REDUCING NEGATIVE ECOLOGICAL IMPACTS OF CAPTURE FISHERIES THROUGH GEAR MODIFICATION

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By

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A thesis submitted to the School of Graduate Studies

in partial fulfilment of the

requirements for the degree of

Master of Science

Biology Department, Faculty of Science

Memorial University of Newfoundland

October 2013

St. John's Newfoundland and Labrador

ABSTRACT

Capture fisheries provide the world with a healthy source of protein than can have minimal environmental impacts if harvested sustainably. Negative environmental impacts of capture fisheries include; overexploitation, modification of foodwebs, mortality of non-target species, habitat alteration and biodiversity loss. A mitigation technique often used to reduce ecological impacts of fishing without compromising commercial catches is gear modification. This thesis explores modification of two gear types; shrimp trawl and turbot longline. Modifications were made to shrimp trawl footgear to reduce habitat alteration and to turbot longline gear to reduce Greenland shark bycatch. Testing of modified with traditional gears demonstrated that the modified gears with reduced ecological impacts did not negatively affect commercial catches. The 200 lb monofilament gangion is recommended for commercial testing by turbot longline fishers in Cumberland Sound; however the aligned shrimp trawl requires further modifications due to unexpected increases in turbot bycatch compared to the traditional trawl.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr. Scott Grant, and my co-supervisor, Dr. Paul Winger for their time and support over the past 2 years. I am grateful to Dr. Grant for going above and beyond my expectations for a supervisor, and to Dr. Winger for his guidance and actions that provided me with funding, enabling me to be a part of the CSAR team. I would like to thank Dr. Craig Purchase, who sat on my committee and offered fresh perspectives and ideas to my research.

Thanks to my lab mates Andrew Murphy and Truong Nguyen for their pleasant company and help over the last few years. A special thanks to Kelly Moret for her understanding and kindness, helping me out in any way she could, including enabling me to have a once in a lifetime international work experience in the Philippines. Thanks to Roy Gibbons of CSAR through his background in commercial fishing provided me great help in understanding my results with regard to gangion material. Thanks to David Mercer for his patience and guidance in helping me create the maps for my thesis. Thanks to Carey Bonnell for his support in helping me get to the ASM 2012 in Vancouver for a fantastic first ever conference. I would like to thank all the CSAR staff for their help along the way; Claudene Hartery, Tara Perry, Harold DeLouche and Phil Walsh.

Thanks to the industry partners Vónin Canada and Vónin Ltd., as well as the crews of the Newfie Pride and Nuliajuk. A special thanks to Devin Imrie for hosting us in Pangnirtung.

Financial support for chapter two was provided by the Atlantic Canada Opportunities Agency (ACOA), Fisheries and Marine Institute of Memorial University of

Newfoundland, the Department of Fisheries and Aquaculture of Newfoundland and Labrador, Research and Development Corporation of Newfoundland and Labrador (RDC),Vónin Canada and Vónin Ltd. Financial support for chapter three was provided by the National Research Council of Canada, the Nunavut Offshore Allocation Holders Association-Nunavut Exploratory Fishery Fund, Department of Environment of the Government of Nunavut, CanNor, Ducks Unlimited, Oceans North, and Fisheries and Oceans Canada.

Lastly, I would like to thank my family for their constant support and encouragement, especially my mother and J.M.F.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Bait absent
AS	Arctic skate
C-200BN	Control gangion; 200 lb made of multifilament braided nylon
CL	Carapace length
CSAR	Centre for Sustainable Aquatic Resources
DFO	Fisheries and Oceans Canada
E1-200M	Experimental gangion; 200 lb made of monofilament nylon
E2-100M	Experimental gangion; 100 lb made of monofilament nylon
E3-50M	Experimental gangion; 50 lb made of monofilament nylon
FAO	Fisheries and Agriculture Organization of the United Nations
GS-D	Greenland shark-dead
GS-L	Greenland shark-alive
GS-TOTAL	All Greenland shark captures including; GS-D, GS-L, GT-D and GT-L
GT-D	Greenland shark and turbot on same hook-shark dead
GT-L	Greenland shark and turbot on same hook-shark alive
HL	Hook loss

HT-G	Hook snarl suspected to be caused by Greenland shark interference, location immediately before or after a recorded shark capture
ICES	International Council for the Exploration of the Sea
IFMP	Integrated Fisheries Management Plan
IUCN	International Union on the Conservation of Nature
NRC	National Research Council
P	Bait present
S	Hook snarl suspected to be caused by environment or fishing process
T	Turbot
TP	Turbot with predation evidence
T-TOTAL	All turbot captures including; T and TP
UN GA	United Nations General Assembly
WWF	World Wildlife Fund

CO-AUTHORSHIP STATEMENT

The research described in this thesis was carried out by Jenna Munden, with guidance from Scott Grant, Paul Winger, Kevin Hedges, George Legge and Truong Nguyen.

Jenna Munden was responsible for data collection and analysis. Manuscripts resulting from this thesis were prepared by Jenna Munden, with editing assistance and intellectual input from co-authors as follows:

Authorship for **Chapter 2** is J.G. Munden, S.M. Grant, P.D. Winger, G. Legge and T.X. Nguyen
Authorship for **Chapter 3** is J.G. Munden, S.M. Grant and K.J. Hedges

CHAPTER 1: INTRODUCTION

1.1 Importance of Maintaining Capture Fisheries

The importance of maintaining global food sources including capture fisheries, aquaculture and agriculture is greater now than ever. With human population growth estimated to reach over 9 billion by 2050 (UN, 2009) and uncertainty regarding how climate change will impact food security, proper management of the earth's natural resources is important. Fisheries, including wild capture and aquaculture provide 148 million tonnes of food to the world's population, representing 16.6% of global dietary protein intake (FAO, 2012). The reliance on capture fisheries for the consumption of protein in developing countries however is 27% which is almost twice that of the global average (Allison et al., 2009). With increasing demand for food in the foreseeable future and a worsening state of world marine fisheries, practicing sustainable fishing will be necessary if fisheries are to continue to be a major provider of protein (FAO, 2012). The most recent estimates suggest that > 80% of global fish stocks are fully or overexploited and it is generally accepted that there are no new major fishing grounds to be exploited (Godfray et al., 2010). Since stocks produce less when systematically overexploited (Garcia and de Leiva Moreno, 2003), taking every precaution to ensure sustainable fishing will not only result in healthier marine ecosystems, but also provide more fish. Fisheries management should focus on fishing sustainably, efficiently and being aware of the ecological links in marine food webs to ensure the abundance of marine fishes.

Consuming fish protein is a healthier choice for the environment and consumer than other types of protein (Hilborn, 2011; FAO, 2012). Sustainable fishing of wild stocks has a smaller ecological footprint than does farming poultry, pork or beef, and the agriculture needed to support production (Hilborn, 2011). Food production for capture fisheries is more energy efficient on average than agriculture as more edible protein is produced for the same amount of greenhouse gas input (Hilborn, 2011). The agricultural sector accounts for 22% of global total emissions, with livestock production accounting for nearly 80% of this sector's emissions, substantially contributing to climate change (Michael et al., 2007). In capture fisheries there are fewer environmental impacts on habitat and more ecosystem properties are preserved compared with the transformation of terrestrial habitat into agricultural land (Hilborn, 2011). In addition, fish consumption is a healthier food choice than meat with many nutritional benefits that contribute to well-being. Fish is low in saturated fats, carbohydrates and cholesterol. It provides many micronutrients including vitamins A, B and D as well as minerals such as calcium, iodine, zinc, iron and selenium (FAO, 2012). It is a source of omega 3 fatty acids and there is evidence of beneficial effects in relation to coronary heart disease, age-related macular degeneration and mental health (FAO, 2012). Further, fish consumption has benefits for growth and development, especially for children and pregnant women as it aids in brain development (FAO, 2012). Although some risk of contaminants such as mercury, dioxins and polychlorinated biphenyls (PCBs) exist with the consumption of some fish species, the benefits of fish intake exceed the potential risks (Mozaffarian and Rimm, 2006). Eating meat is associated with many adverse health effects such as; heart disease, obesity and colorectal cancer (Michael et al., 2007). In addition, consuming poultry, pork or beef can be harmful or even fatal due to bacteria and parasites which can be contained in products made from these animals such as; *Salmonella* spp., trichinosis or *Escherichia coli* (E.coli). With increasing pressure on ecosystems by anthropogenic activities caused by rapid human population growth, if managed properly, capture fisheries can provide a valuable, healthy source of protein with minimal environmental and biological impacts compared to other sources.

1.2 Negative Ecological Impacts of Capture Fisheries

Although capture fisheries have fewer environmental impacts on habitat and ecosystems compared to the production of livestock, negative impacts do result from fishing activities. These include; overexploitation, modification of foodwebs, mortality of non-target species, habitat alteration and biodiversity loss (Rogers and Laffoley, 2011; Frid and Paramor, 2012).

Overexploitation or overfishing occurs when more fish are harvested than can be replaced naturally by reproduction within the population and a reduction in population size occurs. There are two types of overfishing; recruitment and growth overfishing (NRC, 2002). Recruitment overfishing is described as when overfishing results in a reduction in spawning biomass to such an extent that future recruitment is compromised. Growth overfishing is described as when fish are caught before they grow large enough to achieve maximum yield per recruit (NRC, 2002). If overexploitation is maintained over a number of years, stock collapse may ensue with dramatic drops in abundance. Stock collapse increases the chance of local extinction as smaller populations are subjected to Allee effects, described as a reduction in fitness associated with a declining number of conspecifics in a population (Stephens et al., 1999). Overexploitation is thought to have the ability to change population parameters as fishing mortality behaves as a selective pressure, favouring smaller body size and earlier age at maturity. These changes are often associated with a loss of genetic diversity and can be irreversible even with the cessation of fishing activities (Hutchings and Fraser, 2008). Stock collapse can result in modification of food webs and ecosystem shifts. The niche that was occupied by the collapsed stock is filled by a similar species or trophic cascades can result affecting the entire marine community (Frank et al., 2005). Thus overexploitation directly reduces the abundance, spawning potential and possibly population parameters and genetic diversity of the target species (Garcia et al., 2003), but also indirectly results in ecosystem shifts and modification of foodwebs. These effects can lead to negative social and economic consequences for those dependent on marine ecosystems for their livelihood, an estimated 10-12% of the world's population (FAO, 2012).

Mortality of non-target species in the form of discards or bycatch is a consequence of many fishing operations. Bycatch is a result of unselective fishing methods. Although internationally there is debate on the exact definition of bycatch (FAO, 2008), it is broadly defined as the incidental catch of unwanted organisms. Bycatch is discarded at sea or kept and can be categorized as regulatory or economic (Chuenpagdee et al., 2003). Economic bycatch are those species or sizes that are discarded because they are of little or no economic value (Chuenpagdee et al., 2003). Regulatory bycatch are marketable species/sizes that are discarded because of management regulations in place, such as size limits, allocations and seasons (Chuenpagdee et al., 2003). It has been estimated that a quarter of the total world catch is bycatch (Cook, 2003). Discard rates are the highest for crustaceans and flatfish fisheries, intermediate for large pelagic and roundfish fisheries, and lowest for small pelagic fisheries (Cook, 2003). Additionally, mortality of target or non-target species can occur from fishing operations where individuals are killed through interactions with fishing gear, although they may not necessarily be brought on board the vessel. This type of mortality, known as unaccounted fishing mortality can be difficult to estimate. The capture and mortality of non-target species from capture fisheries can have several ecosystem effects. It can reduce the abundance of large individuals, increase the abundance of small individuals, lower total biomass reducing productivity and favour the increase of scavengers.

Habitat in regard to aquatic species is defined as spawning grounds, nursery, rearing, food supply, migration and other areas on which species depend directly or indirectly in order to carry out life processes (DFO, 2010). The unique assemblage of sediment types, bed forms and biological structures found within a defined area determines habitat type. The degree of overall habitat damage caused by fishing practices is highly variable depending on gear type (He and Winger, 2010). Active fishing gears have the greatest habitat impacts, where as passive or fixed gears can have minimal impact (Gascoigne and Willsteed, 2009; Chuenpagdee et al., 2003).

There are three general fishing gear categories; active, mobile, and passive or fixed (Gascoigne and Willsteed, 2009). Active gears are those that are towed across the seabed. This category includes dredges and trawls. Passive or fixed gears are those that are placed on the seabed and do not move until lifted by the fishing vessel. Some examples include gillnets, traps and demersal longlines. Mobile gears are intermediate between active and passive gears. Mobile gears are those that involve movement of the fishing vessel to deploy but are not actively towed such as seines.

Habitat damage associated with fishing gears includes damage to living seafloor structures and alteration to geologic structures. Living seafloor structures include sessile, epibenthic organisms like corals and sponges. These organisms are often classified as ecosystem engineers because of their habitat forming role and contribution to habitat complexity (Schwinghamer et al., 1996; NRC, 2002). These structures provide refuge and food for various benthic invertebrate and fish species (Auster et al., 1996). Benthic geologic structures include substrate types such as boulders, cobble, gravel, sand and mud. Changes to substrate can affect the functional type of organisms able to survive there, thus disturbance to geologic structure can result in ecosystem assemblage shifts. With the destruction of living seafloor and geologic structures; habitat complexity and structural diversity is reduced (NRC, 2002). This can have consequences on species richness in habitats that experience interactions with fishing gears.

1.3 Mitigation Options for Reducing Negative Impacts of Capture Fisheries

The risk of overfishing can be minimized by fishing sustainably, following the precautionary approach and harvesting less than the maximum sustainable yield. To minimize the mortality of non-target species and habitat alteration caused by fishing activities, several options are possible; changing the spatial and temporal components of the particular fishing operation, the establishment of closed areas or area restrictions, introducing bycatch quotas, reduction of fishing effort, implementing gear substitutions or gear modifications (NRC, 2002; ICES, 2000).

1.3.1 Gear Modifications

Gear modifications are a favoured mitigation technique for reducing bycatch or habitat effects for business minded fishers who would like the ability for continued economical capture of available stocks without substantial increases in harvesting costs or decreases in commercial catch rates. Methods that can affect economic return such as reducing fishing effort or gear substitutions are much less desired by fishers and ultimately have a hard time being accepted and successful in commercial fishing industries without legal mandates.

Different types of gear modifications are used depending on the sustainability issue. To reduce the capture of non-target species, often modifications which improve gear selectivity are used. These modifications are designed to take advantage of either morphological or behavioural differences between target and non-target species which are used to separate them during the catching process (Winger, 2008). If habitat damage is a concern, modifications include reducing the pressure exerted on the seabed by the gear or reducing total contact area of the gear with the seabed.

1.3.1.1 Example of Successful Gear Modification, the Nordmøre Grid

An example of a highly successful gear modification used to reduce the capture of non-target species is the Nordmøre grid (Fig. 1.1). In shrimp fisheries, bycatch of commercially important juvenile and sub-adult fish is especially concerning as it may have effects on recruitment, biomass and stock yields that form other fisheries (Broadhurst, 2000). The Nordmøre grid bycatch reduction device takes advantage of the morphological difference between shrimp and larger bycatch species. The rigid rectangular sorting grid was invented by a Norwegian shrimp fisher originally trying to exclude jellyfish bycatch (Gillett, 2008). It was developed in 1989-1990 and is effective in reducing bycatch by 60-90% while maintaining commercial catch rates of shrimp (Broadhurst, 2000). The original design consists of a guiding funnel positioned in front of the codend (trawl component, back of the net where catch accumulates) which directs the catch to the base of the sorting grid made of longitudinally oriented bars (Broadhurst, 2000). Small organisms fit through the bar spacings and pass through the grid into the codend, while larger individuals are directed upwards to an opening in the top of the trawl where they can escape. The Nordmøre grid has been adapted to many shrimp fisheries around the world and numerous countries have made the use of the grid mandatory, including Canada (Hickey et al., 1993). In several instances fishers had adopted the grid before it became mandatory, voluntarily implementing the gear change due its economic benefits. With the reduction of bycatch, there is reduced time needed to sort bycatch, less shrimp are broken and catch per unit effort is increased, all while shrimp catches remain the same as without the grid. This win-win situation for sustainability and fishers is the key for gear modifications to become commercially successful.

1.4 Thesis Outline

The objective of this thesis was to test gear modifications designed to improve fishery sustainability using comparative fishing techniques *in situ*. Increased sustainability was achieved by reducing negative ecological impacts of bycatch or habitat damage. Modifications for two separate gears and fisheries were tested and each comprises a chapter of this thesis.

The first experimental chapter (Chapter 2) investigates a modification to an inshore northern shrimp (*Pandalus borealis*) trawl designed to have reduced contact area with the seabed. Through flume tank trials conducted at the Fisheries and Marine Institute of Memorial University in St. John's, the modified (aligned) trawl was shown to have less contact area with the seabed compared to the traditional trawl. The purpose of the study was to test the following hypotheses, the aligned and traditional trawl are not different in terms of (i) shrimp catch rate or (ii) size, (iii) the percent of total catch made up of the most abundant bycatch species, as well as (iv) the sizes of these major bycatch species captured. These hypotheses were investigated through comparative at-sea fishing trials conducted between trawl types on the north-western coast of Newfoundland. Commercial catch and bycatch composition, size and catch rates were compared between paired tows of each treatment. To compare these parameters between treatments, *t*-tests and

Kolomogrov-Smiroff tests were conducted. Commercial catch rates were significantly higher with the modified trawl compared to the traditional trawl without affecting the size of shrimp caught. Out of the most abundant bycatch species, the proportion of capelin (*Mallotus villosus*) was not significantly different between trawl types, however the proportion of catch composed of turbot (*Reinhardtius hippoglossoides*) was significantly higher with the aligned trawl. I discuss possible reasons for these findings as well as limitations to this study.

The second experimental chapter (Chapter 3) investigates modifications to longline gear aimed to reduce Greenland shark (*Somniosus microcephalus*) bycatch without affecting commercial catches of turbot (*Reinhardtius hippoglossoides*) within the Cumberland Sound fishery. The modification investigated was changing gangion breaking strength and material. Four gangion treatments were tested through experimental longline fishing in the Cumberland Sound, Nunavut, Canada. This included a 200 lb multifilament braided nylon gangion used as the control, and three experimental gangions made of monofilament. The experimental monofilament gangions had breaking strengths of 50 lb, 100 lb or 200 lb. Catch labels were used to quantify catch and indicate hook condition upon haulback of longline gear. Using catch label frequencies for each treatment per 100 hooks, one way Analysis of Variance tests were used to determine if the frequency of catch labels and size of turbot was significantly different between gangion treatments. Monofilament gangions were found to have lower catch rates of Greenland shark and higher rates of hook loss. Turbot catches or size was not significantly different among treatments. I discuss the possible reasons for these findings as well as the gangion best suited for the Cumberland Sound turbot longline fishery.

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1.6 Figures

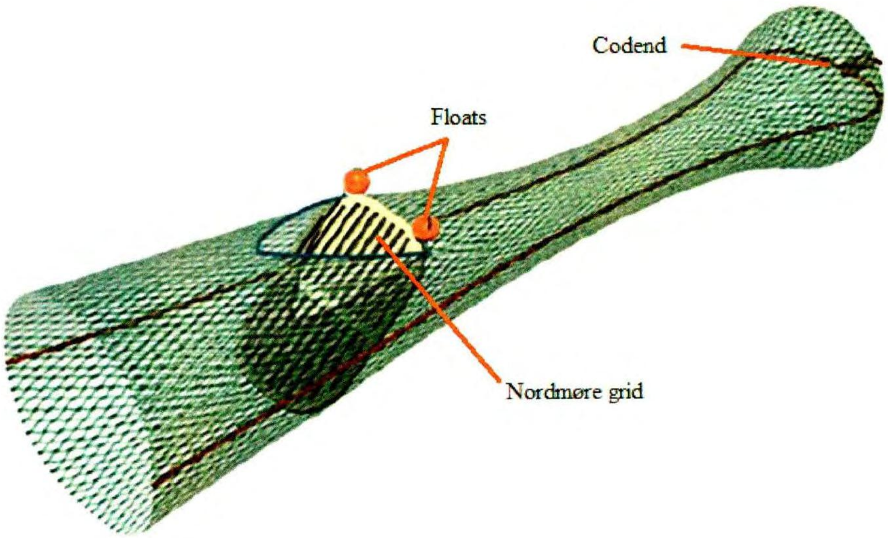

Figure 1.1. Bottom trawl equipped with a Nordmøre grid; a bycatch reduction device used in shrimp trawl fisheries (Graham, 2006).

CHAPTER 2: COMPARATIVE FISHING TO DETERMINE THE COMMERCIAL VIABILITY OF A LOW IMPACT SHRIMP BOTTOM TRAWL

The codend of the aligned trawl being hauled onto the F/V "Newfie Pride" during at-sea comparative fishing trials in September 2012.

2.1 Abstract

Concern over the impacts of bottom trawling is widespread due to its adverse ecological impacts. We investigated gear modifications to reduce the total contact area of a traditional shrimp (*Pandalus borealis*) trawl on the seabed for the Newfoundland and Labrador inshore fishery. We designed, flume tank tested, and conducted sea-trials with a modified, experimental (aligned) trawl that demonstrated 39% reduced contact area with the seabed compared to a traditional, Vónin 2007-1570 trawl. This chapter focuses on the sea-trials. The purpose of this study was to test the null hypotheses that the aligned and traditional trawl are not different in terms of; shrimp catch rate or size, the percent of total catch made up of the most abundant bycatch species and the sizes of the major bycatch species captured. The aligned trawl was found to capture significantly 23% more shrimp, outperforming the traditional trawl in 17 of the 20 paired tows during comparative fishing trials. Major bycatch species caught in the experiment were Greenland halibut (a.k.a., turbot; *Reinhardtius hippoglossoides*) and capelin (*Mallotus villosus*). Mean percent contribution of capelin to the total catch was not significantly different between trawl types, however the aligned trawl captured significantly average 77% more turbot than the traditional trawl. Due to unacceptable increases in turbot bycatch, a commercially important species, further modifications to the aligned trawl are required before commercialization. This study represents a first step towards the development of a low impact shrimp trawl for the northern shrimp Newfoundland and Labrador inshore fishery.

