at icehr@mun.ca or by telephone at (709) 737-8368.

MEMORIAL
UNIVERSITY

CONSENT FORM FOR DATA STORAGE

Because this is publicly funded research, tapes, drawings and transcripts or copies of these will need to be held in a secure location for at least 5 years after publication up to a maximum of ten years after the data were collected. However, there are a number of options you can choose based on your interest in having a personal record, in how you would like records stored and what you would like to be done with these records when the research is completed.

You can ask to have the interview tapes, transcripts and/or drawings retained by the primary researcher. Any subsequent uses of the data could be subject to your written approval. You can request that the tapes, transcripts and/or drawings be destroyed after the completion of the project and the data analysis. You may wish to receive a copy of the interview for your own personal files and family records. Please check the option(s) you would prefer below.

OPTION 1: _____ Retention of tapes, transcripts and maps by the primary researcher. She must get written approval for any use of the information other than this project.

OPTION 2: _____ Destruction of tapes and maps after completion of the research.

OPTION 3: _____ In addition to the options I have checked above, I wish to have a copy sent to me.

I agree to participate in an interview with the researcher named below, and understand my rights as a participant and the potential risks and benefits of participating.

Name ___________________________

Signature_____________________________ Date _________

I agree to maintain the confidentiality of information gathered from this interview and to respect the choices of those interviewed.

Researchers' Name ___________________________

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CONSENT FORM FOR RECORDING AND USE OF QUOTES

Thank you for agreeing to be interviewed. The method used to record this interview is up to you. Taping ensures that I get all of the information you provide accurately. If you agree to a taped interview, you may ask me to turn off the tape recorder at any time over the course of this interview. You may also choose to have only one portion of the interview taped. However, if you prefer not to have the interview recorded on audiotape (but agree to be interviewed) I will take notes during the conversation.

You also have control over how this interview is reported. At the end of the interview, I will ask if I can use quotes, either attributed to you or anonymous, in publications or presentations. Or you can choose that I ask your permission when I want to quote you.

I agree to audio taping of the interview and understand that I can, at any time, ask that the tape recorder be turned off and that I will have the right to decide what happens to this tape and the resulting transcript in the future.

Participants' Name ____________________________

Signature____________________________ Date _______

Use of specific quotes or drawings in publications or presentations of this information is:

OPTION 1: ________ Permitted provided that quotes or drawings are attributed to me.

OPTION 2: ________ Permitted provided that quotes or drawings are anonymous.

OPTION 3: ________ Permitted on a case by case basis. The researcher is required to contact me and secure permission for each use.

OPTION 4: ________ Not permitted. Specific information, such as that in quotes or drawings should only be presented in a general form when at least two other participants provide similar information.

Name ____________________________

Signature____________________________ Date _________

I agree to maintain the confidentiality of information gathered from this interview and to respect the choices of those interviewed.

Researchers' Name ____________________________

Signature____________________________ Date _________

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APPENDIX III: RESEARCH SUMMARIES FOR MEMBERS OF THE PELAGIC LONGLINE FISHERY

MEMORIAL UNIVERSITY

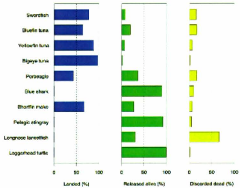
November 2008

Increasing the odds of bycatch survival in the Canadian Atlantic pelagic longline fishery

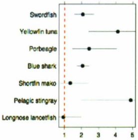
Erin Carruthers, Dave Schneider and John Neilson

Recently, we wrote a research paper using information collected by observers in your fishery. Fisheries observers record whether animals were released alive or discarded dead. We estimated the odds of survival - the likelihood that unwanted catch were released alive – for different hook types, soak times and fish lengths. We expected more fish would be alive on circle hooks and on shorter sets. We also expected larger fish would survive better than small ones.

We estimated the odds of survival for 10 common species. Here are the average percentages for fish and turtles landed, released alive and discarded dead. This is based on observer data collected between 2001 and 2004. Most pelagic stingray, blue shark and loggerhead turtles were released alive. More than half of longnose lancetfish bycatch were discarded dead. Over 3/4 of swordfish were landed but most swordfish bycatch was discarded dead.

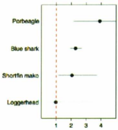


Odds of survival were 2 to 5 times higher for swordfish, yellowfin tuna, porbeagle, blue shark (blue dogs), and pelagic stingray (black skates) caught on circle hooks instead of J-hooks. Here, the dashed line indicates no change in the odds of survival. When error bars cross the dashed line there was no difference whether the fish were discarded dead or released alive on the two hook types. Points and error bars to the right of the dashed line show that more fish survived on circle hooks. However, when we used information from 2005 & 2006 to check these results, porbeagle, blue shark and swordfish were just as likely to be released alive from J-hooks.