2.2 Introduction

Newfoundland and Labrador supports the world's largest northern shrimp (*Pandalus borealis*) fishery (Mullowney et al., 2012). The fishery is a major economic driver in the region and was valued at $192 million in 2012 (Newfoundland and Labrador, 2013). Overall, the offshore fleet employs 625-650 crew members. The inshore fleet provides employment for approximately 2,000 fishers aboard 360 multi-species enterprises. In addition, it provides shrimp to 12 inshore processing plants with a core workforce of approximately 1,350 workers (IFMP, 2007).

The only way to commercially harvest northern shrimp in the Newfoundland and Labrador region is by the use of active fishing gear, the bottom trawl. Industrial scale harvesting of shrimp using passive fishing methods does exist in some areas which have unsuitable bottom types for trawling, however most large-scale commercial fishing is done using trawls (Gillett, 2008). The use of bottom trawls can have negative ecological impacts through destruction of habitat, decreased benthic biomass, community shifts, sediment suspension, changes in chemistry and bycatch of non-targeted species (e.g., Prena et al., 1999; Hansson et al., 2000; Johnson, 2002; Løkkeborg, 2005). Despite the interest in replacing bottom trawling with an alternate fishing method, no substantial progress has been made and the trawl has remained the predominant method for fishing shrimp over the last century. Efforts are thus concentrated on improving the shrimp trawl to reduce negative impacts, rather than into replacement technologies (Gillett, 2008).

A bottom trawl is essentially a large net bag towed along the ocean floor. At the back of the net is the codend which holds the accumulated catch. The net is held open horizontally by two doors. One side each door is attached to sweeps and bridles connecting to the net and the other side is attached to to wires called warps that are secured to the fishing vessel (Graham, 2006). When towed, the doors are pushed outwards by the force of seawater which prevents the mouth of the net from closing. The net is held open vertically by floats attached to the rope running along the upper mouth of the net (headline) and weighted bobbins or other footgear attached to the lower mouth of the net (fishing line). Footgear is attached to the fishing line with the use of toggle chains. There are different variations of footgear that are used depending on substrate type, to maximize the capture of target species, minimize gear damage while maintaining bottom contact (Løkkeborg, 2005; Valdemarson et al., 2007; Gillett, 2008). To ensure bottom contact, an important factor influencing catch rates, the footgear may include chain or weighted rope, or be equipped with rubber discs, bobbins or spacers (Gillett, 2008).

Individual gear components of the trawl system have different physical impacts on the seabed. The doors have the most significant impact due to their size and weight (Gilkinson et al., 1998; Valdemarsen et al., 2007; He and Winger, 2010; Polet and Depestele, 2010). The doors act like a plough, digging into the sediment, leaving visible furrows with the depth of penetration dependent on substrate type (NRC, 2002). The time it takes for the furrows to disappear depends on substrate type and natural disturbance regime. This can range from a few hours to a few years (Løkkeborg, 2005). The doors also cause re-suspension of sediment into the water column, increasing water turbidity.

The footgear has minor smoothing or compressing effect on the substrate that it contacts, which can result in packing or compression over repeated trawling (Gillett, 2008). The sweeps have discontinuous contact with the seabed and usually have the largest contact area with the bottom producing a flattening effect (Løkkeborg, 2005; Valdemarson et al., 2007; Gillett, 2008). When the codend becomes extremely full it can drag along the bottom and produce a minor compressing effect on the seabed.

Bottom trawling is often criticized as a fishing practice, with concern shared by many groups. Aggressive campaigns by environmental NGO's (Non-Government Organizations) have led to a widespread negative stigma being associated with this fishing gear among the general populous, even though many trawl fisheries hold sustainability certifications such as the Marine Stewardship Council (MSC). The unease over impacts of bottom trawling is shared by the international scientific community, including well respected organizations such as; the International Council for the Exploration of the Sea (ICES), Food and Agriculture Organization of the United Nations (FAO), and National Research Council (NRC) of Canada.

A reflection of the wide spread concern over bottom trawling was demonstrated at the UN General Assembly in 2006 when there was an attempt to establish an international ban on deep sea trawling (UN 61/105). Some national governments have banned trawling completely, in certain areas or produced mandates for the use of less destructive gear. Some countries with national trawl bans include Belize and Indonesia (Stiles et al., 2010). Due to the commercial importance of bottom trawling in Canada, a widespread ban is not an option. However bottom trawling exclusion zones do exist, such as the 8,610

km^2 Hawke Box off southern Labrador (Mullowney et al., 2012). Low impact bottom trawling gear is defined as a trawl which has been modified to either reduce physical pressure exerted on the seabed or to reduce the total contact area with the seabed. It is anticipated that within the next 3-5 years the use of low impact bottom trawling gear will be enforced. Strong recommendations by Fisheries and Oceans Canada (DFO) into gear modification research to reduce impacts of trawled gears demonstrate the need for improving shrimp fishing gear technology (Gilkinson et al., 2006; Rice, 2006).

When it comes to bottom trawling impacts, the major concerns have to do with damaging living seafloor structures as well as the alteration of geologic structures (NRC, 2002). A single pass of a bottom trawl can displace large boulders and damage or remove biogenic habitat such as corals and sponges which are attached to these substrates.

Habitat forming epibenthic organisms found in Newfoundland and Labrador can be negatively affected by shrimp trawling. In this region, sponges are distributed on the slope edge at depths greater than 800 m (Kenchington et al., 2010; Edinger et al., 2011). In the Gulf of St. Lawrence, shrimp trawling is most common from 200-300 m (DFO, 2013). Due to limited habitat overlap, few instances of sponge bycatch have been reported from shrimp trawling (DFO, 2013). Some species of soft bodied corals (sea pens) are expected to be negatively impacted by trawling. Sea pens are restricted to muddy habitats (Williams, 2011) and span a wide depth range from 30 m to greater than 1,900 m (Baker et al., 2012). Sea pens can form unique habitats of dense meadows over 1 km in length with up to 622 colonies per 10 m segment (Baker et al., 2012). These meadows may be important habitat for other taxa. It has been suggested that sea pen meadows may create important refugia for small invertebrates and influence prey availability (Tissot et al., 2006). Baillon et al. (2012) demonstrated that larvae of several fish species including redfish (*Sebastes* spp), lanternfish (*Benthosema glaciale*) and eelpout (*Lycodes esmarkii*) use deep water sea pens as habitat, most likely due to the shelter they provide from predators. It is hypothesized that some fish species (i.e. *Sebastes* spp) may spawn directly on sea pens to increase the chance of larval survival (Baillon et al., 2012). Sea pens are thought to be fairly common in shrimp trawling grounds in the Northern Gulf of St. Lawrence (the study site for this experiment) however sea pen meadows have only been confirmed further south in the Laurentian Channel (Colpron et al., 2010). Shrimp fishers of southwestern Newfoundland have been reported to specifically target areas containing sea pen meadows as they correlate to high shrimp catches (Colpron et al., 2010). The destruction of sea pens by shrimp trawling is a concern as sea pens are an ecologically important habitat forming species that may have a specialized role in the larval survival of several fish (Baillon et al., 2012).

There is also concern regarding the indirect effects of bottom trawling on commercial groundfish and shellfish catches. Bottom trawling has been shown to reduce the complexity of the benthos by flattening substrate and removing upright epibenthic organisms. Reduced habitat complexity is thought to have negative implications for juvenile fish survivorship (Auster et al., 1996; Schwinghamer et al., 1996; NRC, 2002). In addition, the reduction in benthic biomass caused by trawling related mortalities may lead to decreased food availability for commercial species (Linnane et al., 2000). In Newfoundland and Labrador this is particularly concerning due to depleted groundfish stocks and the possibility of poor juvenile survivorship and reduced prey abundance acting synergistically to hinder stock recovery.

Some snow crab (*Chinoecetes opilio*) fishers on the northeast coast of Newfoundland and southern Labrador (NAFO Division 2J) are concerned over the impacts of shrimp trawling on the valuable crab resource (Newfoundland and Labrador, 2001b; Mullowney et al., 2012). The snow crab and northern shrimp fisheries overlap both spatially and temporally. In particular, they claim trawling activities increase crab leg loss and mortality (Gilkinson et al., 2006; Mullowney et al., 2012). However, poor handling practices in the snow crab fishery can also result in high limb loss and mortality of both undersized and soft-shelled crab discards (Miller, 1977; Dufour et al., 1997; Grant, 2003). Although there has been no scientific evidence to suggest that shrimp trawling has a significant negative impact on snow crab populations (Newfoundland and Labrador, 2001b; Dawe et al., 2007), a recent high-profile study was conducted to document the nature of interactions between snow crab and the footgear of shrimp trawls (Nguyen et al., 2013). That work builds on the previous work of Dawe et al. (2007) and is expected to lead toward improved trawl designs with reduced impact on crab resources.

The effects of trawling on soft bottom habitat and associated communities are related to the sensitivity of the benthic fauna, natural disturbance regime, water depth as well as the frequency and duration of trawling activity. Relatively shallow, high energy regions that experience annual or decadal scale natural physical impacts such as hurricanes are generally found to be resistant to the effects of trawling because the benthic organisms that occur there have become adapted to the local natural disturbance regimes. Generally deep water (> 200 m), soft bottom habitats are thought to receive less natural physical disturbance. However, natural biologically induced changes in benthic community structure over periods of 3-5 years have been documented in deep (280-350 m) soft bottom areas (Josefson, 1981). Several studies investigating the impacts of bottom contact gear on benthic biodiversity and community structure have been conducted in the past 2-3 decades and conclusions from reviews of these studies are that the understanding of fishing related impacts on soft bottom habitats is still only rudimentary (Løkkeborg, 2005).

The development of a low impact shrimp trawl would have many benefits for local fishers. Developing a low impact trawl before any mandates are put in place, allows shrimp fishers to become familiar with and learn how to most effectively handle the gear. Fishers in the Newfoundland and Labrador region will also be better prepared for future gear restrictions which will minimize potential economic loss associated with lost fishing time due to changing gear type. This preparedness will give the trawl manufacturing industry in the region and shrimp harvesters a competitive edge over other regions and nations. For example, local fishers and producers will be able to market their catch as being harvested by a low impact shrimp trawl which could provide access to emerging markets and result in a higher price being received for their catch. Further, use of low impact fishing gear will help the region's northern shrimp fishery in gaining Marine Stewardship Council (MSC) re-certification. Some shrimp fishers are part of multi-species enterprises, where other species are fished in addition to shrimp, such as groundfish and snow crab. By using a low impact bottom trawl, fishers would reduce their physical footprint on a habitat which is shared among all commercially exploited species, during some part of their life cycle. This could increase regional ecosystem productivity as well as job security for local fishers. Non-profit and scientific organizations have expressed a need for the development of low impact fishing gears (Løkkeborg, 2005; Gilkinson et al., 2006; Gascoigne and Willsteed, 2009). Economic incentives for fishers listed above may aid in promoting voluntary implementation by industry in the absence of regulatory enforcement.

The development of gear modifications to reduce the physical impact of shrimp trawling on the seabed is not a new concept. Many researchers have developed and tested novel trawls which aim to reduce the total contact area of the trawl on the seabed and/or reduce the downward pressure of the trawl on the seabed (e.g., DeLouche and Legge, 2004; He, 2007; Valdemarsen et al., 2007; He and Winger, 2010). Despite these developments, no low impact trawls have been produced which would effectively work at a commercial scale for the Newfoundland and Labrador inshore northern shrimp fishery. A successful low impact trawl must not only reduce seabed impacts, but it must be user-friendly for fishers and where possible have economic incentives to be successfully implemented (Valdemarsen and Suuronen, 2003). Ultimately the goal of this project was to determine the commercial viability of a new low impact shrimp bottom trawl through comparative at-sea fishing trials with a traditional trawl.

The novel gear developed for this project has modified footgear to reduce total contact area with the seabed compared to the traditional trawl. The footgear of the trawl is 'aligned' as the rubber discs in the footgear are aligned to be parallel with the direction of tow (Fig. 2.1). This was achieved by boring the centre holes of the discs diagonally rather than concentrically with customized angles depending on their position within the trawl footgear. These modifications allow the physical footprint of the trawl to be reduced as the narrow side of the disc is facing the direction of tow, rather than the blunt side as is the case in the wing section of the traditional trawl footgear. In addition, the number of discs in the footgear is also reduced compared to the traditional gear, further reducing the physical footprint of the aligned trawl on the seabed.

The objective of this project is to determine whether the aligned footgear affects shrimp catch or bycatch when compared to traditional footgear. This was achieved through comparative at-sea fishing trials with the aligned and traditional trawls where the only difference between the two trawls is the footgear. Economically important target and bycatch parameter comparisons were made between trawls. This included shrimp catch rate, counts, mean carapace length and length frequency distribution. In addition, measures of bycatch were calculated including; mean total length, length frequency distribution and percentage of the total catch comprised of individual bycatch species. The null hypotheses were the aligned and traditional trawl are not different in terms of; (i) shrimp catch rate or (ii) size, (iii) the percent of total catch made up of the most abundant bycatch species, as well as (iv) the sizes of these major bycatch species captured.

2.3 Materials and Methods

Gear

The trawl design used for the experimental and control trawls was the 4 seam, Vónin 2007-1570 shrimp trawl (Fig. 2.2). The trawls were equipped with 3.4 m^2 Injector Sparrow steel trawl doors made by Injector Door Limited™ and high density polyethylene Nordmøre grids. The Vónin 2007-1570 shrimp trawl was used as the control (traditional), and the same design was used for the experimental (aligned) trawl but with modified footgear. The experimental trawl was designed to be low impact through the reduction of contact area of the footgear with the seabed compared to the control trawl. This was accomplished by changing the alignment of the footgear rubber discs (Fig. 2.3) as well as reducing the total number of these discs. The rubber discs in the footgear of the control trawl varied in their orientation, with the blunt side often up to 70 degrees out of alignment with the direction of tow, while the experimental trawl had all discs facing with their narrow side parallel to the direction of tow (Fig. 2.1). The number of discs was reduced from 66 in the control trawl to 38 in the experimental trawl. The control trawl consisted of discs with 12"(30.5 cm) and 14"(35.6 cm) diameters, while the experimental trawl discs were 14" and 16"(40.6 cm). The width of all rubber discs was approximately 56 mm. The ability to align all discs with the direction of tow required diagonally positioned centre holes, custom cut at individual angles depending upon their relative position within the footgear and attaching the footgear to the fishing line by a series of toggles rather than with a typical travel chain as in the control trawl. Toggles and travel chains are trawl components used to attach the footgear to the fishing line. Toggle chains are set perpendicular from the fishing line, where as a travel chain is positioned parallel to the fishing line and can be manufactured with wire or chain (Fig. 2.3). As a result of these modifications, the distance from the centre of the footgear rubber disc to the fishing line of the experimental trawl was 20 cm greater than the control trawl. The physical footprint of the experimental trawl on the seabed was reduced by reducing the total contact area of the footgear with the seabed. With all discs in alignment with the direction of tow, it was thought that the curved discs would slide over the sediment, rather than a more destructive ploughing effect thought to be caused by discs out of alignment with the direction of tow.

Flume tank tests

Scaled engineering models of the experimental and control trawls were tested in the flume tank at the Fisheries and Marine Institute of Memorial University of Newfoundland in St. John's, Newfoundland, as per Winger et al. (2006). First, 1:8 scale models were tested then 1:4 scale models. Flume tank testing demonstrated the trawls were similar in net geometry but the experimental trawl had a 39% reduction in contact area with the bottom compared to the control trawl, with no presumed differences in pressure (G. Legge, unpublished data, January 2012).

Trawl quality control

Quality control was performed on the full-scale experimental and control trawls prior to sea-trials to ensure that the trawls were similar with the exception of the footgear. This included; measuring 60 meshes per panel with an ICES standard spring-loaded gauge, counting meshes, producing a full description of each trawl with all associated components such as ropes, floats and weights, net drawing as well as a rigging plan. For full detailed protocol, consult DFO (1998).

Sea-trials

Sea-trials were carried out between 29 August and 7 September 2012 off Port au Choix, Newfoundland, on traditional fishing grounds, at depths ranging from 129-149 m (Fig. 2.4). In total, 40 tows or 20 paired tows were completed in 6 fishing days. The F/V "Newfie Pride", a 19.8 m (65′) inshore shrimp trawler based out of Anchor Point, NL, was used for all comparative fishing trials. All tows were 15 min in duration and towing speed was 2.3 knots. The towing speed used for experimental sea-trials was standard for the shrimp industry; however tow duration is typically 2-3 hr (H. Delouche, personal communication, March 15, 2013).

Comparative fishing using the alternate tow method was employed to compare catches among trawls. The alternate tow method alternately hauls an experimental gear and a control gear, where the hauls are made as close as possible to each other in both time and space (DFO, 1998). The gears were identical except for the modified footgear being tested. All tows were conducted during the daylight period at least 1 hr after sunrise and concluded at least 1 hr before sunset. Time between paired tows ranged from 20 to 42 min. A maximum distance of 400 m between paired tows was chosen to ensure similar habitat was fished (Hannah et al., 2005). Paired tows were fished in the same direction, either with or against the tide. Towing order followed the ABBA, or BAAB protocol, where A is the control trawl and B is the experimental trawl (DeAlteris and Castro, 1991). This protocol was used to eliminate time of day effect (He and Balanzo, 2012). The port and starboard towing side of the second tow in relation to the first tow was alternated to reduce side effects.

Acoustic net mensuration equipment including a combination of E-Sonar™ and Netmind™ technology was used to record measurements of trawl net geometry during sea-trials. Net geometry parameters measured were door spread (m), wingspread (m) and headline height (m). Door spread was recorded in order to ensure proper upright alignment of the doors. Wingspread and headline height were recorded throughout each tow as they are important parameters for determining catch rates.

Catch sampling and analysis

The shrimp catch and incidentally captured fish species were sorted and measured after each tow. Bycatch species were counted and body lengths (± 1 cm) were measured for an arbitrary sample of 55 individuals of each fish species. Published length-weight regressions were used to estimate biomass for the most abundant bycatch species (Bowering and Stansbury, 1984; Hubutubise, 1993).

The shrimp catch was apportioned among 20 L baskets and weighed (± 1 kg). A 750 ml sub-sample of shrimp was removed from the first five 20 L baskets. Sub-sampled shrimp were separated into broken and non-broken individuals. Non-broken individuals were counted and measured for carapace length (CL ± 0.01mm) using a digital caliper. Carapace length was defined as the measurement between the posterior margin of the eyestalk and the posterior mid-dorsal edge of the carapace (Hansen and Aschan, 2000). All sub-samples of shrimp were taken back to the laboratory and weighed individually (± 0.01 g) to obtain count data from non-broken shrimp.

Comparative fishing data were analyzed using independent samples *t*-tests or the Mann Whitney U test as described below. Length frequency distributions were analyzed using independent samples Kolmogrov-Smirnov (K-S) tests. Software used to conduct statistical tests was SPSS® 17.0.0 (SPSS, 2008).

Shrimp

To determine if there were differences between trawl types in terms of shrimp catch rate (kg/min), an independent samples *t*-test was used. To determine if there were differences between trawl types in terms of the size of shrimp caught, three tests were used; (i) an independent samples *t*-test to compare shrimp counts (number/kg), (ii) a Mann Whitney U test to compare mean shrimp carapace length (mm) as these data violated the assumption of normal distribution required for parametric tests, and (iii) a K-S test to compare carapace length distributions. A Bonferronii correction was applied to the probability level for tests analyzing shrimp size (n=3, p=0.016) to reduce the experiment-wise type one error rate.

Bycatch

Bycatch species were split into major and minor species (Table 2.1, Appendix 1 and 2) based on prevalence, where major species were captured consistently by both trawls and minor species were captured sporadically and in low abundance. Major bycatch species were included in statistical analysis, however minor bycatch species were considered to be negligible and not analyzed.

To determine if there were differences in catch rates of major bycatch species, independent samples *t*-tests were used to compare the percent of catch composed of capelin and turbot of the total catch between trawl types (Appendix 3 and 4). All proportion data were arcsine transformed, a standard statistical procedure which consists of taking the arcsine of the square root of the proportion (Sokal and Rohlf, 1995). Bycatch rates of the total catch were used rather than amounts to account for any differences that may have existed between trawls in terms of spreading capacities which would affect total area fished. To determine if there were differences between trawl types in terms of the size of major bycatch species captured, two tests were used for each species; (i) an independent samples *t*-test to compare total mean length (cm) and (ii) the K-S test to compare length frequency distributions. A Bonferronii correction was applied to the probability level for tests analyzing capelin and turbot size (n=2, p=0.025) to reduce the experiment-wise type one error rate.

Trawl geometry data

Trawl geometry data, including wingspread and headline height were compared between paired tows using independent samples *t*-tests. A Bonferronii correction was applied to the probability level for tests analyzing wingspread (n=4, p=0.0125) and headline height (n=2, p=0.025) to reduce the experiment-wise type one error rate.

2.4 Results

Trawl quality control

Mean mesh size of the control and experimental trawls were calculated for all 36 panels of the trawl net (Table 2.2). The percent difference in mesh size between trawl types ranged from 0.07%-4.71%, with a mean of 1.00%. It is highly unlikely that the minor percent differences between mesh sizes influenced catches of targeted and non-targeted species. Various measurements of the Nordmøre grid, headline length, fishing line length and footgear length were similar between trawl types (Table 2.3). The distance from the centre of the footgear rubber disc to the fishing line were over the minimum requirement of 71 cm for the inshore shrimp fishery (Newfoundland and Labrador, 2001a) for both the experimental (108 cm) and control trawls (88 cm) (Table 2.3).

Shrimp catch

The experimental trawl out fished the control trawl in 17 of 20 paired tows, representing a 23% increase in mean shrimp catch rate (Fig. 2.5). The difference between trawls in shrimp catch rate was statistically significant (Table 2.4). Shrimp carapace length or counts did not differ significantly between trawls (Table 2.4). The total weight of sub-sampled shrimp per tow ranged from 1.65 to 2.41 kg for the experimental trawl, and 0.83 to 2.52 kg for the control trawl. Size distribution of shrimp did not differ significantly ($z = 0.047$, $p = 1.00$) between trawls (Fig. 2.6). On average, shrimp made up 99% of total catch biomass for both the experimental and control trawls.

Bycatch

The major bycatch species; capelin and turbot (Fig. 2.7), comprised 93.1% and 92.8% of the total number of animals captured incidentally by the control (Appendix 1) and experimental trawls (Appendix 2), respectively. Capelin and turbot accounted for 0.16% to 2.20% (mean = 0.72%, s.e. = 0.12) of the total catch weight for the control trawl. For the experimental trawl, capelin and turbot accounted for 0.28% to 2.94% of the total catch weight (mean = 0.98%, s.e. = 0.15).

Turbot

The experimental trawl captured significantly more turbot in relation to the total catch compared to the control trawl in 15 of 20 paired tows, by an average of 76.7% (Table 2.5, Fig. 2.8). Mean body length of turbot (Table 2.5), or length frequency distribution (Fig. 2.9) was not significantly different between trawl types (z =1.248, p = 0.089).

Capelin

Percent of total catch comprised of capelin (Fig. 2.9) did not differ significantly between trawl types (Table 2.6); however the experimental trawl captured on average, 33.8% less capelin than the control trawl. Mean body length (Table 2.6) or length frequency distribution of capelin caught did not differ significantly between trawl types (z = 0.555, p = 0.918) (Fig. 2.10).

Trawl geometry data

Trawl sensors mounted on the upper wings and headline produced only intermittent data, where some tows rendered no data measurements and others gave several hundred measurements. For tows where measurements were recorded, the number of measurements obtained per tow ranged from 1 to 147 for wingspread and from 5 to 304 for headline height (Appendix 5). The control trawl obtained 958 measurements (mean/tow = 47.9, s.e. = 45.62) for wingspread and 4441 (mean/tow = 222.05, s.e. =

90.09) measurements for headline height. The experimental trawl obtained 657 measurements (mean/tow = 32.85, s.e. = 41.33) for wingspread and 717(mean/tow = 35.85, s.e. = 43.13) measurements for headline height.

In an attempt to correct for the great variability in n values between tows, an arbitrary requirement of including only those paired tows which obtained at least 25% of the maximum number of measurements recorded for that parameter was deemed necessary for analysis. There were four paired tows for wingspread, and two paired tows for headline height which passed the arbitrary data requirement and were analyzed statistically to test the null hypotheses; wingspread or headline height are not different between trawl types.

Wingspread

Mean wingspread and standard error was calculated for tows that passed the arbitrary data requirement (Table 2.7). Percent difference was calculated between mean wingspreads of each tow in a pair. Independent samples *t*-tests between paired tows demonstrated that wingspread was significantly different between trawl types in two out of four paired tows (Table 2.7). In all four paired tows, the experimental trawl had a greater mean wingspread than the control trawl.

Headline height

Mean headline height and standard error was calculated for tows that passed the arbitrary data requirement (Table 2.8). Percent difference was calculated between the mean headline heights of each tow in a pair. Independent samples *t*-tests between paired tows demonstrated that headline height was significantly different between trawl types in one of the two paired tows (Table 2.8). In both paired tows, the control trawl had a greater mean headline height than the control trawl.

2.5 Discussion

The results of the study revealed that the aligned trawl captured significantly more shrimp than the traditional trawl, without affecting the size of the shrimp captured. The size of major bycatch species captured was not significantly different between trawl types. However, the experimental trawl caught significantly more turbot than the control trawl. Mean capelin catch rate was lower with the experimental trawl but not significantly different between trawl types. Overall the results of this study indicate that the aligned trawl represents a good first step towards the development of a low impact shrimp trawl for the inshore Newfoundland and Labrador fishery as it does not negatively affect commercial catches. Before the commercialization of the aligned trawl it will be necessary to conduct industry scale sea-trials with appropriate monitoring tools to understand the cause(s) of the increases in turbot catch, and then apply modifications to neutralize the effect once it becomes known.

This study demonstrated that the aligned trawl had significantly higher catches of both shrimp and turbot compared to the traditional trawl. This was an unexpected result as the trawls were the same in all aspects with the exception of the modified footgear demonstrated by a thorough quality control, and it was predicted that the modified footgear would not affect catches. Shrimp do not herd, are unable to sustain an escape response and are generally found to be in higher volumes closer to the seabed during the daylight period (Eayrs, 2005; DeLouche et al., 2006). Shrimp catch rates generally increase with an increase in area fished as well as with a reduction in the height of the fishing line off the seabed (Hannah et al., 1996). Thus, an increase in area fished (Hannah and Jones, 2000) or reduction in fishing line height may explain why the aligned trawl had higher shrimp catch rates compared to the traditional trawl.

Exploring potential sources for the increased turbot catches of the aligned trawl is a much more difficult task than is exploring potential sources for increased shrimp catch due to the complex behaviour of flatfish, their ability to be herded and increased swimming capacity which allows them to actively escape capture. As we collected no video footage that could aid in the ability to determine the cause of the increased catches of turbot in the aligned trawl, the most parsimonious solution is to explore the potential sources for increased shrimp catch and see if these could also account for increased turbot catches. The most common response of flatfishes to an approaching trawl is an inverted or sideways rolling manoeuvre, keeping very close to the seabed (Bublitz, 1996). Flatfishes tend to stay within 1 m of the seabed when disturbed by an approaching trawl, with an average distance of 35 cm off bottom (Bublitz, 1996). Fishing line height is inversely related to the capture of flatfish species, where an increase in fishing line height will reduce the catch of flatfish and vice versa (Brewer et al., 1996; Weinberg et al., 2002; Hannah and Jones, 2003; Winger et al., 2010). Thus, an increase in area fished or reduction in fishing line height would also affect turbot catches and may explain why the aligned trawl had higher catch rates of both shrimp and turbot compared to the traditional trawl.

Trawl geometry was monitored over the course of the experiment using an acoustic net mensuration system. This system consists of sensors, receivers and hydrophones that work together to collect acoustic data on trawl geometry for post trawl analysis. The sensors gave measurements for door spread, wingspread and headline height. Wingspread can be used to estimate the horizontal spread of the trawl and headline height can be used to estimate the vertical spread. When these estimates are used together, total area fished can be calculated. The wingspread of the trawl would affect shrimp and turbot catching efficiency, however increases in headline height would most likely have no effect on catches as shrimp and turbot are benthic species, most commonly found in bottom sediments or close to the seabed (Bublitz, 1996; Eayrs, 2005; DeLouche et al., 2006). Due to technical difficulties with the sensors producing intermittent data or none at all (Appendix 1), the ability to use the trawl geometry data for any type of comparison or analysis was greatly reduced due to the high variability in the number of measurements obtained between tows and trawl types, reducing sample size.

Although the number of trawl geometry measurements obtained was highly variable between tows and trawl types, the variability within a tow was quite low (Table

2.7 and 2.10). From the four paired tows which passed the arbitrary data requirement for wingspread, two of these tows were significantly different between trawl types, and in all four paired tows, the aligned trawl had a greater mean wingspread (Table 2.7). One of the two paired tows for headline height demonstrated a significant difference between trawl types, and in both pairs the control trawl had a greater mean headline height (Table 2.8). Godø and Engås (1989) have demonstrated that wingspread and headline height have an inverse linear relationship, where an increase in wingspread leads to a decrease in headline height. Although the data from this study are sparse, they do seem to support this relationship, where the aligned trawl had a greater wingspread but lower headline height than the traditional trawl. Whether the difference in spread is biologically significant, and could explain the differences in catch observed between trawl types cannot be determined within this study. A greater sample size of reliable trawl geometry data is required through further sea-trials to determine differences between the horizontal and vertical spreads of the aligned and traditional trawls confidently.

It would make sense that a trawl with increased horizontal spread and deceased vertical spread would capture more benthic species such as shrimp and turbot, and fewer pelagic species such as capelin (DFO, 2011). Although the aligned trawl had on average 33.8% reduced capelin catches compared to the traditional trawl, there was no statistical difference between trawl types. Further sea-trials are recommended to better understand the relationship between trawl geometry and catch rates.

An alternative solution in explaining the increases in shrimp and turbot catch by the aligned trawl compared to the traditional trawl is a lowered fishing line. To determine the height of the fishing line above the seabed, an inclinometer is an effective tool; see Hannah and Jones (2003) for full description of this device. No such device was used in this study, thus it was not possible to explore the hypothesis that the aligned trawl had a lowered fishing line and fished closer to the seabed causing increased shrimp and turbot catches compared to the traditional trawl. To be able to test the hypothesis that the aligned trawl has a lower fishing line than the traditional trawl, an inclinometer would be required to determine fishing line height in future comparative sea-trials.

The minimum toggle chain length established for the inshore shrimp trawling fleet in Newfoundland and Labrador is 71 cm to minimize flatfish bycatch (Newfoundland and Labrador, 2001a). However *in situ*, toggle chains can be slack, or become wrapped around the footgear, reducing their effective length (T. Perry, personal communication, June 3, 2013). Although the aligned trawl had toggle chains 20 cm longer than the traditional trawl, it is possible that *in situ* the aligned trawl had toggle chains with a shorter effective length compared to the traditional trawl, causing the trawl to fish closer to the seabed. There are differences between the traditional and aligned trawl with respect to their attachment of rubber discs in the footgear to the fishing line. In the traditional gear, the rubber discs attach to the fishing line through a typical travel chain, however the rubber discs of the aligned trawl are attached through a series of toggles. Without this travel chain, the rubber discs of the aligned trawl are more rigidly fastened to the toggles which may increase their tendency to roll forward, bringing the fishing line closer to the seabed. Video footage as well as the use of an inclinometer will be necessary to test this hypothesis during future sea-trials with the aligned trawl.

Turbot are an important commercial species in the Northwest Atlantic region and have been fished in Newfoundland and Labrador since the mid 1880s. After the collapse of many major groundfish stocks in the 1990s they composed the largest groundfish fishery (Bowering and Brodie, 1995). Data collected from research vessel surveys generating biomass and abundance estimates have shown a general declining trend in turbot abundance since the 1980's, as well as a decline in older larger cohorts (Bowering et al., 1995; Bowering and Brodie, 1995). Recruitment has also been a concern over the last number of years, with no strong year classes being produced (DFO, 2010). Size of fish caught by both trawls combined ranged from 6-32 cm, all below the legal limit of 44 cm (DFO, 2010). These fish are considered 1-2 year old recruits. Turbot bycatch in the Gulf of St. Lawrence shrimp trawl fishery is usually 3 kg or less per tow when observers are present, ranging from 1–7% of total catch (DFO, 2010b. Although accurate weights were not collected for this project, using a length-weight regression developed by Bowering and Stansbury (1984) demonstrated that on average 0.53% of total catch was turbot for the aligned trawl and 0.30% for the traditional trawl. Both trawl averages are below the commercial range (1-7%) calculated by DFO (2010). The cause of the low turbot catches demonstrated in this study is unknown; however it most likely is a product of local juvenile turbot abundance which may have been low in the study area. Although overall turbot catches were low in this study, the aligned trawl caught significantly more turbot than the traditional trawl, and if this trawl was fished in an area of high turbot abundance, representing 7% of the total catch, the current study suggests the aligned trawl would yield turbot catches representing 12% the total catch. The increase in turbot catches by the aligned trawl is not acceptable due to the importance of this species commercially and the additional costs it would cause for fishers including; increased fuel consumption, increased sorting time and possibly less valuable shrimp catches caused by crushing and damage during sorting.

The ability of the aligned trawl to reduce its physical footprint on the seabed could be increased with a higher shrimp catch rate. The aligned trawl has reduced contact area with the seabed by 39% and with its higher shrimp catch rate, fishing effort may be reduced, reducing the total area of seabed impacted. Reduced fishing effort could act as a driving incentive for fishers to use the aligned trawl, as less time at sea would be required to catch quotas. As discussed however, the increases in shrimp and turbot catch could be related, thus modifications to reduce turbot catches may also reduce shrimp catches. Therefore, until the increases in turbot catch are understood, it is unknown whether the increases in shrimp catch will remain once the aligned trawl is modified to reduce turbot catches. Nevertheless, even without significant increases in shrimp catch rate; the aligned trawl would have many incentives for its use and fill the void for a low impact trawl choice in the Newfoundland and Labrador northern shrimp inshore fishery.

2.5.1 Limitations to Approach

Industry scale tow duration for the inshore northern shrimp fishery ranges from 2-3 hr (H. Delouche, personal communication, March 15, 2013) however the tow duration chosen for this experiment was 15 min as it was considered to be the most efficient (Godø et al., 1990). By using shorter tows, more tows can be conducted increasing sample size.

Fish or shrimp size is not affected by tow duration and catch composition of short (i.e. 30 min) and long tows (i.e. 165 min) are similar (Wassenberg et al., 1998; Wieland and Storr-Paulsen, 2006). Wieland and Storr-Paulsen (2006) demonstrated that for northern shrimp and turbot, biomass densities or numerical densities did not differ between 30 and 15 min tows. However, there is some evidence that fish and invertebrate catch rates are higher at shorter tow durations (Godø et al., 1990; Wassenberg et al., 1998). Despite greater nominal catch rates that can be found with shorter trawl durations, our study compared catch rates between treatments with no intention of estimating commercial catch rates. Based on previous studies, using 15 min tows was valid for our study as it is the most efficient and does not affect the size or species composition of catch, and although catch rates may be higher, they were compared relatively. It can be reasonably assumed that the results of this study are likely to be mirrored by commercial scale tows for the inshore Newfoundland and Labrador shrimp fishery; however *in situ* testing will be required to know for certain.

The basis for calling the aligned trawl a low impact trawl was strictly dependant on flume tank testing. No actual field sampling or monitoring was conducted to compare the contact area or pressure exerted between the aligned trawl and traditional trawl. Although the science and engineering of flume tank testing is well developed (Winger et al., 2006), its ability to estimate full-scale performance at-sea is only predictive and can sometimes be difficult (Fiorentini et al., 2004). Due to time and financial constraints, physical monitoring of the seabed pre- and post- trawling for both trawls was not possible in the current study, however before commercialization of this product and marketing it as low impact, evaluations of the aligned trawl's interaction with the seabed *in situ* is strongly recommended.

Scientifically sound experiments which study seabed impacts of trawling tend to be labour intensive, expensive and time consuming. Due to the lack of resources available for these types of studies, using cameras attached to the trawl which will allow observation of the footgear and its physical interaction with the seabed may be sufficient to determine if the aligned trawl behaves how it was predicted by flume tank testing. This camera work could be piggy backed to future commercial testing of the aligned trawl by fishers.

2.6 Conclusion

The purpose of this experiment was to test the aligned shrimp trawl at sea in comparison to the traditional trawl to determine if differences existed in catch efficiency or catch composition that could introduce negative effects to shrimp fishers by using the aligned trawl. This included quantifying shrimp catch parameters such as shrimp catch rate and size, as well as the amount and size of bycatch species captured. The aligned trawl demonstrated mixed results. It had significantly higher catches of shrimp and turbot, no significant effect on capelin, while presumably reducing the physical footprint of the trawl on the seabed compared to the traditional trawl. Increased turbot bycatch is a concern as turbot are a commercially important species that were in decline during the early 1990's and increasing juvenile mortality of this vulnerable species by shrimp trawling could have negative effects on ecosystem sustainability (Bowering et al., 1995; Bowering and Brodie, 1995). This research represents a first step towards the development of a low impact trawl for the northern shrimp Newfoundland and Labrador inshore fishery. It demonstrated that a low impact trawl can be effectively used without compromising commercial catch rates. Further comparative sea-trials with industry-scale tow durations using video footage and inclinometers are recommended as a next step towards commercial development of the aligned trawl.

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2.8 Tables

Table 2.1. Species captured incidentally during the shrimp trawl experiment.

Major		
	capelin	*Mallotus villosus*
	turbot	*Reinhardtius hippoglossoides*
Minor		
	Atlantic herring	*Clupea harengus*
	American plaice	*Hippoglossoides platessoides*
	redfish	*Sebastes* spp.
	sandlance	*Ammodytes* spp.
	lanternfish	*Ceratoscopelus maderensis*
	witch flounder	*Glyptocephalus cynoglossus*
	eelpout	*Zoarces* spp.
	alligator fish	*Aspidophoroides monopterygius*
	snakeblenny	*Lumpenus lampretaeformis*
	mud star	*Ctenodiscus crispatus*
	sea pen	*Pennatula aculeata*

Table 2.2. Mean mesh size (mm) per panel with standard error for the experimental and control trawls. The percent differences between mesh size means are also reported.

	Control		Experimental		
Panel	Mean	S.E.	Mean	S.E.	% difference
Top Wing Starboard	92.30	0.19	91.50	0.17	0.87
Top Wing Port	92.13	0.15	91.58	0.14	0.60
Top Bunt Wing Starboard	46.10	0.12	45.48	0.13	1.36
Top Bunt Wing Port	45.47	0.14	45.75	0.13	0.61
1st Upper Belly	45.82	0.12	45.45	0.13	0.81
2nd Upper Belly	45.87	0.12	45.83	0.14	0.09
3rd Upper Belly	45.43	0.17	45.15	0.15	0.62
4th Upper Belly	44.70	0.11	45.08	0.12	0.84
Side Panel 1 Starboard	44.98	0.18	45.18	0.12	0.44
Side Panel 1 Port	46.23	0.13	45.68	0.17	1.20
Side Panel 2 Starboard	45.17	0.14	45.68	0.13	1.12
Side Panel 2 Port	45.80	0.12	46.35	0.14	1.19
Side Panel 3 Starboard	45.52	0.14	45.98	0.10	1.00
Side Panel 3 Port	45.57	0.15	45.63	0.13	0.13
Side Panel 4 Starboard	44.63	0.12	45.47	0.10	1.85
Side Panel 4 Port	44.88	0.15	45.05	0.17	0.38
Side Panel 5 Starboard	45.57	0.12	46.05	0.15	1.04
Side Panel 5 Port	45.57	0.10	45.32	0.15	0.55
Side Panel 6 Starboard	43.78	0.13	44.12	0.16	0.77
Side Panel 6 Port	44.68	0.11	44.58	0.10	0.22
Lower Wing Starboard	91.88	0.13	91.55	0.16	0.36
Lower Wing Port	91.68	0.15	92.12	0.17	0.48
Lower Bunt Wing Starboard	45.65	0.11	45.72	0.15	0.15
Lower Bunt Wing Port	45.98	0.13	45.55	0.13	0.94
1st Lower Belly	43.47	0.11	43.13	0.15	0.79
2nd Lower Belly	45.13	0.11	46.03	0.10	1.96
3rd Lower Belly	45.15	0.16	46.02	0.12	1.89
4th Lower Belly	44.80	0.13	44.67	0.14	0.29
Lengthening Piece Top	43.48	0.18	42.62	0.24	2.02
Lengthening Piece Bottom	43.07	0.17	45.20	0.20	4.71
Grid Section Top	44.08	0.20	44.53	0.17	1.01
Grid Section Bottom	43.13	0.18	42.88	0.16	0.58
Extension Top	41.98	0.17	42.65	0.15	1.57
Extension Bottom	42.50	0.17	42.53	0.12	0.07
Codend Top	42.45	0.16	43.72	0.16	2.90
Codend Bottom	43.42	0.15	43.67	0.15	0.57

Table 2.3. Summary of the trawl quality control measurements conducted with the experimental and control trawls.

	Measurement	
Trawl parameter	Experimental	Control
Nordmøre grid		
length (m)	1.23	1.27
width (m)	1.01	1.04
thickness (mm)	23.80	26.13
mean distance between 2 bars (mm)	21.05	21.49
Length of the headline (m)	33.65	33.14
Length of the fishing line (m)	32.84	32.84
Length of footgear (m)	32.9	32.9
Distance between footgear and fishing line (cm)	108	88

Table 2.4. Results of statistical analysis are illustrated for shrimp catch rate (kg/min), counts (number/kg) and mean carapace length (mm) of the control and experimental trawls. Significant p-values are indicated by *.

Shrimp				Statistical analysis		
	trawl	mean	S.E.	d.f	*t*-stat	p-value
Catch rate	Control	8.28	0.49	38	2.881	0.006*
	Exp.	10.19	0.45			
Counts	Control	225.9	2.2	94	0.824	0.412
	Exp.	257.1	8.8			
Carapace length	Control	17.5	0.03	-	-	0.660
	Exp.	17.5	0.03			

Table 2.5. Summary of turbot catches by trawl type including mean length (cm) and percentage of total catch comprised of turbot. Significant p-values are indicated by *.

Turbot				Statistical analysis		
	trawl	mean	S.E.	d.f	*t*-stat	p-value
% of total catch	Control	0.30	0.065	38	2.105	0.042*
	Exp.	0.53	0.097			
Length	Control	17.75	0.470	360	1.816	0.070
	Exp.	18.85	0.370			

Table 2.6. Summary of capelin catches by trawl type including; mean length (cm) and percentage of total catch comprised of capelin. Significant p-values are indicated by *.

Capelin				Statistical analysis		
	trawl	mean	S.E.	d.f	*t*-stat	p-value
% of total catch	Control	0.37	0.07	38	1.624	0.113
	Exp.	0.25	0.04			
Length	Control	12.83	9.54	1,239	0.650	0.516
	Exp.	12.87	10.11			

Table 2.7. Mean wingspread, n value and standard error for paired tows that passed the arbitrary data requirement. The percent difference between average wingspreads for each paired tow is demonstrated. Results of statistical analyses are shown, with significant p-values indicated by *.

	Control trawl			Experimental trawl				Statistical analysis		
Pair #	Wingspread mean	n	S.E.	Wingspread mean	n	S.E.	% difference	d.f	*t*-stat	p-value
3	19.39	147	1.03	19.58	47	0.76	0.98	102.99	1.309	0.194
4	19.74	120	0.85	20.02	47	0.75	1.42	165.00	1.986	0.049
7	20.35	124	0.85	21.61	75	0.92	6.19	197.00	9.819	<0.001*
8	21.05	79	1.00	22.06	45	1.18	4.80	122.00	5.024	<0.001*
Overall mean	20.01			20.91			3.35			
Overall s.e.	0.97			0.98						

Table 2.8. Mean headline height, n value and standard error for paired tows that passed the arbitrary data requirement. The percent difference between average headline heights for each paired tow is demonstrated. Results of statistical analyses are shown, with significant p-values indicated by *.