We could not estimate survival odds for loggerhead turtles, bigeye and bluefin tunas. Almost all the loggerheads survived. You can't estimate why an animal (likely) died if very few did. We think changes to bluefin tuna regulations made it difficult to estimate survival odds. Longer soak times increased landed catch, but also increased the likelihood of dead discards.

Circle hooks are promoted for conservation because they decrease the number of severe hooking injuries, when animals are gut-hooked. We compared the type of hooking injury for 5 animals that are often released alive. Most pelagic stingray were hooked in the mouth, so we were unable to estimate odds of gut-hooking for this fish. Loggerhead turtles were just as likely to be mouth-hooked on J-hooks as on circle hooks. The estimate for loggerheads falls right on the no-change line. But sharks had less severe injuries when caught on circle hooks. For example, blue shark were 2 times more likely to be mouth-hooked when caught on circle hooks. We did not consider which hook was easier to remove nor did we consider how using different hook types is related to targeting choices.



Possible management changes based on this research include limiting J-hook use, and using area closures to protect small swordfish instead of using minimum size regulations. Using circle hooks seems to increase the odds of survival and the odds of less severe hooking injuries. Swordfish minimum size regulations may do little for overall stock health if few are released alive.

If you have any questions or comments on this research, please contact Erin Carruthers.
cell: (902) 433- 5743 work: (709) 737-3068 email: ehcarrut@mun.ca

MEMORIAL UNIVERSITY

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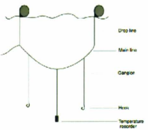
Measuring soak time and temperature effects on swordfish and blue shark catch

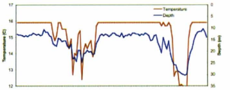
Erin Carruthers, John Neilson, and Sean Smith



We set temperature recorders along longline gear to see if within-set temperature differences affected catch rates. We didn't see clear temperature effects. Instead, we found that neither swordfish nor blue shark catch increased with longer soak times.

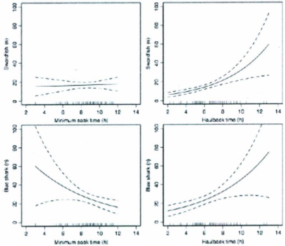
With the help of Gus Reyno and the crew of the Oran II, we set 16 temperature recorders along the length of the longline set. Recorders replaced baited hooks at the end of a gangion. We also placed a depth recorder at the mid-point of the set.

You can see that hooks fished at about 15 m (8 fathoms) and in 16 °C (or 61 °F). We think the big drop in temperature and depth was from blue shark. No hooks were missing and only blue dogs were caught near that recorder.



The biggest surprise was that there was no increase in either swordfish or blue shark catch with longer soak times. We knew how long each temperature recorder was in the water; therefore, we knew the soak time for each section between temperature recorders. Also we expected blue shark catch to increase in colder water. This did not happen across all three sets.

Of course, three sets are not enough to see a pattern. We used fisheries observer data from 42 swordfish sets fished in 2008 and 78 from 2009 to check these results. Was there no relationship between soak time and catch? Was there no relationship between cool water and blue shark catch?



The relationship between catch and soak time depends on how we measure soak time. Swordfish and blue shark catch did not increase when soak time was measured as the time from the end of hauling to the start of with minimum soak time, which is the time between setting and hauling (minimum soak time). You can see that it takes longer to haul your gear if there are more fish on the line – not surprising! But we wrote the paper for fisheries scientists who argue that longer soak times increase catch. In fact, we made this mistake in the past because we included haulback time in our soak time measure. The rug along the bottom shows the number of sets and the dashed lines show how sure we are.

A possible management interpretation of these results is that minimum soak time limits would decrease dead discards without decreasing swordfish catch. However, we point out that limiting soak time might affect your safety. Shorter minimum soak times may mean less sleep which can lead to more accidents – and managers need to consider this.

Blue shark catch was higher in colder water but the relationship was not as strong in the second year tested. This may be because of how we defined swordfish trips, or it may be that blue sharks were found in warmer waters in 2009 than in 2008. As always, the trick is trying to figure out how fish behaviour, your fishing practices, and our data-crunching decisions affect what we see.

If you have any questions or if you'd like a copy of the paper, please call or email Erin.
cell: (902) 433- 5743 email: ehcarrut@mun.ca