	Control trawl			Experimental trawl				Statistical analysis		
Pair #	Headline mean	n	S.E.	Headline mean	n	S.E.	% difference	d.f	*t*-stat	p-value
1	4.88	279	0.021	4.82	184	0.027	1.24	461.00	1.677	0.094
20	5.50	268	0.021	4.92	103	0.028	11.79	220.22	16.646	<0.001*
Overall mean	5.18			4.86			6.52			
Overall s.e.	0.38			0.34						

2.9 Figures

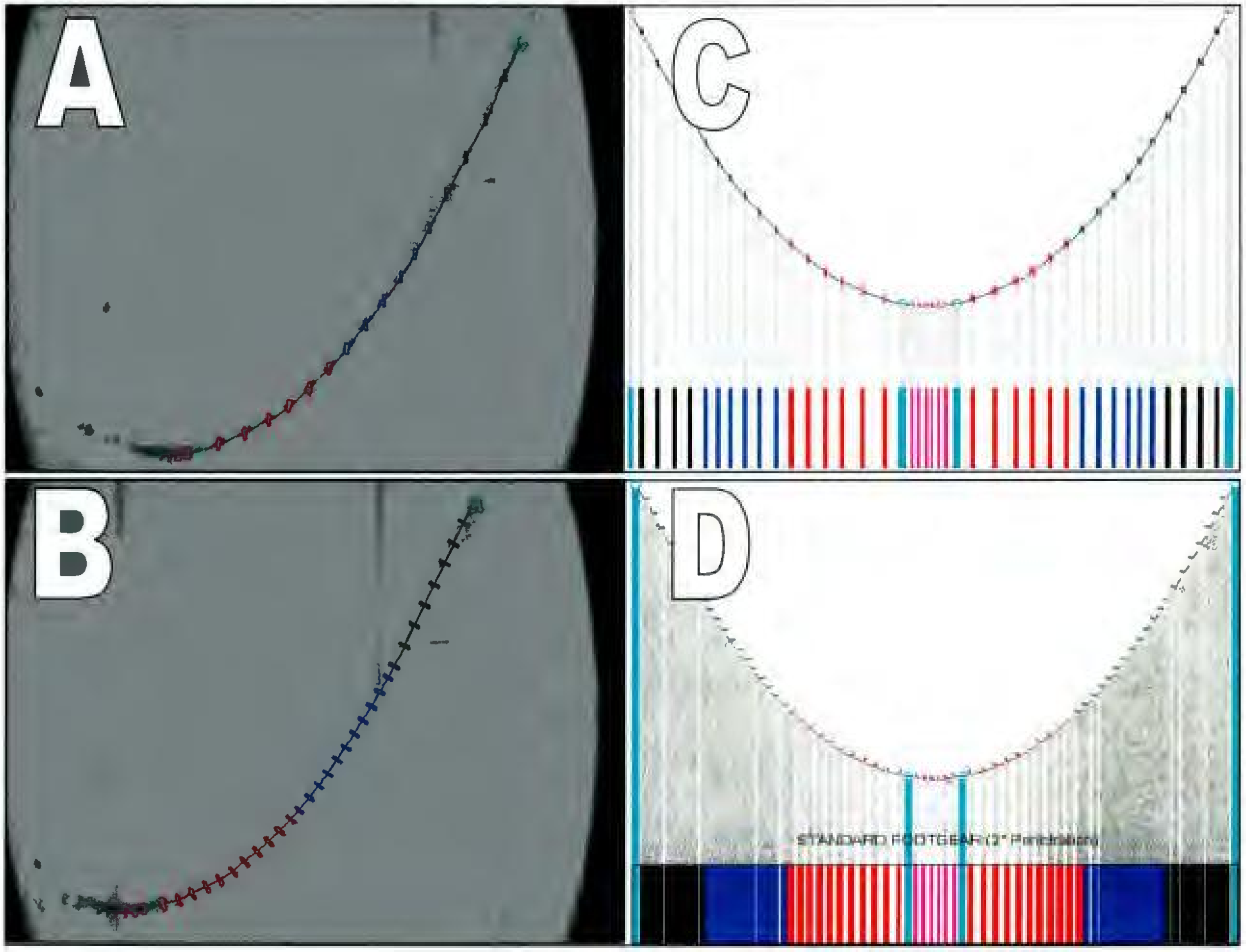

Figure 2.1. Photograph of the spatial positioning of the footgear rubber discs in the experimental (A) and control (B) trawls, as well as the modeled two inch penetration pathways for each trawl type (C and D) (Legge, 2012). Colours indicate different sections of the trawl and are consistent between the photograph and modeled pathways.

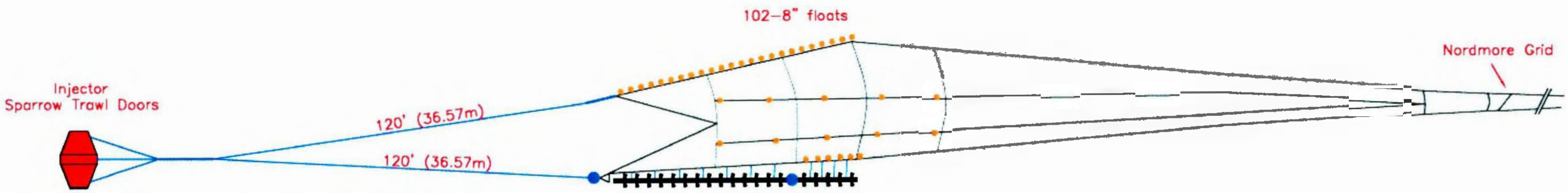

Figure 2.2. Profile drawing of the Vónin 2007-1570 shrimp trawl. The same design is used for both the experimental and control trawls (DeLouche, 2013).

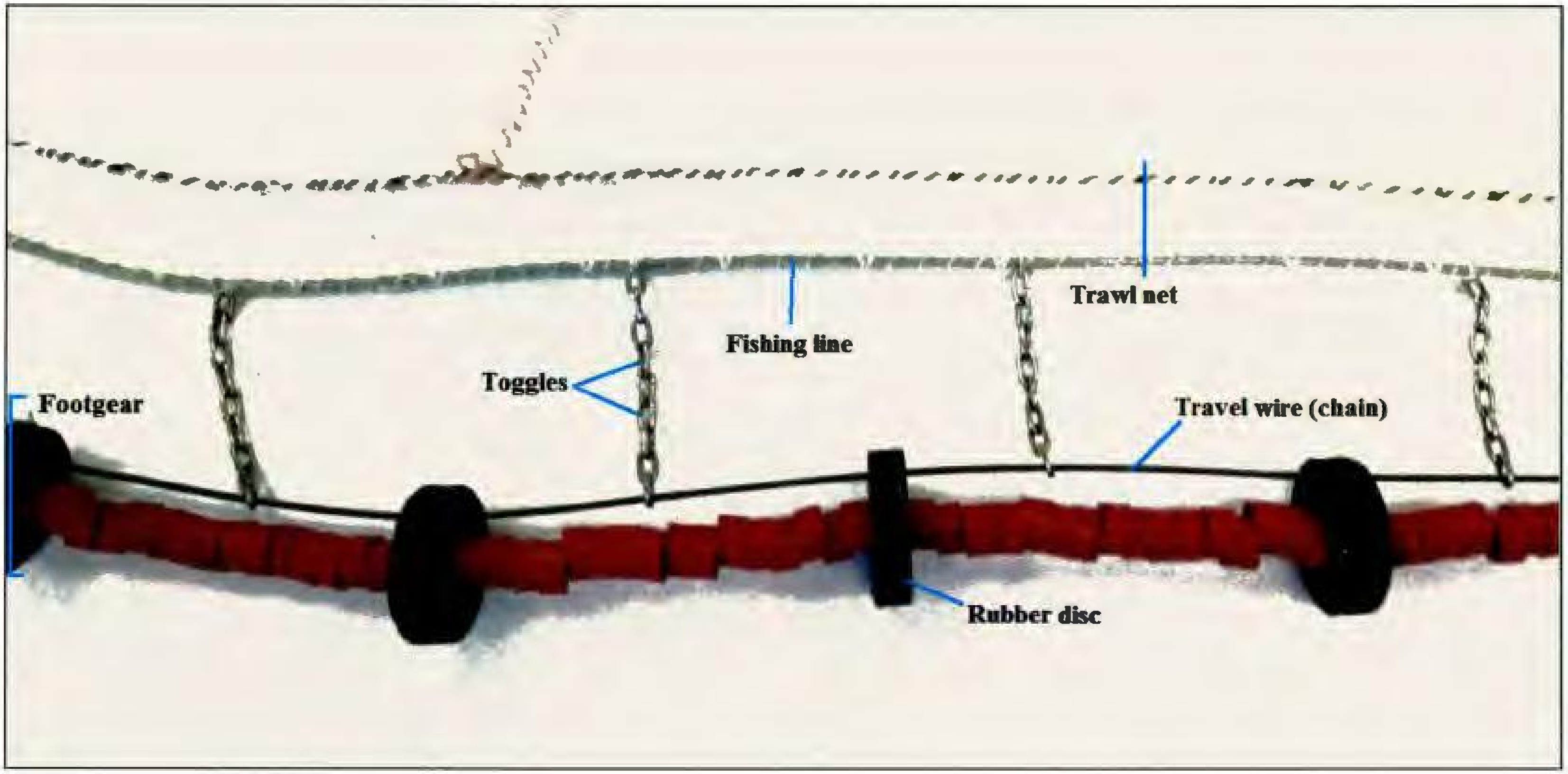

Figure 2.3. Trawl model with gear components indicated.

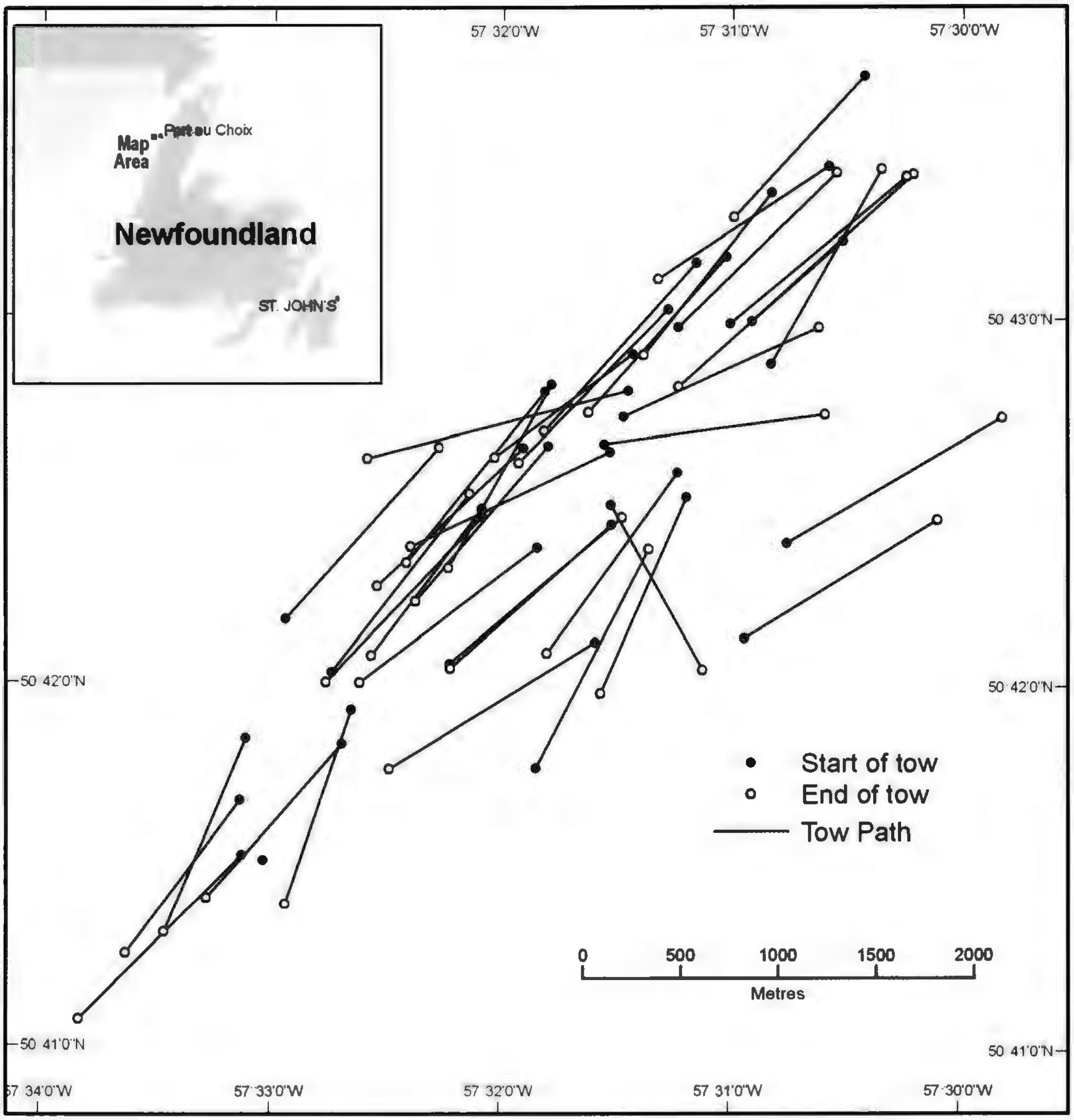

Figure 2.4. Location of experimental fishing transects in the northern Gulf of St. Lawrence.

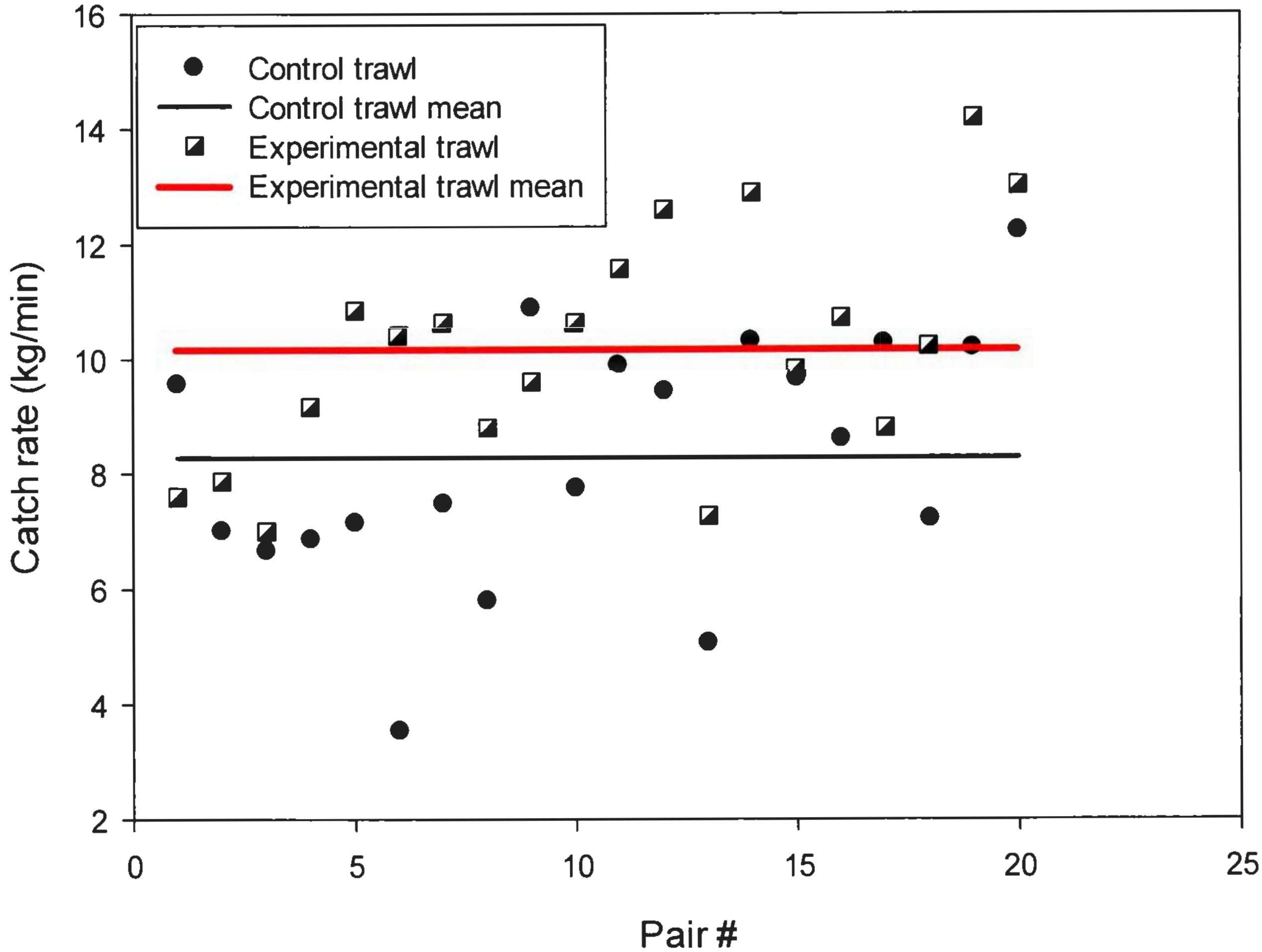

Figure 2.5. Catch rates (kg min^{-1}) of shrimp for the experimental and control trawls during the 20 paired tows, with mean line for each trawl type.

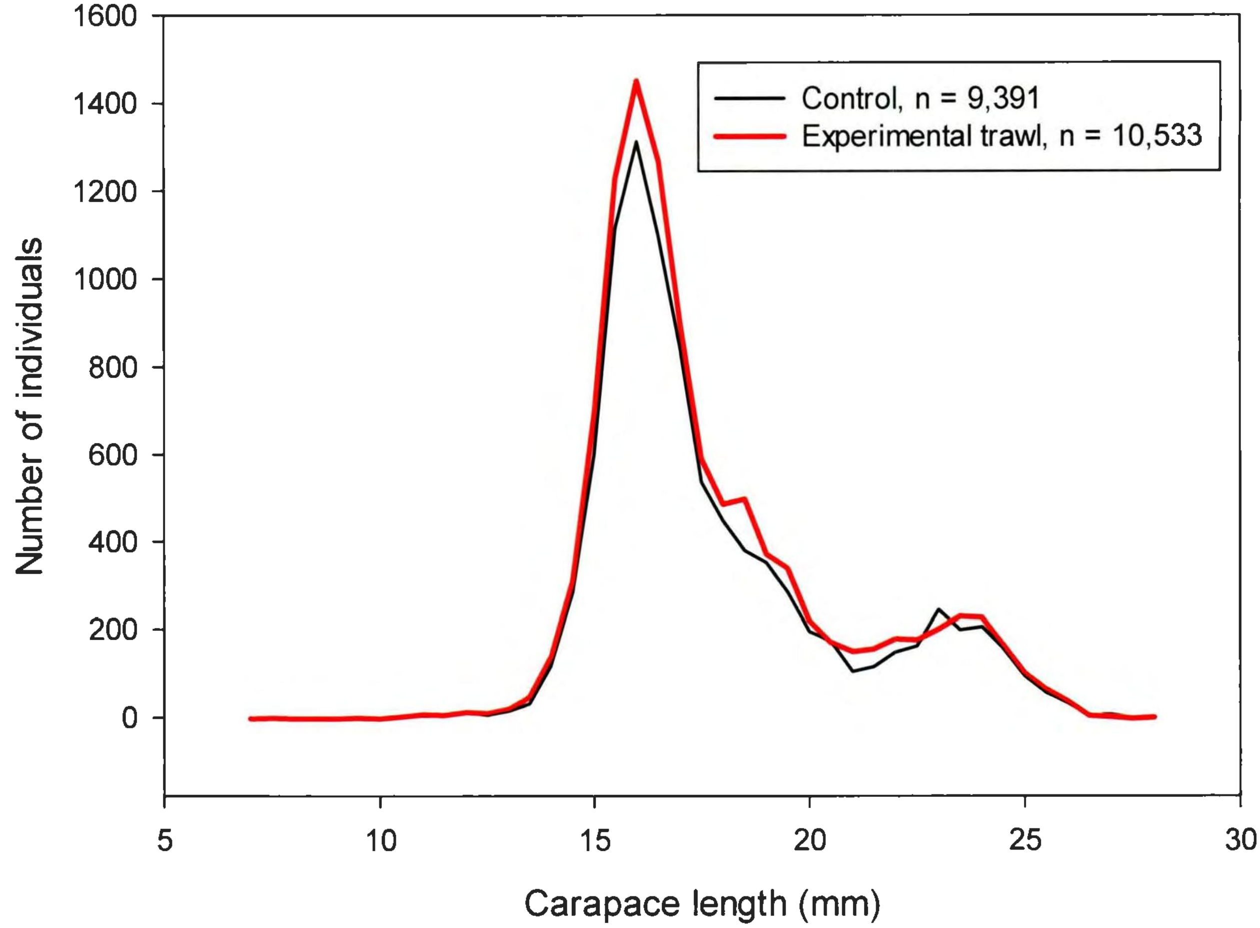

Figure 2.6. Northern shrimp carapace length distributions for the control and experimental trawls. Total number of shrimp measured (n) is also shown.

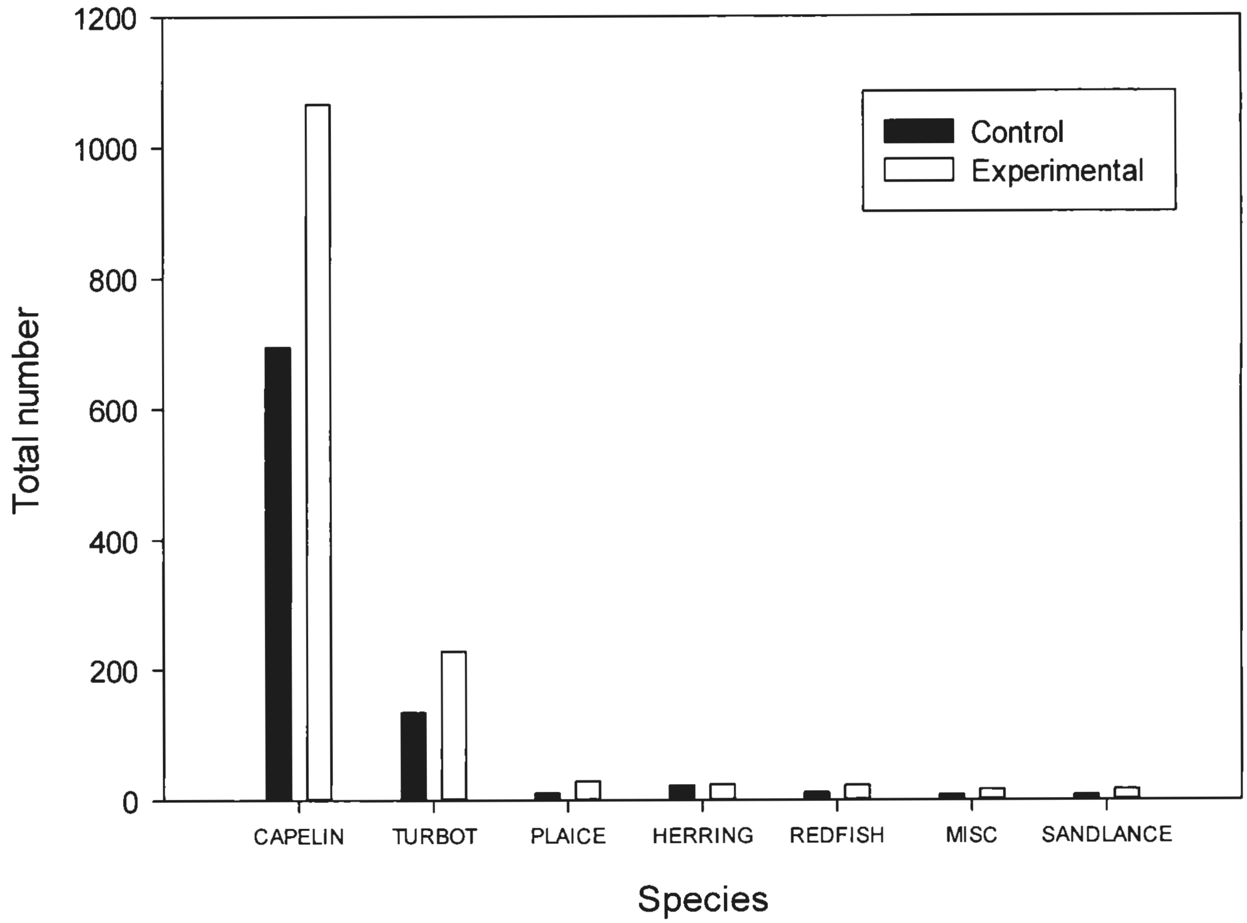

Figure 2.7. Total of number of animals captured incidentally by the control and experimental trawls during 20 paired tows. Species include; capelin, turbot, American plaice, Atlantic herring, redfish, miscellaneous species and sandlance. Miscellaneous species include; witch flounder, eelpout, alligator fish, snakeblenny, mud star and sea pen.

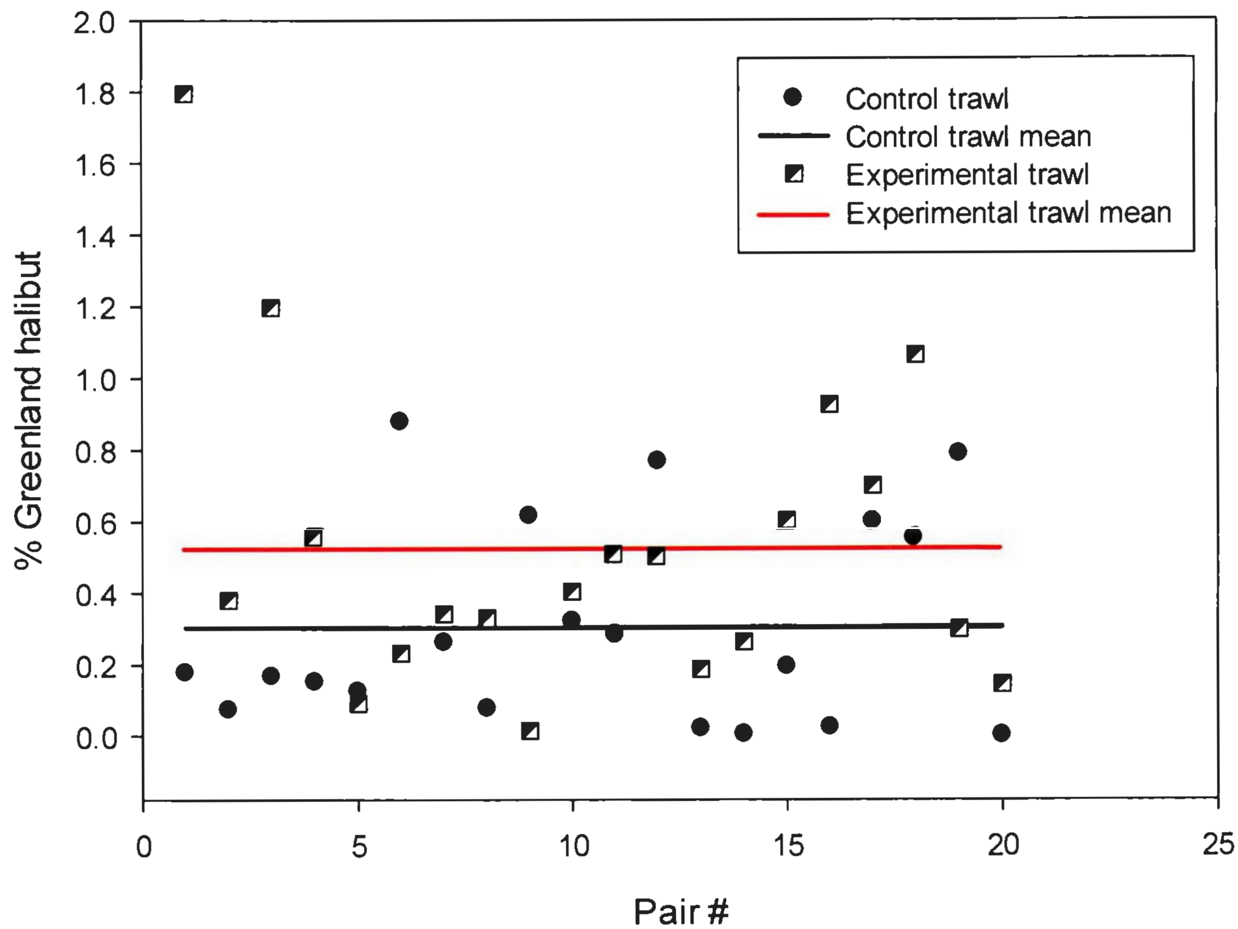

Figure 2.8. Percent contribution of turbot to the total catch by the control and experimental trawls during 20 paired tows, with mean line for each trawl type.

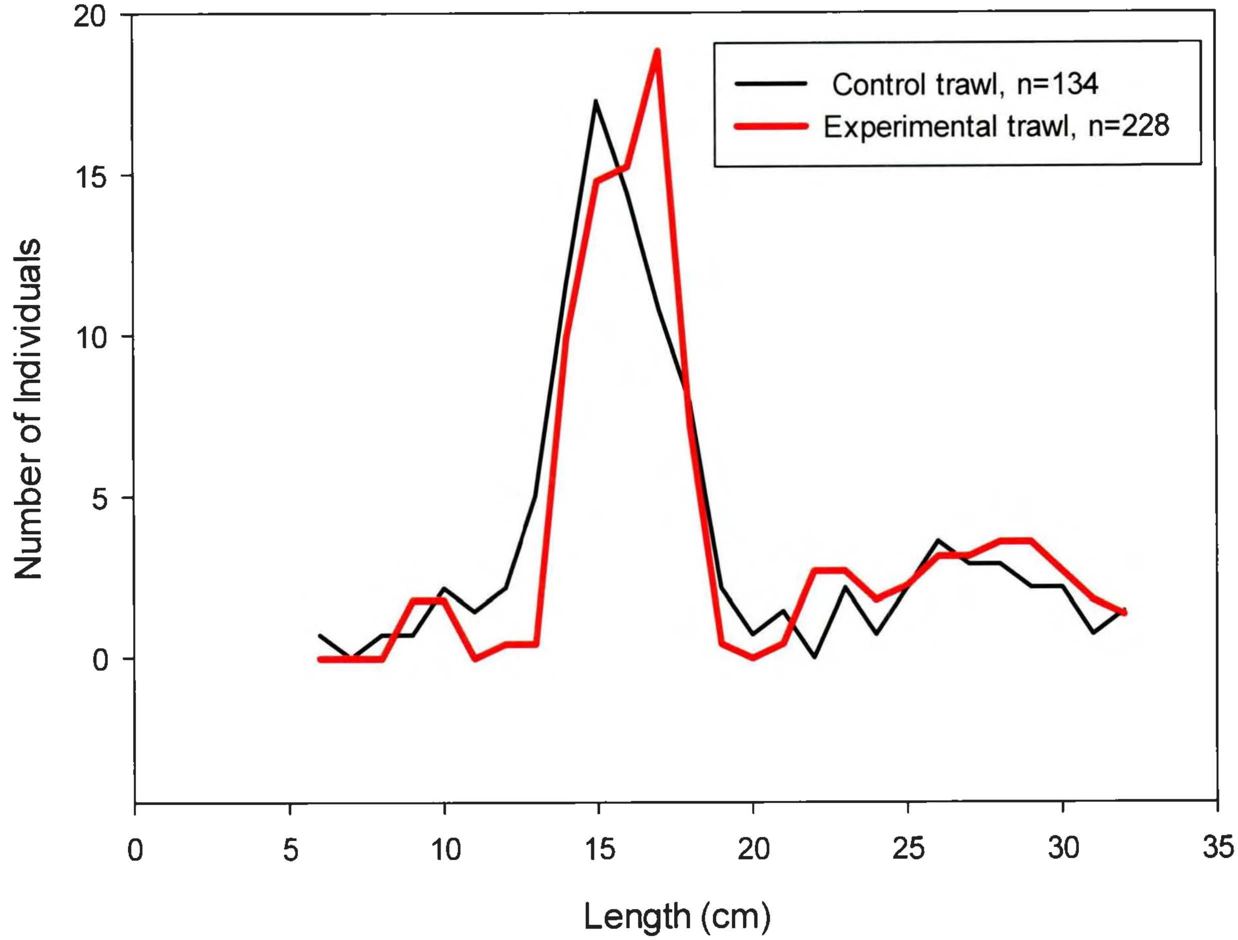

Figure 2.9. Turbot length distributions for the control and experimental trawls. Total number of turbot measured (n) is also shown.

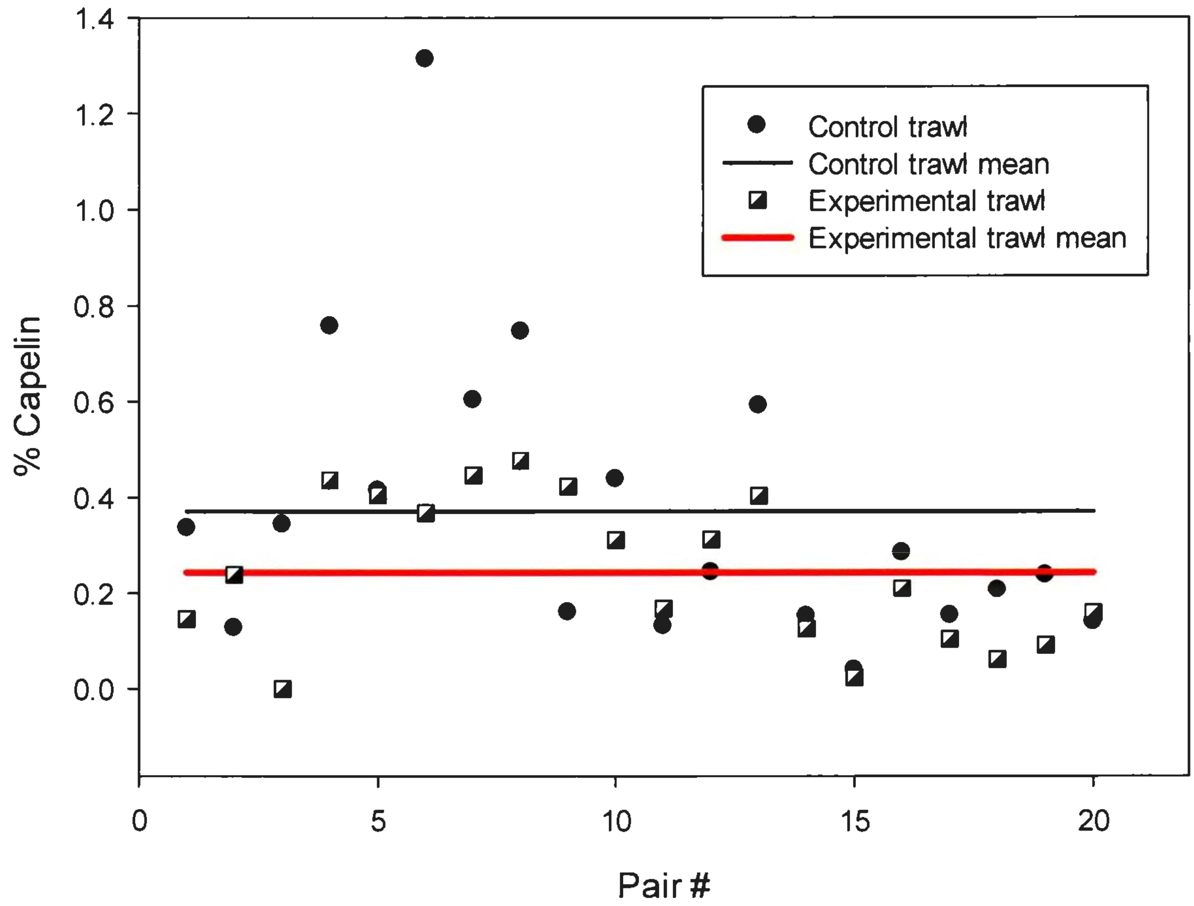

Figure 2.10. Percent contribution of capelin to the total catch by the control and experimental trawls during 20 paired tows, with mean line for each trawl type.

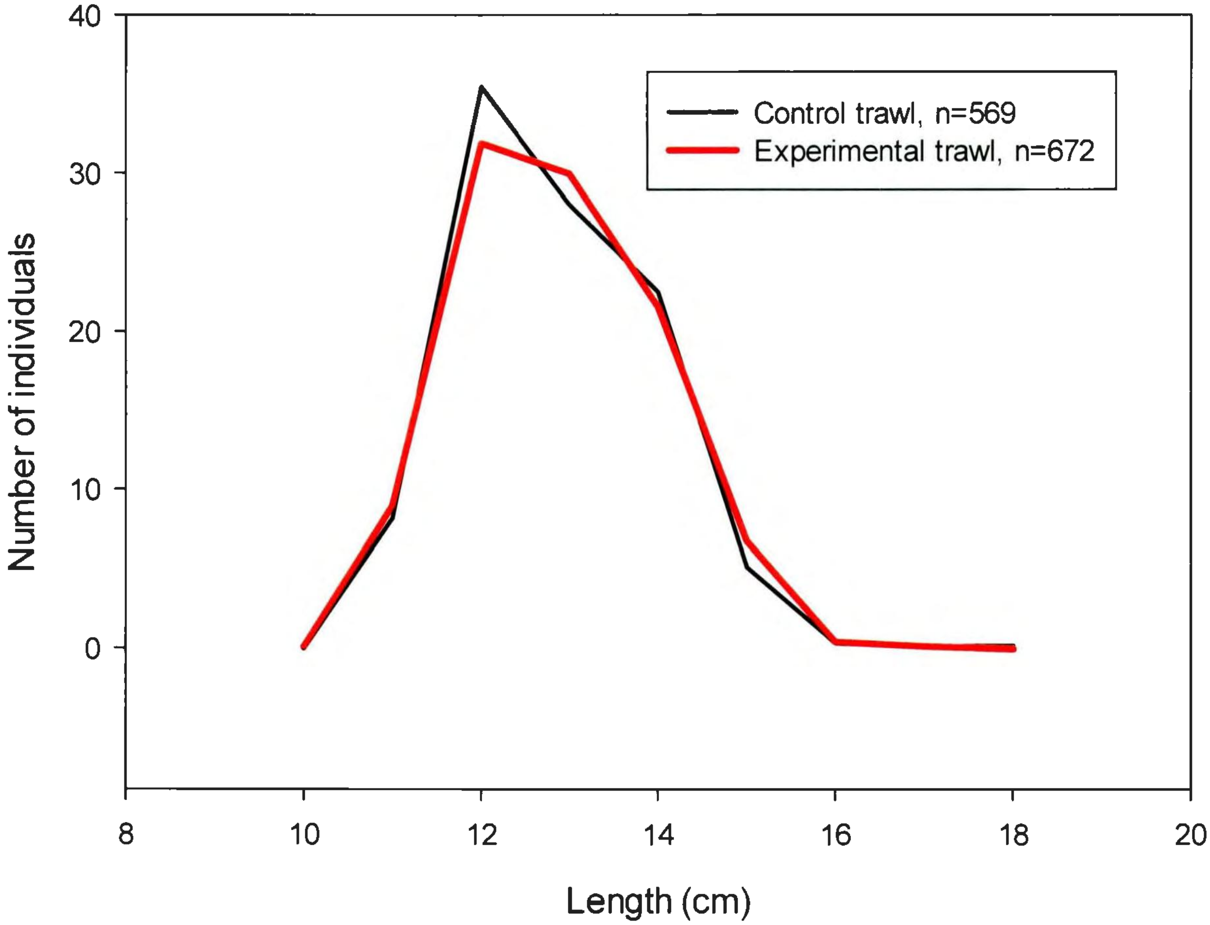

Figure 2.11. Capelin length distributions for the control and experimental trawls. Total number of capelin measured (n) is also shown.

CHAPTER 3: TESTING MODIFIED GANGIONS TO REDUCE GREENLAND SHARK BYCATCH IN THE CUMBERLAND SOUND TURBOT LONGLINE FISHERY

Crew member of the M/V Nuliajuk and Pangnirtung resident, Levi Ishulutaq holding a turbot caught during experimental fishing trials in the summer of 2012.

3.1 Abstract

To develop a sustainable and economically viable open water Greenland halibut (aka turbot; *Reinhardtius hippoglossoides*) fishery in the Cumberland Sound, it is important to find a way to reduce Greenland shark (*Somniosus microcephalus*) bycatch. The objective of this study was to test modifications to turbot longline gear to reduce Greenland shark bycatch without affecting turbot catches or individual body size when compared to traditional gear. Experimental longline fishing was conducted with modified gangions from that of the traditional gangion. Gangions are leaders attached perpendicularly to the mainline that contain a baited hook on the terminal end. Twelve sets of 400 hooks were fished with each set containing 100 hooks of each treatment; 200 lb multifilament braided nylon (traditional), 200 lb monofilament, 100 lb monofilament and 50 lb monofilament. Each hook was assigned a catch label upon haul back describing hook condition or catch. Monofilament gangions captured significantly fewer sharks than the traditional gangion but turbot catch rates and body size did not differ significantly between treatments. Higher frequencies (number/100 hooks) of hook loss were demonstrated for all monofilament gangions compared to the traditional multifilament gangion. The 200 lb monofilament gangion is recommended for turbot longline fishing in Arctic communities as it significantly decreases shark catch rates compared to the traditional gangion and has improved operational efficiency compared to the other monofilament treatments tested. Overall this study suggests the bycatch of Greenland shark can be significantly reduced by changing from the traditional 200 lb braided nylon gangion to monofilament gangions without any negative effects on turbot catch rates.

3.2 Introduction

The Cumberland Sound is an inlet located on the southeastern side of Baffin Island in Nunavut, Canada. The only settlement in the Sound is the community of Pangnirtung. The people of Pangnirtung have traditionally sustained themselves by fishing Arctic char and hunting marine mammals (Pike and Mathias, 1995). More recently, fishing for turbot (*Reinhardtius hippoglossoides*) has represented an alternative form of game and income through commercial fishing. In the winter of 1986 a small-scale fishery was developed and in 1994 the quota of this winter fishery was set at 500 t (DFO, 2008a) and has remained unchanged. Landings peaked in 1992 with 430 t harvested, however since then landings have fluctuated greatly, dipping as low as 3 t in 2007 (Fig. 3.1).

The highly variable success rate of the Cumberland Sound winter turbot fishery since around 1995 is due to variable ice conditions and unpredictable winter storms which have led to low fisher participation (DFO, 2008b; Dennard et al., 2010). Turbot migrate from relatively shallow waters to deeper depths as they grow and mature, thus the best fishing grounds are in the deepest waters located in the centre of Cumberland Sound (Dennard et al., 2010; Nunavut, 2010). Due to climate warming, some years have had poor ice formation and led to fishers having limited or no access to deep water fishing grounds. Harsher than normal winter storms have led to landfast ice breaking up sooner than usual (DFO, 2008b) leading to a reduction in the length of the fishery season due to unsafe conditions. Harsh winter storms have also led to substantial gear loss and damages. In 1996, a particularly fierce and sudden storm resulted in 20 of the 30 fishers losing a significant amount of gear (DFO, 2008b; Dennard et al., 2010). The synergistic effects of these environmental factors have led to low fishery participation and landings, with only 0.6 % of the quota being harvested in 2007 and of 115 fishers active in the mid-1990's, no more than 10 participated in the winter of 2008 (DFO, 2008a; DFO, 2008b). Although the winter of 2012 was a more successful year for the fishery, a more consistent and reliable method to access the turbot resource is necessary. The fishery provides employment opportunities and is an important component of the local economy. In 1993, the turbot fishery was valued at $750,000 and employed about 130 people seasonally as either fishers or plant workers (Pike and Mathias, 1995). It provides an alternative to traditional Inuit fisheries, as well as increasing food security which can be a great challenge in isolated Arctic communities like Pangnirtung.

A summer fishery has been proposed to supplement the winter fishery, using vessels instead of fishing through the ice. A summer fishery would operate during the open water season, generally from mid-July to mid-October (DFO, 2008a). Although this alternative shows promise, experimental longlining in Cumberland Sound during the summer has demonstrated catch rates of Greenland shark (*Somniosus microcephalus*) are much higher than in the winter fishery, and often outweigh turbot catches (Nunavut, 2010). This is thought to be caused by a shift in Greenland shark primary foraging location between seasons. In the winter the primary prey is seals, thus sharks are found closer to the surface (Bigelow and Schroeder, 1953) patrolling seal breathing holes in the ice. In the summer its thought that the shark shifts to more demersal feeding (Bigelow and Schroeder, 1953) where the primary prey is fish, including turbot (Yano et al., 2007). The consequence of this is a direct overlap between turbot fishing gear and shark habitat, which leads to increased interactions of sharks with fishing gear.

Greenland shark bycatch has a number of costs to fishers. Sharks can depredate hooks, removing bait and reducing turbot catch rates. When hooked sharks become entangled in the gear (most often around their caudal peduncle); fishers lose time associated with releasing the shark, lose turbot catch as the entangled hooks are no longer available to catch the target species, lose time disentangling the gear and may accrue gear damages or loss. Shark mortality caused by the turbot fishery is either a result of severe entanglements or cannibalism of hooked sharks (Borucinska et al., 1998; Nunavut 2010). It is estimated that 50% of hooked Greenland shark are released alive (Nunavut, 2010). Finding a way to reduce Greenland shark bycatch is important as it will reduce costs for fishers, Greenland shark mortalities and help ensure a sustainable and economically viable summer turbot fishery in Cumberland Sound.

Sharks, skates and rays are cartilaginous fish of the subclass Elasmobranchii (Musick et al., 2000). Elasmobranches tend to be more vulnerable to overexploitation due to their life history characteristics in comparison to commercially fished teleost species (Musick et al., 2000). Sharks are often apex predators with few predators and low natural mortality rates (Stevens et al., 2000). They possess a reproductive strategy which includes the characteristics of slow growth, long life span, low reproductive potential and late sexually maturity. Having a low intrinsic rate of increase, depleted shark populations are slow to recover, often in the range of decades (Stevens et al., 2000). Mortality associated with fishing activities has resulted in large population declines of several shark species.

Currently, 67 species of elasmobranches are considered critically endangered or endangered by the International Union for the Conservation of Nature (IUCN, 2011). Large population declines of these top predators have the potential to critically alter marine ecosystem structure. Top predators play a vital role in maintaining controls on ecosystem structure, functioning and diversity (Baum et al., 2003). With the elimination of top predators like sharks, detrimental cascading effects could ensue (Stevens et al., 2000). Sharks have a long evolutionary history and their intrinsic biodiversity provides cause for the preservation of this group (Dulvy et al., 2008).

Threats to shark species include; directed fishing, bycatch mortality (Stevens et al., 2000; Dulvy et al., 2008), marine pollution (Seitz and Poulakis, 2006) and habitat destruction (Knip et al., 2010). Bycatch is defined as the incidental capture of non-targeted species as well as undesirable size or under aged individuals of target species (FAO, 2010). Bycatch can be sold or simply discarded at sea. Bycatch mortality is one of the leading causes of shark population declines (Cosandey-Godin and Morgan, 2011). At best, sharks captured as bycatch are released alive without harmful effects, however many sharks die as a result of encounters with fishing gears. Fishing gears that sharks interact with include; longlines, purse seines, gillnets, and trawls. Vulnerability to fishing related mortality depends on the particular shark species, fishing gear involved, and the length of time the shark is entangled, hooked or exposed to air before being released.

The Greenland shark is a member of the family *Somniosidae* (sleeper sharks) known to be found in the North Atlantic and Arctic oceans (MacNeil et al., 2012). It is the only shark that can tolerate polar temperatures year round and is the largest fish found in these regions. Its ability to tolerate very cold temperatures and a broad depth range, results in a wide range distribution. Greenland shark have been identified from the intertidal zone to abyssal depths of 2,647 m in the Gulf of Mexico which attests to the potentially wide habitat range (Benz et al., 2007). The Greenland shark can reach a total length of up to 5-7 m and weight of 1,020 kg (Bigelow and Schroeder, 1953). Greenland sharks exhibit sexual dimorphism and the females typically grow to a larger size than the males (Yano et al., 2007). The Greenland shark is an opportunistic feeder which preys and scavenges upon a great diversity of animals. Most frequently it feeds on teleost fishes (especially turbot) and marine mammals (Fisk et al., 2002; Yano et al., 2007; MacNeil et al., 2012). Cephalopods and crustaceans appear to be important prey items for smaller sharks. Little direct research has been conducted on this species due to a lack of commercial interest and the remoteness of its habitat. Despite the lack of knowledge of population trends, the International Union for the Conservation of Nature has listed the Greenland shark as near threatened due to its vulnerability to overfishing (IUCN, 2011). Species classified as near threatened are considered likely to meet a threatened threshold in the near future.

A number of methods have been attempted to reduce shark bycatch or reduce the danger of line-based fishing operations to shark species (e.g., Erickson et al., 2000; Kerstetter and Graves, 2006; Gilman et al., 2007; Kaimmer and Stoner, 2008; Ward et al., 2008). These include using alternate gear types, gear modifications and altered fishing strategies. Alternate gear types that are used to harvest turbot include gillnetting and trawling. Examples of gear modifications include changing hook type, gangion material, and bait type. Altered fishing strategies include; fishing season, location, depth and reduced soak-time. Before discussing of these methods, I will give a brief overview of longline fishing and gear components as a basic understanding of these topics is necessary to understand bycatch mitigation techniques.

Longlining is a passive fishing method, where the gear is stationary and captures are a result of fish moving towards the gear (Bjordal and Løkkeborg, 1996). The ability of longlines to capture fish is based on attraction to bait which is the chemical stimulus that lures fish to the gear to ingest the baited hook (Bjordal and Løkkeborg, 1996; Løkkeberg et al., 2010). The success of capture is based on the ability of the hook to catch and retain the fish until the line is hauled onto the fishing vessel. As the name suggests, there is a longline or mainline which has shorter branch lines called gangions attached perpendicularly. The gangions are spaced at a fixed interval and contain the baited hooks at the terminal end. They are typically attached to the mainline by a swivel which allows the gangion to rotate freely around the mainline, reducing gear entanglements.

There are three main ways to set longlines; bottom, semi-pelagic and pelagic. The Cumberland Sound turbot fishery is a bottom fishery, meaning the lines are set on the seabed. The mainline is manufactured with materials that cause it to sink and remain in contact with the seabed. The mainline is kept in position with the use of anchors. The anchors are attached to long buoy lines which connect to buoys at the ocean surface. These buoys function as markers. Longlines must be baited prior to setting. Baiting can be done by hand or mechanically using baiting machines. In the turbot longline fishery, hand baited longlines are coiled into tubs to store neatly before deployment. Typically there are approximately 200 hooks per tub. After the lines are baited they are deployed into the water. Longlines are left in the ocean for a certain amount of time (soak time) depending on target species, size of the vessel, and number of hooks (Bjordal and Løkkeborg, 1996). Longlines are typically hauled onto the vessel using a power driven wheeled hauler called the gurdy. The gurdy is controlled by a fisher, who lands the fish, clears snarled gangions, and can stop the haul back process if there is a tangle or problem (Skud, 1978a). During haul back fish are removed. Before the longline can be baited and set again, old bait must be removed, broken hooks and gangions must be replaced, and tangles must be removed from the mainline.

Changing gear type is a way to reduce or eliminate the capture of unwanted bycatch. Other ways to harvest turbot include trawling and gillnetting. Changing gear type from longlining to trawling would not be a solution as this fishing method has been known to catch Greenland shark (C. Bourne, personal communication, December 21, 2012) and trawling is banned in the Cumberland Sound (Northlands Consulting, 1994). Gillnetting is not recommended (DFO, 2008a) as it would pose a risk of entanglement for marine mammals, as well as Greenland shark. In addition, it is highly selective for large female turbot, making it unfavourable for fishery sustainability (DFO, 2008a). Longlining is the only appropriate fishing method for the Cumberland Sound turbot fishery as the selectivity range for turbot includes both sexes, a broader size range, and this method poses a lower risk of entanglement for large animals in the Sound (DFO, 2008a).

To reduce the bycatch of sharks or reduce the danger of line-based fishing operations to shark species, gear modifications are often used to increase selectivity without compromising the catch of the targeted species. Changing hook type from circle to J-hooks can result in increased post-capture survival of shark discards (Kerstetter and Graves, 2006). Laboratory studies suggest hooks that incorporate rare earth metals and/or magnetic alloys such as SMART hooks may deter shark predation and thereby reduce captures in longline gears (WWF, 2006; Kaimmer and Stoner, 2008). However, results have been mixed in field trials (Brill et al., 2009, Tallack and Mandelman, 2009; Godin et al., 2013). Changing gangion material or bait type can also increase gear selectivity (Erickson et al., 2000). Changing gangion materials (i.e. from wire to nylon) allows larger animals or those with sharper teeth to avoid capture. This is a particularly good method for reducing bycatch of predatory species such as sharks (Ward et al., 2008; Vega and Licandeo, 2009). Changing bait type takes advantage of species specific prey preference between targeted and non-targeted species (Erickson et al., 2000).

Altered fishing strategies can be a relatively easy way to reduce bycatch if the overlap between target and non-target species is not spatially consistent. Changing the location of fishing grounds in relation to environmental, topographic, and oceanographic features can reduce shark interactions and shark capture rates (Gilman et al., 2007). Adjusting the depth fished has been used to reduce fishing area and to avoid overlapping with shark habitat (Afonso et al., 2011). Reducing soak time reduces the potential length of time a shark remains hooked on the line and can increase the chances of post-capture survival (Carruthers et al., 2011).

Some of the methods outlined above may also reduce the catch of the targeted species, an unfavourable outcome for business minded fishers. Gear modifications or altered fishing strategies are more likely to be successfully implemented in commercial fisheries when they do not reduce the catch of targeted species and have an economic incentive for implementation. There are already many economic incentives to reduce catch rates and entanglements of Greenland shark in the Cumberland Sound turbot fishery, thus the only issue is finding a gear modification or altered fishing strategy that achieves its purpose without compromising turbot catch rates.

The winter fishery for turbot in Cumberland Sound uses circle hooks, multifilament braided nylon gangions, and mainline swivels. SMART hooks have been shown to be ineffective (Grant, 2012). Changing bait type can be a successful bycatch reduction tool (Gilman et al., 2007), however Greenland shark are opportunistic and scavengers that have been documented to eat just about anything (Yano et al., 2007). There is little confidence that changing bait type will be effective in reducing shark catch rates in the Cumberland Sound turbot fishery. Turbot are abundant at the greatest depths in the Sound during the summer (Nunavut, 2010) and a preference by Greenland shark for bottom waters and finfish during the summer (Yano et al., 2007) suggest changing the fishing location would not be beneficial. Further experimental longline fishing and DFO turbot surveys indicate Greenland shark are captured at shallow and deepwater areas throughout the Sound (Nunavut, 2010; K. Hedges, personal communication, August 25, 2012). Reducing soak time is unlikely to be a viable option as it would result in reduced effort and hence reduced catch rates of turbot. It would appear that modifications to the gangion represent the most promising options for reducing bycatch of Greenland shark.

Recent studies have integrated the effects of gangion length (Grant, 2012) but studies on the effect of gangion breaking strength and material are lacking. Greenland shark are on average four times the length of turbot and have 45 times the mass (Bigelow and Schroeder, 1953; DFO, 2008b). By using gangions of reduced breaking strength, the mass of the shark and tension exerted on the gangion during haulback may permit increased gangion breaks and shark escape rate compared to the traditional gangion. The use of monofilament gangions instead of the traditional multifilament gangion may lead to increased shark bite-offs (Berkeley and Campos, 1988; Ward et al., 2008). Many studies have documented the importance of gangion material in terms of shark catch rates (Berkeley and Campos, 1988; Branstetter and Musick, 1993; Bjordal and Løkkeborg, 1996; Stone and Dixon, 2001; Ward et al., 2008; Vega and Licandeo, 2009; Afonso et al., 2012). The combination of reducing gangion breaking strength and changing gangion material may facilitate increased escape rate of hooked sharks, reducing bycatch of Greenland shark.

To test the effect of changing gangion material and breaking strength on Greenland shark and turbot catch rates, longline fishing experiments carried out in Cumberland Sound during Aug - Sep 2012. Catches and hook status were assessed for monofilament gangions of three different breaking strengths and the traditional 200 lb multifilament braided nylon gangion (control). The goal of this research was to reduce fishing related mortalities of the Greenland shark while creating a sustainable and economically viable open water turbot fishery for residents of Pangnirtung. If one of the experimental gangions was found to reduce shark catches and entanglement without compromising turbot catch rates then the next step would be introduce this technology to local fishers in Pangnirtung for verification under commercial conditions.

3.3 Materials and Methods

Gear design and configuration

Four gangion treatments were tested in the experimental turbot longline fishing gear. Treatments included one control and three experimental gangions (Table 3.1). All experimental gangions were manufactured by Momoi®, part of the Hi-Catch brand. Monofilament material is made out of a single fibre of nylon whereas multifilament braided nylon is composed of three or more fibres woven together. All gangions had a 14/0 Mustad® circle hook with a gape size of 15.4 mm attached to the terminal end. Each hook was baited with cut squid (*Illex* sp.), measuring on average 15.2 cm (s.e. = 0.34). The bait length was within the 15-20 cm range used in the Cumberland Sound winter turbot fishery (Pike and Mathias, 1995).

Experimental longline fleets consisted of 400 hooks with alternating treatments every 20 hooks. Pattern of alternation remained consistent through the experiment, in the following order; C-200BN, E3-50M, E1-200M and E2-100M. Every set contained five 20 hook replicates of each treatment. Colour coded line was braided into the mainline before the first hook and after the twentieth hook of each section to allow easy identification of gangion type as the experimental treatments all looked quite similar (Fig. 3.2). The mainline was comprised of 14 mm tarred braided polyester line fitted with Mustad® rotor swivels at 1.8 m (1 fathom) intervals. Gangions were attached to the mainline by swivels spaced at 1.8 m intervals and total length of each longline set was 731.5 m (400 fathom).

Experimental fishing trials

At-sea experimental fishing took place in Cumberland Sound at depths ranging 685-1,278 m from 19 August to 7 September 2012. In total, 12 longline sets were fished in 17 fishing days (Fig. 3.3). Fishing locations were chosen haphazardly within known depth strata. The M/V "*Nuliajuk*", a 19.8 m (65') research vessel owned by the Government of Nunavut was used for all experimental fishing.

Experimental fishing was conducted in order to test the null hypothesis that there is no difference in Greenland shark or turbot catch rates between gangion treatments. Longlines were set at dusk between 1800-2100 hr and hauled the next morning starting at 0700-0900 hrs. For 11 of 12 sets, soak time ranged from 12 hr to over 14 hr; however one set was left for 36 hr (Table 3.2) due to inclement weather. Haul back operations varied in duration, ranging from 3-5 hr.

Catch sampling

To test the null hypothesis, every hook fished was assigned a catch label upon haul back that determined hook condition or identified species captured (Table 3.3). All turbot were measured for total length to the nearest cm, and then released. Body length of

Greenland shark was estimated based on a baseline marker of known length on the hull of the vessel. Three size classes were estimated; < 3 m, 3 - 4 m, and > 4 m. Sharks were sexed based on the presence or absence of claspers. Time to release the shark and to resume fishing was recorded. Number of hooks fouled by Greenland shark, hook location on sharks, and details of entanglement were also noted. Captured sharks were released by severing the gangion(s) as quickly and safely as possible to reduce stress and increase chances of post-capture survival.

Additional data

Research survey longlines were set at the same location as the experimental longlines for an unrelated study assessing turbot population abundance in the Cumberland Sound. The survey longlines were fished in the same manner and data was recorded in the same format as the experimental longlines. The survey longlines used the same type of hooks, mainline and gangion spacing as the experimental longlines. The gangions used in the survey fleet were composed of braided nylon of 360 lb breaking strength. The survey fleet was attached to the experimental longlines by a 10-15 m length of rope.

The data from the survey fleet were incorporated in this study for two reasons. Since the survey fleets fished at the same locations as the experimental longlines, shark captures on the survey fleet could be used to indicate shark presence in the study area when none was captured on the experimental longline. Using these data could help to explain hook losses when no sharks were captured on the experimental longline. Also, gangions used by the survey fleet were multifilament braided nylon, although a higher breaking strength than what was used in the experimental longline. By using the information on time lost due to shark entanglements from the survey fleet, another reference point for multifilament gangions could be utilized when attempting to compare multifilament to the monofilament gangions in terms of time lost due to shark entanglements, or entanglement severity.

Analysis

Catch label frequencies for each treatment were combined by set to give a frequency per 100 hooks. For analysis of effect of treatments on catch label frequencies, sets where the catch label of interest was recorded at least once were included. Catch labels included in analysis were those with 10 or more total observations recorded. Set 8 was excluded from bait absent (A) analysis as soak time was 1.5 times longer than the next longest and bait loss has been shown to increase with soak time (Skud, 1978b).

All catch and hook status data were log (n+1) transformed to increase normality and obtain homogeneity of variances. Levene's test for homogeneity of variances was used to determine if parametric or non parametric tests were required. To compare mean turbot lengths between treatments a one-way ANOVA was conducted. To analyse the effect of gangion treatment on catch label frequency, one-way ANOVAs were conducted for each catch label. Post-hoc analysis was conducted with Duncan's new multiple range test. Significance level was set at 0.05 for all analyses. Software used to conduct statistical tests was SPSS® 17.0.0 (SPSS, 2008).

Due to the small sample size of some of the more detailed catch labels describing catches of Greenland shark, (GS-L, GS-D, GT-L, GT-D) and turbot, (T, TP) the labels were combined for analysis as GS-TOTAL and T-TOTAL, respectively.

3.4 Results

Summary of fishing results

Over the course of the experiment, a total of 4,800 hooks were fished, with data collected for 4,780 hooks (99.6 %). The missed data were the result of human error during the data collection and recording process. Data exist for 1,193 hooks of treatment C-200BN and E1-200M and 1,197 hooks of E2-100M and E3-50M. In total; 17 sharks, 233 turbot and 100 Arctic skate were captured (Table 3.4). Out of all finfish (turbot, Arctic skate and Greenland shark) captures; the C-200BN treatment accounted for 26.6 %, E1-200M for 33.1 %, E2-100M for 22.3 % and E3-50M for 18.0 %.

Greenland Shark

Sharks were captured in seven of the 12 longline sets, however when catches in the survey fleet and Greenland shark predation on turbot were included, sharks were clearly present in at least 10 of the 12 longline sets (Table 3.2). Mean catch rates were calculated from the seven experimental longline sets that captured Greenland shark. The mean number of Greenland shark captures was significantly greater within the C-200BN gangion compared to the experimental gangions with the latter comprising a homogenous sub-set, demonstrated by post-hoc tests (Table 3.5 and Fig. 3.4). The traditional multifilament braided nylon gangion accounted for only 25% of gangions, yet accounted for 65% of Greenland shark captures.

Sharks brought to the surface did not appear to struggle, only displaying slight movements. Size class was estimated for 15 sharks; three were < 3 m, eight were 3-4 m and four were > 4 m. Sex was determined for 13 sharks. There were seven females and six males captured. For the 10 sharks that could be assessed for the prominent ocular ectoparasitic copepod *Ommatokoita elongata* (Grant, 1827), 100% were infected with the parasitic copepod in both eyes. Sharks were hooked by the mandible or caudal fin. Entangled sharks were wrapped around the caudal peduncle, caudal fin or in the head region. The number of hooks fouled by an individual shark ranged from 1-52. Total time lost per shark capture including; time to release shark, time to disentangle the gear and resume fishing ranged from 0-128 min (Table 3.6).

Turbot

Turbot were captured in all 12 longline sets (Table 3.2). The number of turbot captured was not significantly different between gangion treatments (Table 3.5 and Fig.

3.4). Turbot body length did not differ significantly between gangion treatments (Table 3.7, Fig. 3.5).

Turbot brought to the surface upon haul back struggled fiercely, thus a hand held net was necessary to safely bring the fish aboard for length measurements. There were 15 turbot caught with evidence of shark predation out of the 233 caught, representing 6.4% of turbot.

Arctic skate

Arctic skate were captured in 11 of the 12 longline sets (Table 3.2). The number of Arctic skate captures was not significantly different between gangion treatments (Table 3.5 and Fig. 3.4).

Hook condition

Catch labels describing hook condition (A, HL, HT-G, P, S) were not significantly different between treatments except for HL (Table 3.5). There were significantly more hook losses with the monofilament gangions which comprised a homogenous sub-set, compared to the traditional C-200BN gangion as demonstrated by post-hoc tests (Fig. 3.5).

3.5 Discussion

The goal of this study was to introduce a longline gear modification that would reduce catch rates of Greenland shark without reducing either the individual body size or catch rate of turbot. This study has demonstrated that catch rates of Greenland shark can be significantly reduced by changing gangion material from multifilament braided nylon to monofilament without negatively influencing turbot catch rates. Breaking strength of monofilament line did not have a significant impact on catch rates or hook status categories. It is concluded that switching gangion type from multifilament to the 200 lb monofilament will decrease catch rates of Greenland shark without negatively effecting catch rates of turbot.

The fact that Greenland shark captures and hook loss mirrored the same post-hoc results, with monofilament gangions grouped together as a homogenous sub-set, indicates there were no differences between experimental gangions for these catch labels. Gangion material seems to have a greater effect than breaking strength. The effect of gangion material on catch rates of sharks has been demonstrated by many groups (Branstetter and Musick, 1993; Bjordal and Løkkeborg, 1996; Stone and Dixon, 2001; Ward et al., 2008; Vega and Licandeo, 2009; Afonso et al., 2012).

Monofilament fishing line is a thin, typically clear material, which is less visible than darker multifilament braided nylon or steel. It has been suggested that this decrease in visibility explains the increased catch rates of some fish species (Bjordal and

Løkkeborg, 1996; Stone and Dixon, 2001; Ward et al., 2008). Catch rates of cod and haddock have been shown to be as much as three times higher on monofilament compared to multifilament gangions and thinner gangions tend to have higher catch rates than thicker gangions (Bjordal and Løkkeborg, 1996). It is thought that finfish have a harder time identifying monofilament compared to the multifilament braided nylon and are more apt to prey upon these baited hooks (Bjordal and Løkkeborg, 1996; Stone and Dixon, 2001). The ability of the Greenland shark or turbot to detect multifilament braided nylon fishing line easier than monofilament will depend on the role that vision plays as a key sensory mechanism during predation.

The Greenland shark is thought to have severely limited vision (Borucinska et al., 1998; MacNeil et al., 2012) thus changing gangion visibility should not affect catch rates. Limited vision of the Greenland shark is caused by the prominent ocular ectoparasitic copepod *Ommatokoita elongata* which attaches to and dangles freely from the shark's cornea (Grant, 1827). Borucinska et al. (1998) and Benz et al. (2002) suggest that infected eyes are only capable of light reception and rough image formation. In addition, vision is not thought to play a dominant role in foraging for Greenland shark due to the relatively small eye (Bigelow and Schroeder, 1953) and the deep dark environment it inhabits which is often ice covered. The shark's well developed olfactory sense and electrosensory modalities are thought to be most important for survival (MacNeil et al., 2012). Therefore, decreased catch rates of Greenland shark on monofilament line compared to multifilament are not likely to be related to differences in ability to visually detect the gangion.

The pelagic prey items consumed by turbot (Vollen and Albert, 2008) and results of vision tests conducted with related species (Matsuda et al., 2009), suggests it is plausible that turbot have good vision which is capable of identifying multifilament braided nylon more easily than monofilament. Turbot are a deepwater flatfish, but there is evidence to suggest that their use of the pelagic zone is significant as adults (Vollen and Albert, 2008). Turbot prey upon bathypelagic, mesopelagic and epipelagic species such as capelin and herring, demonstrated by stomach content analysis (Vollen and Albert, 2008). Successful capture of these species would require good visual acuity. Matsuda et al. (2009) demonstrated that related members of the family *Pleuronectidae*, the Point head flounder (*Cleisthenes pinetorum*) and red halibut (*Hippoglossoides dubuis*) have colour vision. It is likely that turbot rely on vision for successful prey capture and that they have the ability to detect multifilament braided nylon fishing line easier than monofilament, which is expected to lead to higher catch rates on monofilament. However it is important to note that the role of vision at depths fished is unclear.

Although there is evidence to suggest that turbot are visual predators, the results of this study demonstrated that turbot catch rates were not significantly different between gangion treatments. The reason for this may be that perhaps at the depths fished (Table 3.2) it was too dark for gangion visibility to have an effect on catch rates. Stone and Dixon (2001) suggest that the ability of some fish species to distinguish thicker multifilament lines easier than monofilament lines can be achieved during nightfall under darkness. An alternate hypothesis to explain the results would be that due to the low catch rates, and the high variability between catches (Fig. 3.4), sample size was too low to accurately assess differences between gangion treatments in turbot catch rate. Fishing grounds chosen for this study were based on depth strata, not on known commercial fishing grounds, which produced high variability in turbot catch rates between sets. For example, set seven yielded 62 turbot, however six sets (2, 3, 5, 6, 9 and 11) yielded less than ten turbot (Table 3.2). Variability in catch rates between sets most likely stemmed from the fact that turbot were not abundant in some of the areas fished. It is possible that fishing on only commercial turbot grounds would have yielded different results with regard to turbot catch rates between gangion treatments.

With regard to Greenland shark, monofilament gangions were demonstrated to have lower catch rates than traditional multifilament but breaking strength did not affect Greenland shark catch rates. This study supports the findings of Vega and Licandeo (2009) which demonstrated that using monofilament gangions reduces shark catch rates as sharks are able to bite through monofilament gangions easier than multifilament. The hypothesis that reducing breaking strength of monofilament gangions can reduce Greenland shark catch rates is rejected. The reason why breaking strength did not affect shark catch rate may be related to behaviour of Greenland sharks. If the shark is hooked in such a way that it is unable to successfully bite through the gangion, its docile behaviour (Idrobo and Berkes, 2012; MacNeil et al., 2012) suggests it does not put great effort in escaping. Because it is expected that Greenland sharks do not thrash or exhibit resistance when hooked, breaking strength is not put to the test and reducing gangion breaking strength would have no effect on Greenland shark catch rates.

A consequence of an increased ability of sharks to bite through monofilament gangions is increased hook loss (Berkeley and Campos, 1988). This was found in the current study with experimental monofilament gangions having significantly more hook loss than the control multifilament gangions. The actual cause of individual hook losses cannot be determined by this study. In similar studies however, hook losses are attributed to shark bite-offs, or escaped sharks (Berkeley and Campos, 1988; Branstetter and Musick, 1993; Afonso et al., 2012). Berkeley and Campos (1988) suggest that although a large fish may occasionally break off a worn gangion, most missing hooks are believed to be bitten off. In addition, they state that among captured species, sharks should be responsible for most bite-offs. Sharks are known to have been present in 10 of the 12 sets determined by shark captures in either the experimental or survey fleet and predation upon turbot (Table 3.2). Of the two sets where sharks were not captured, in one set a turbot caught was observed to have been preyed upon (Table 3.2), and many more sharks could have been present in fished areas but were able to avoid capture. Due to evidence confirming the presence of sharks and the fact that they are assumed to be the main source of hook loss in other studies, the Greenland shark is suspected to be the major cause of hook loss in the current study through bite-offs. It is expected that to a lesser extent, turbot, Arctic skate and environmental factors are also contributing to hook losses.

Although using monofilament gangions may increase the costs for hook replacement, gear damages caused by shark interference will be minimized as only the gangion needs to be replaced compared with larger mainline entanglements that can be caused from hooked sharks on multifilament braided nylon lines. These types of damage are considerably more costly and time consuming to fix compared to replacing gangions (Stone and Dixon, 2001).

The severity of shark entanglements and the duration of time entangled may be an important factor determining post-capture survivorship, as well as costs to fishers. Although small sample size prevented this study from being able to determine whether gangion material or breaking strength has an effect on entanglement severity, it will be an important factor to address with future studies. Time lost due to shark captures, including time to release the shark and time to untangle the gear ranged from 1-19 min (mean = 7, n = 6) with experimental monofilament gangions and from 1-128 min (mean = 15, n = 11) with control multifilament braided nylon gangions. Multifilament braided nylon gangions of 360 lb breaking strength used in the survey fleet, had a time loss range of 1-81 min (mean = 1, n = 16) (Table 3.6). Further studies are required to determine if monofilament has any added benefit affecting shark entanglements.

From a conservation perspective reducing Greenland shark captures through gear modifications can only be successful if sharks that are hooked and escape, survive to reproduce. It was not possible to safely remove hook(s) from captured sharks prior to release, nevertheless, post-capture survival is expected to be very high. Evidence from acoustic tagging studies (K.Hedges, personal communication, August 25, 2012) of one Greenland shark captured during turbot longlining and then released has shown movements after a year post initial capture. Further, one shark captured during this study was observed to have an old hook embedded in its jaw. This was obvious as all hooks used in the present study were new, thus rusted hooks were from previous encounters with fishing gear (Fig. 3.7). Thus, hooked sharks that escape longline gear can survive and resume normal behaviour such as feeding. In addition, the hardiness of this species observed by Pangnirtung residents (Idrobo and Berkes, 2012) and the calm, docile nature of the fish when caught all suggest that post-capture survival will be high.

Out of the three experimental gangions, the 200 lb gangion performed the best in this study. The 200 lb monofilament gangion is the thickest and stiffest of the experimental gangions and has a reduced tendency to become tangled during baiting and when placed in storage tubs. In general, baiting by hand using monofilament line is a more difficult task than when using other types of fishing line as monofilament is thinner, more rigid and has memory (Bjordal and Løkkeborg, 1996). Baiting with gangions that have the tendency to tangle can also increase the total time it takes to bait, with fewer hooks deployed and ultimately reduced revenues per fishing day. Out of the three experimental gangion types used in this study, the 200 lb monofilament gangion proved to be the best as it was the easiest to use and quickest to hand bait.

3.5.1 Limitations to Approach

A challenge to studying solitary, wide ranging marine species such as some sharks or marine mammals is that it can be difficult to achieve the ideal number of samples with limited resources. In total, 17 Greenland sharks were captured through experimental longline fishing. Although sample size is low, the highly significant relationship ($p < 0.01$) demonstrated between gangion treatment and Greenland shark captures reduces the probability that low sample size reduces the power to detect significant differences. Nevertheless, conducting further experimental longline fishing to increase shark sample size would add confidence to the results obtained from this study.

3.6 Conclusion

Substituting the traditional multifilament braided nylon gangions with a monofilament gangions in the open water fishery in Cumberland Sound, may lead to a significant reduction in the bycatch of Greenland shark without negatively impacting commercial catches of turbot. Arctic skate bycatch is not affected by changing gangion type. Although it is not clear why monofilament gangions reduce shark catch rates, it is plausible that sharks are able to bite through the monofilament gangions more easily than traditional multifilament gangions. This is supported by the increase in hook loss of the monofilament gangions compared to the traditional gangions demonstrated by this study. Increased hook loss will increase hook replacement costs. However, economic savings in reducing the total number of shark captures would compensate for these additional costs.

The gangion best suited for the Cumberland Sound turbot longline fishery demonstrated by results of this study is the 200 lb monofilament gangion. Without affecting turbot catches, this gangion captured significantly fewer Greenland sharks than the traditional multifilament braided nylon gangion and were the most efficient operationally out of the experimental gangions. The next step is to share the results of this study with Pangnirtung turbot fishers and have them try out the 200 lb monofilament gangion under commercial conditions.

3.7 References

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3.8 Tables

Table 3.1. Gangion treatment descriptions.

Letter Fig. 3.2	Gangion	Treat.	Material	Colour	Diameter	Breaking strength	Clasp length/knot	Average gangion length (cm ± 1 s.e)
D	C-200BN	control	multifilament nylon	Blue	3.0 mm	200 lb	Knot	37.68 ± 1.35
C	E1-200M	exp.	monofilament nylon	Clear	1.5 mm	200 lb	18 cm	41.56 ± 0.78
B	E2-100M	exp.	monofilament nylon	Clear	1.0 mm	100 lb	8 cm	44.78 ± 0.68
A	E3-50M	exp.	monofilament nylon	Clear	0.5 mm	50 lb	7 cm	43.72 ± 0.90

Table 3.2. Summary of longline soak time, mean depth and catch labels per set, with totals. Greenland shark captures by the survey fleet are included at the bottom of the table.

		Set												
		1	2	3	4	5	6	7	8	9	10	11	12	Totals
Soak time (hr)		12	12	13	14	13	12	14	36	12	13	14	12	
Mean depth (m)		854	1,143	708	863	1,082	720	960	778	891	1,267	833	1,080	
Turbot														
	Total (T-TOTAL)	23	9	5	25	9	1	62	31	7	45	2	14	233
	Preyed upon (TP)	0	1	0	1	2	0	1	0	0	9	0	1	15
Greenland shark														
	Total (GS-TOTAL)	0	0	2	1	3	0	2	0	1	0	5	3	17
	Alive (GS-L + GT-L)	0	0	1	1	2	0	2	0	0	0	4	3	13
	Dead (GS-D + GT-D)	0	0	1	0	1	0	0	0	1	0	1	0	4
Arctic skate (AS)		15	2	10	117	13	0	17	2	5	12	2	5	100
Hook/mainline tangled														
	By shark (HT-G)	0	0	0	0	12	0	27	0	15	0	8	51	113
	No shark present (S)	1	79	5	11	3	4	40	1	3	10	8	10	175
Hook loss (HL)		97	85	96	59	59	49	96	128	140	99	130	122	1,160
Bait absent (A)		47	32	57	57	45	35	75	122	81	78	57	56	742
Bait present (P)		217	192	223	228	254	310	79	113	148	154	188	126	2,232
Research Survey Fleet														
Greenland shark		0	0	2	0	1	0	0	4	2	1	5	2	17

Table 3.3. Catch labels used to determine hook condition or identify catch species.

A	Bait absent
AS	Arctic skate
GS-TOTAL	All Greenland shark captures including; GS-D, GS-L, GT-D and GT-L
	GS-D, Greenland shark-dead
	GS-L, Greenland shark-alive
	GT-D, Greenland shark and turbot on same hook-shark dead
	GT-L, Greenland shark and turbot on same hook-shark alive
HL	Hook loss
HT-G	Hook snarl suspected to be caused by Greenland shark interference
	Location immediately before or after a recorded shark capture
P	Bait present
S	Hook snarl suspected to be caused by environment or fishing process
T-TOTAL	All turbot captures including; T and TP
	T, Turbot
	TP, Turbot with predation evidence

Table 3.4. Catch label totals per gangion treatment.

	Gangion treatment				
	E3-50M	E2-100M	E1-200M	C-200BN	TOTAL
T-TOTAL	35	62	88	48	233
AS	26	15	25	34	100
GS-TOTAL	2	1	3	11	17
HT-G	28	7	17	61	113
HL	150	176	193	66	585
HL-G	188	146	129	112	575
A	174	162	184	222	742
P	554	573	522	583	2232
S	37	47	36	55	175

Table 3.5. Catch label means (± 1 s.e.) per 100 hooks for each gangion treatment. Letters indicate results of post-hoc tests, where groups that make up a homogenous sub-set are indicated by the same letter listed below their mean. The letter A indicates that the sub-set contained the greatest nominal mean of all sub-sets. Significant p-values (< 0.05) are indicated by *.

	Treatments				Statistics		
	E3-50M	E2-100M	E1-200M	C-200BN	d.f	F-stat	p-value
T-TOTAL	2.92 ± 0.99	5.17 ± 1.54	7.33 ± 2.09	4 ± 1.17	3, 44	1.111	0.355
AS	2.36 ± 0.85	1.36 ± 0.51	2.27 ± 0.81	3.09 ± 0.74	3, 40	1.196	0.324
GS-TOTAL	0.29 ± 0.18	0.14 ± 0.14	0.43 ± 0.20	1.57 ± 0.48	3, 24	5.399	0.006*
	B	B	B	A			
HT-G	2.33 ± 1.65	0.58 ± 0.40	1.42 ± 1.04	5.08 ± 7.73	3, 24	1.847	0.166
HL	28.17 ± 2.80	27.33 ± 2.65	26.83 ± 3.02	14.83 ± 2.57	3,44	7.180	0.001*
	A	A	A	B			
A	13.55 ± 1.89	11.82 ± 1.04	14.73 ± 1.92	16.27 ± 1.67	3, 40	0.710	0.552
P	46.17 ± 4.28	47.75 ± 5.32	43.50 ± 4.85	48.58 ± 5.27	3, 44	0.135	0.939
S	3.08 ± 1.67	3.92 ± 1.84	3 ± 1.31	4.58 ± 2.22	3, 44	0.320	0.811

Table 3.6. Summary of lost fishing time due to shark entanglements between three gangion types; monofilament (50, 100 and 200 lb inclusive), 200 lb braided nylon and 360 lb braided nylon (from the survey fleet). Mean values include (± 1 s.e.).

	Monofilament	B. nylon 200	B. nylon 360
N	6	11	16
Max (min)	19	128	81
Min (min)	1	1	1
Mean (min)	7 (± 6.66)	15(± 33.76)	17 (± 26.61)

Table 3.7. Mean turbot length (cm ± 1 s.e.), minimum length (cm) and maximum length (cm) by gangion treatment. Results of the one-way ANOVA comparing mean turbot length and gangion treatment is also shown.

				One-way ANOVA		
Treatment	Mean length	Min	Max	df	F-stat	p-value
C-200BN	67.0 ± 3.07	47	86			
E1-200M	66.3 ± 2.92	50	88			
E2-100M	67.7 ± 3.17	53	90	3,229	0.947	0.41
E3-50M	65.2 ± 2.82	50	81			

3.9 Figures

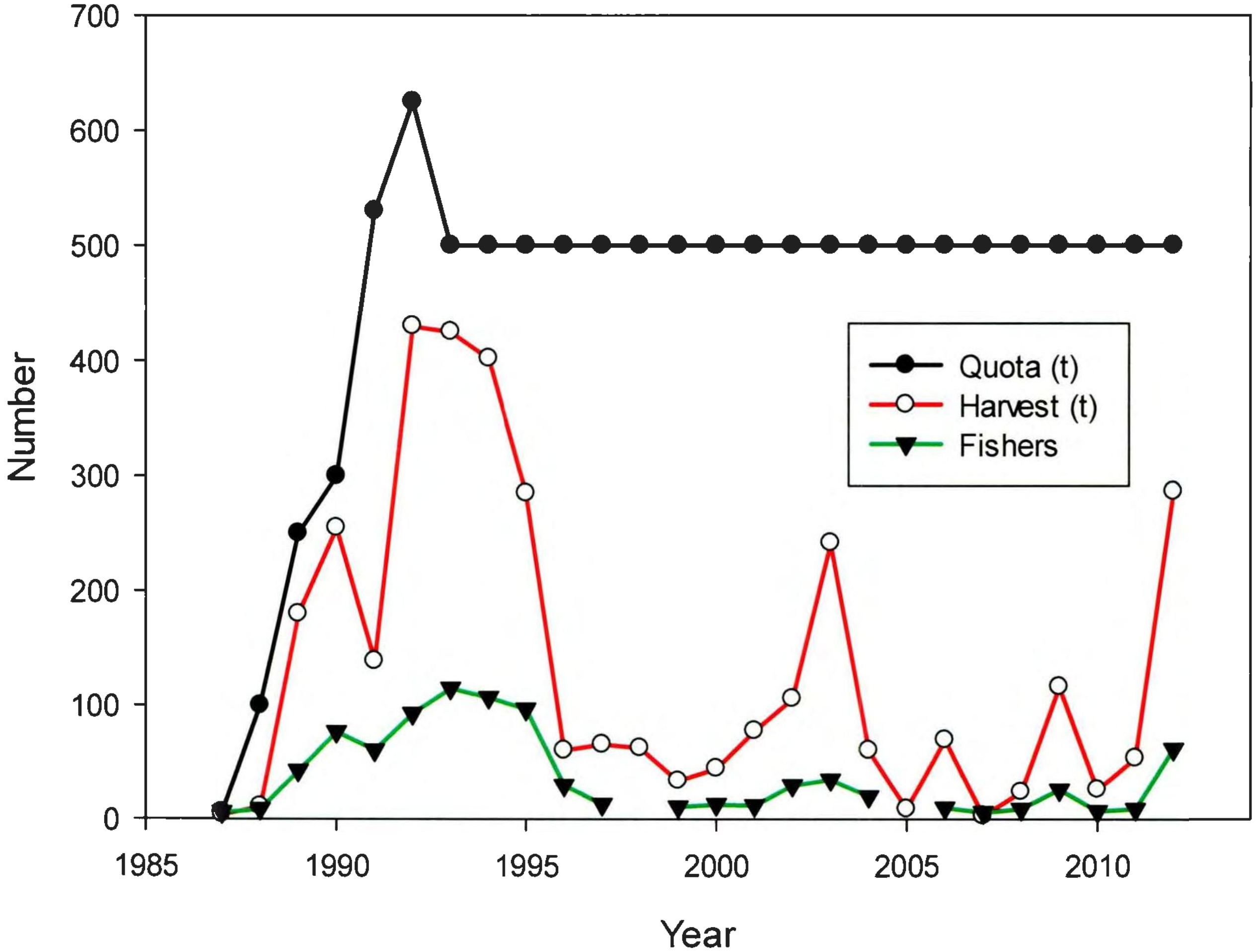

Figure 3.1. The history of the Cumberland Sound winter turbot fishery, including allotted quota (t), amount of fish harvested (t) and number of fishers from 1986-2012 (data provided by K. Imrie, Pangnirtung Fisheries Ltd.).

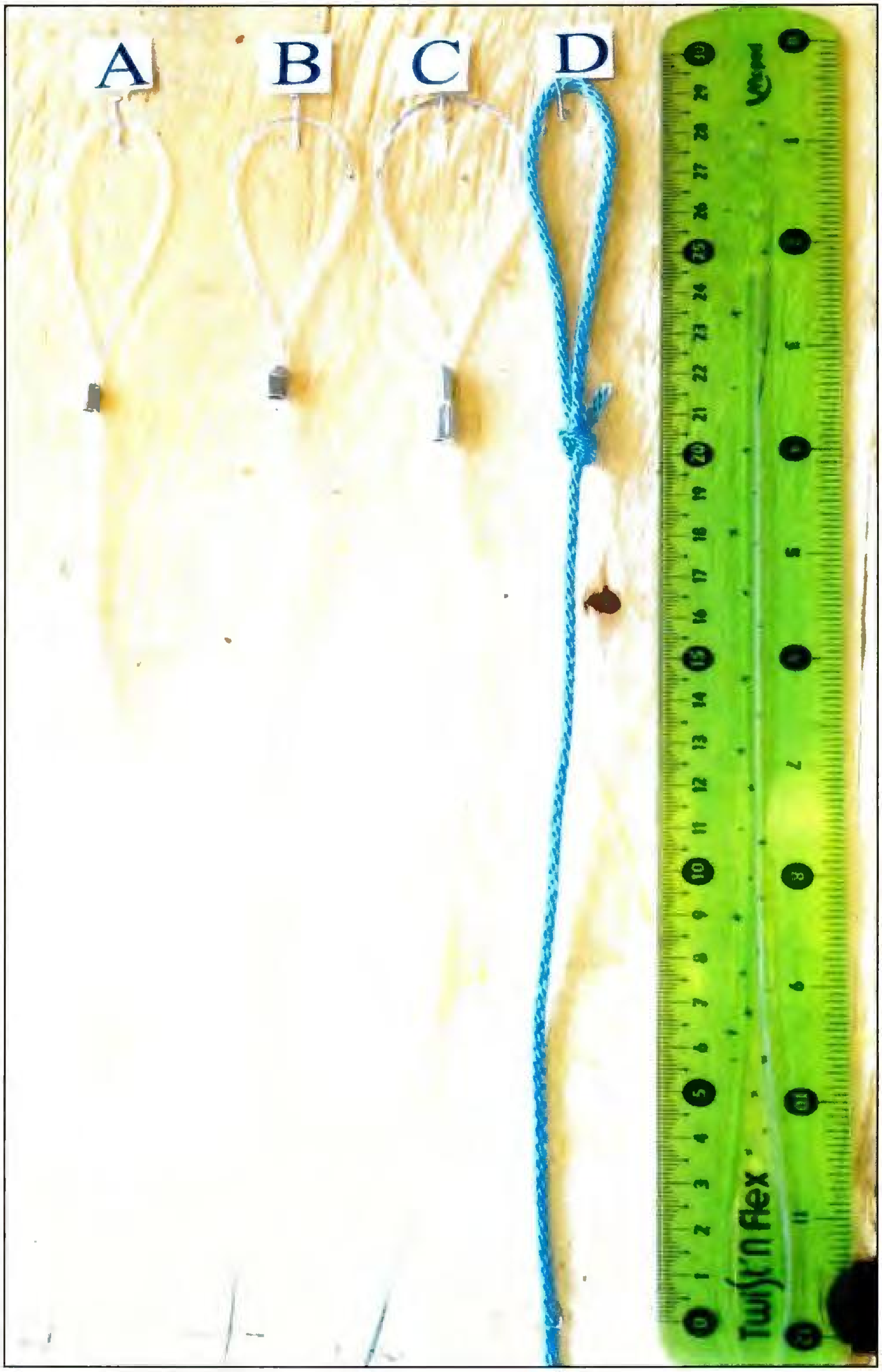

Figure 3.2. Photograph of gangion treatments (Table 3.1 for descriptions).

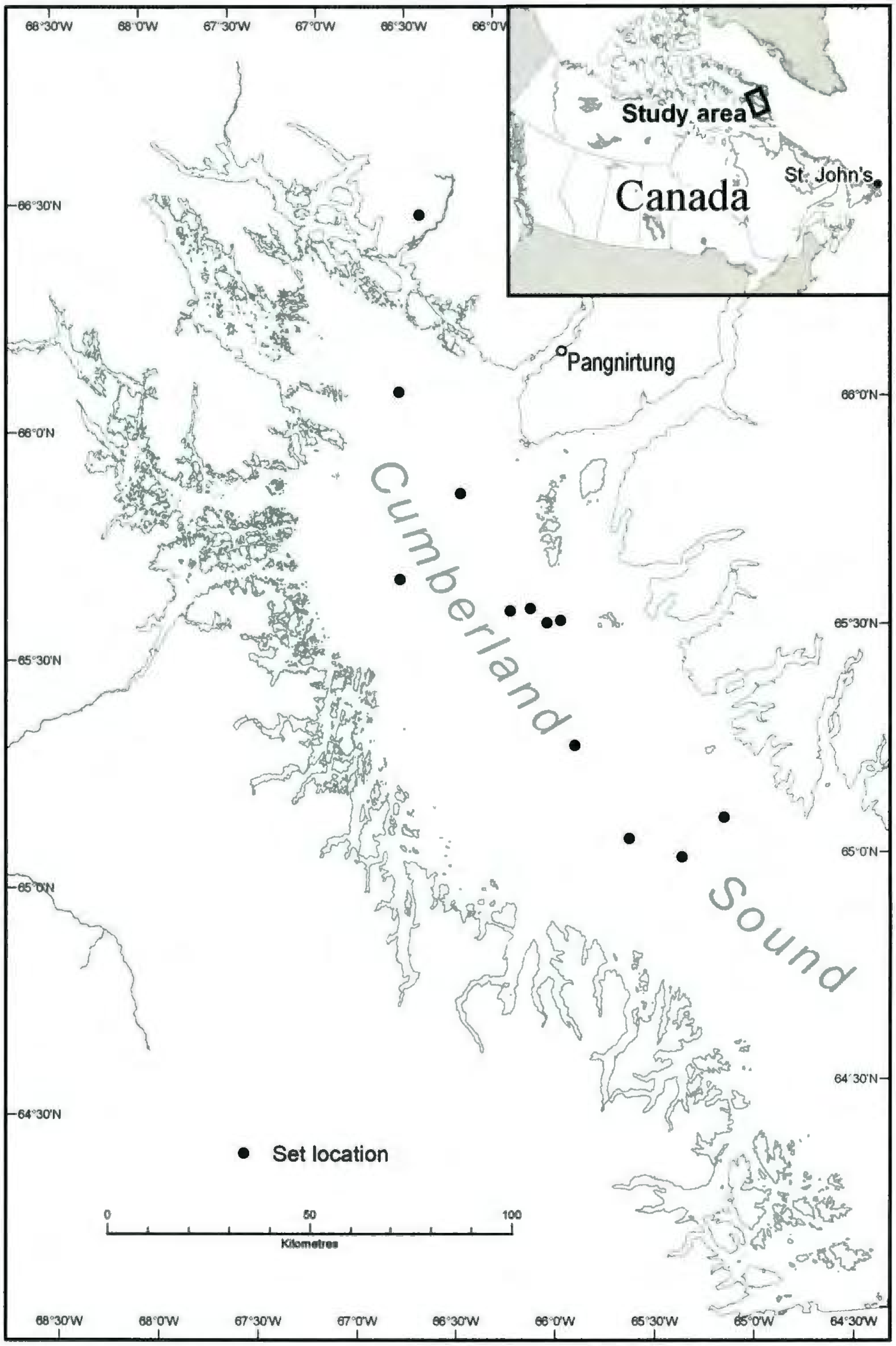

Figure 3.3. Approximate longline set location in the Cumberland Sound, Nunavut. The accuracy of locations plotted is limited due to the lack of reliable cartographic data for this region (i.e. one point positioned on land despite accurate coordinates recorded).

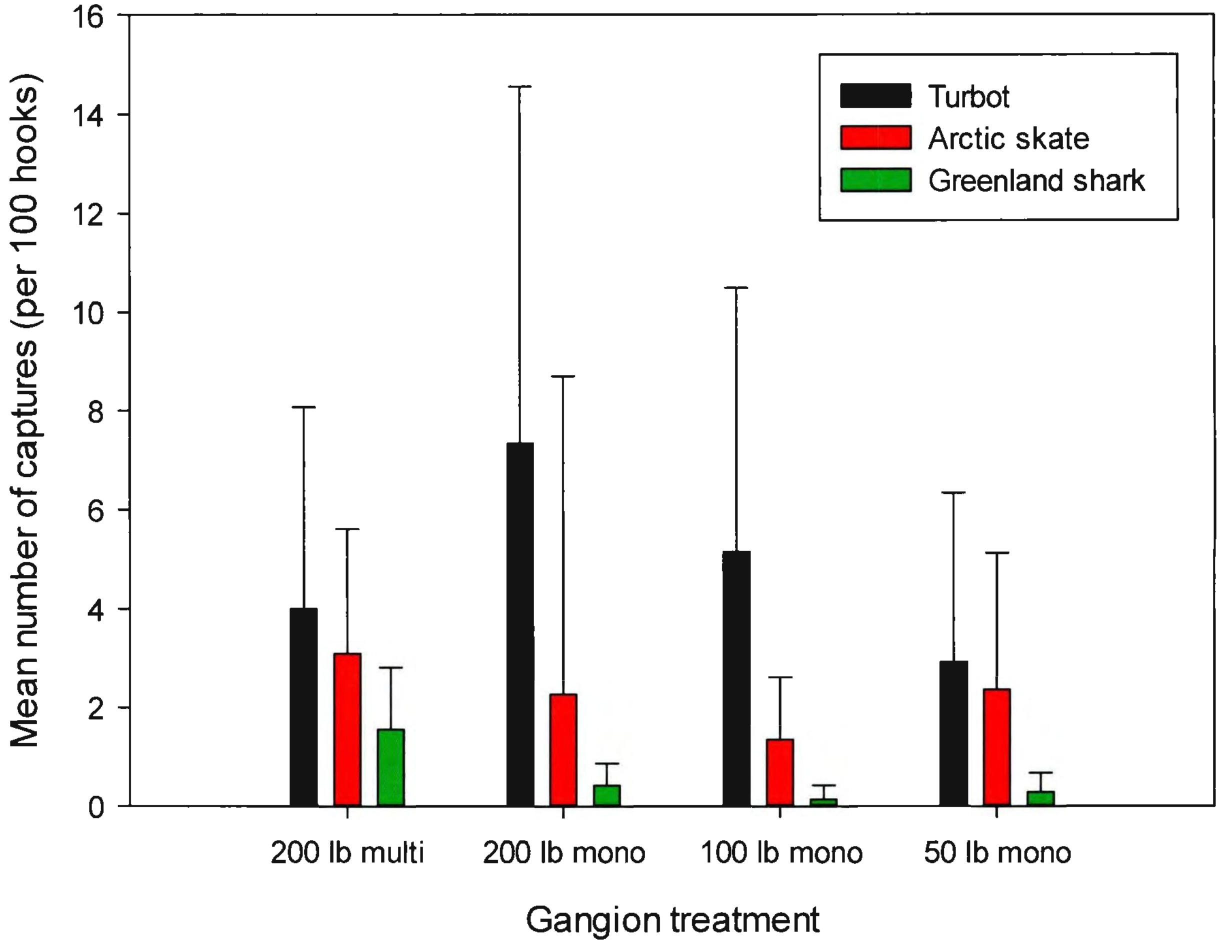

Figure 3.4. Mean number of captures (per 100 hooks) of fish species per gangion treatment. Includes target catch (turbot) and bycatch (Arctic skate and Greenland shark). Error bars indicate standard deviation.

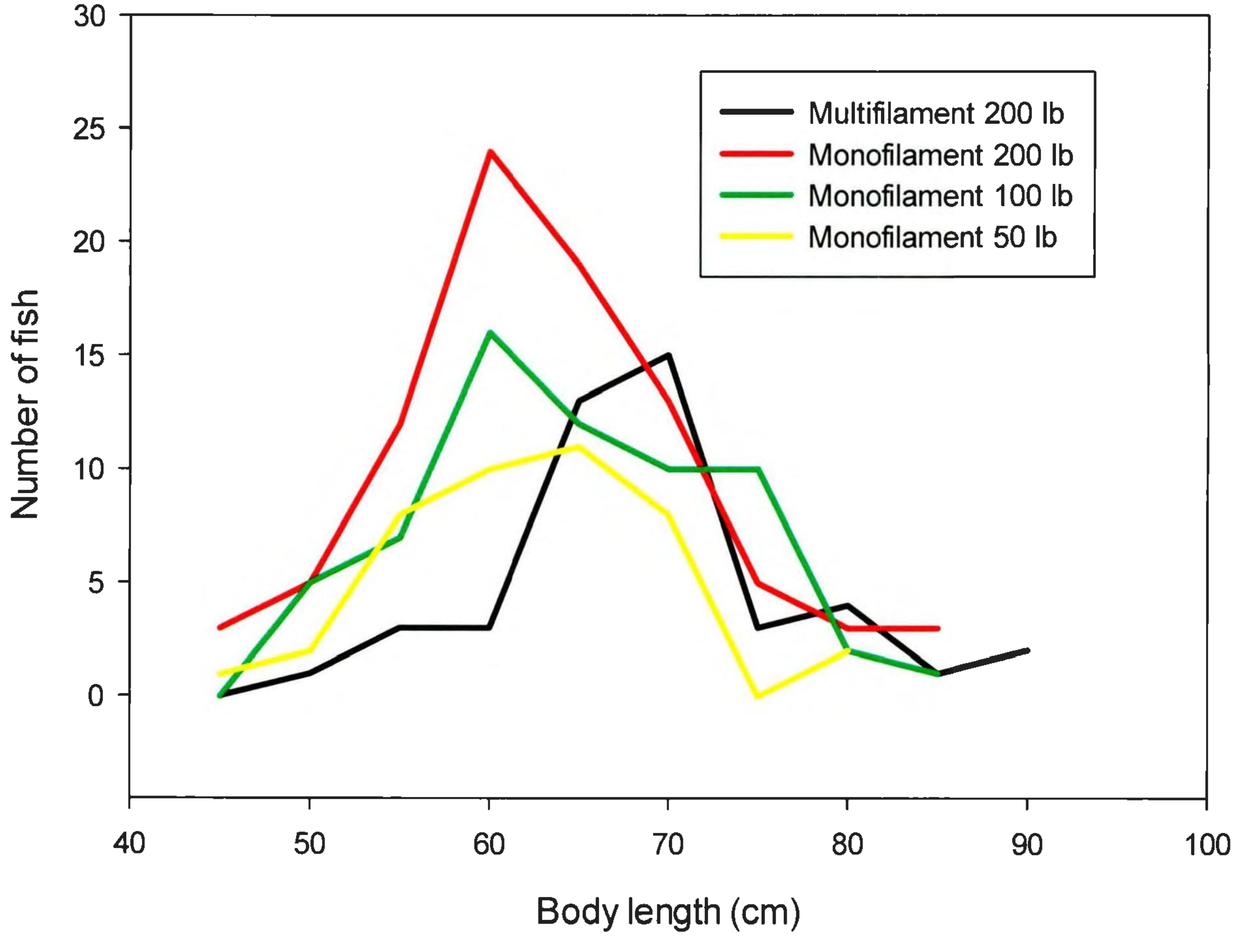

Figure 3.5. Turbot body length distributions by gangion treatment.

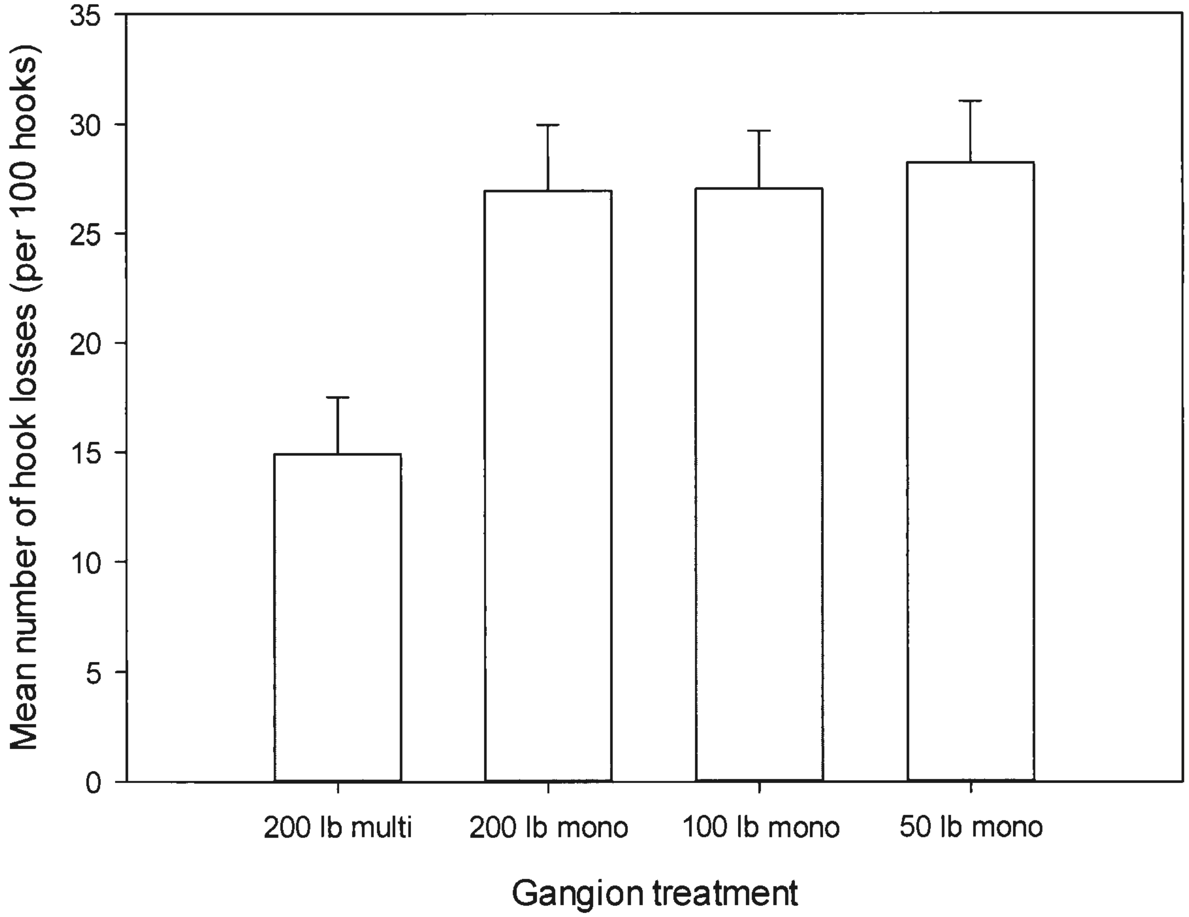

Figure 3.6. Mean number of hook losses (per 100 hooks) per gangion treatment. Error bars indicate standard deviation.

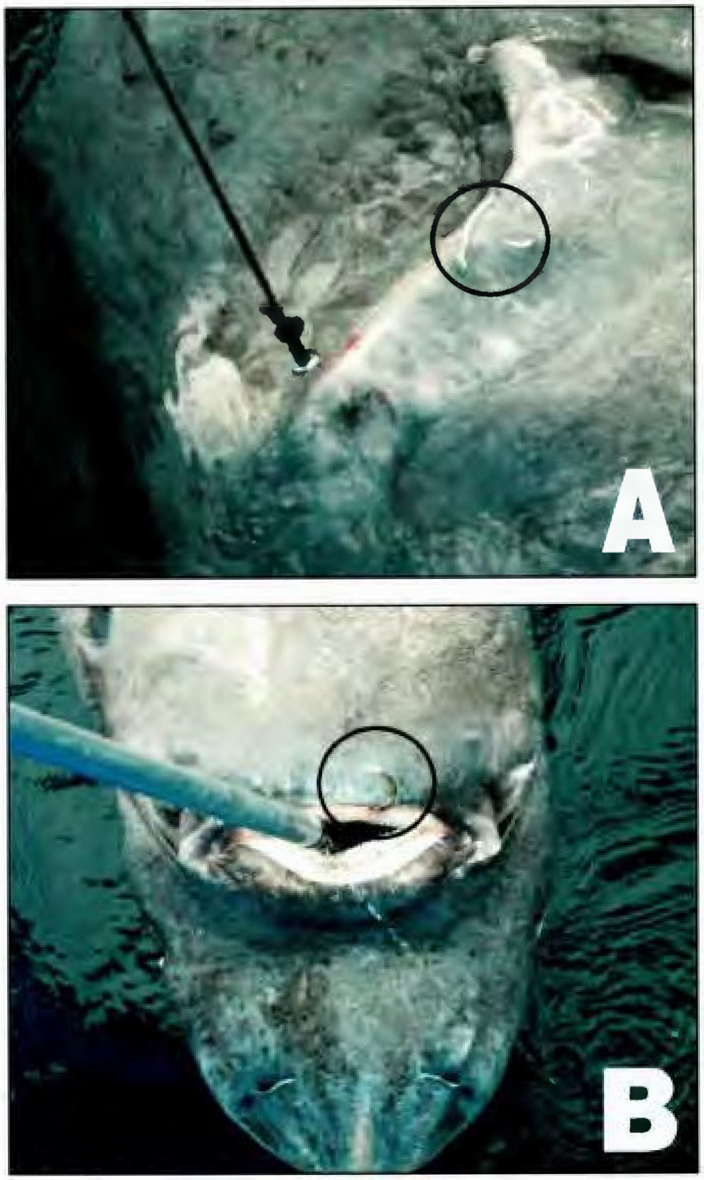

Figure 3.7. Photographs illustrating a new (A) hook bitten off the research longline and an old rusted (B) hook from a previous interaction with turbot longline gear. The presence of a rusted hook in the jaw of a shark caught during the current study suggests that remaining hooks do not compromise the Greenland shark's feeding ability post-release.

CHAPTER 4: SUMMARY

4.1 Recommendations for Fishing Industry

4.1.1 Inshore Newfoundland and Labrador northern shrimp trawl fishery

The aligned trawl demonstrated increased shrimp catches compared to the traditional trawl with a modelled 39% reduction in contact area with the seabed. With its higher shrimp catch rate, the total area of seabed impacted may be reduced over time through reduced fishing effort. In terms of the capture of major bycatch species, trawl types did not differ in terms of capelin catch, however the aligned trawl had significantly higher turbot catch rates. The increases of turbot catch are unacceptable due to the commercial importance of this species and the negative impacts of increased bycatch on fishing efficiency. This trawl is not recommended for commercialization until modifications are implemented and shown to have no effect on turbot catch when compared to the traditional trawl. Due to the lack of appropriate monitoring tools, factors influencing increases in shrimp or turbot catch rates could not be confidently determined from the results of this study. It is recommended that further comparative sea-trials are conducted with the aligned and traditional trawls, using industry scale tows and tools that can aid in determining the cause of increased turbot catches. This would include video footage of the aligned trawl footgear *in situ*, quality net mensuration equipment providing reliable data, and the use of an inclinometer to determine the height of the fishing line off the seabed. This study represents a first step towards the development of a low impact shrimp bottom trawl for the Newfoundland and Labrador inshore fishery, demonstrating seabed contact can be reduced without negatively affecting commercial catches.

4.1.2 Cumberland Sound turbot longline summer fishery

Monofilament gangions are recommended for the Cumberland Sound fishery as they reduce Greenland shark captures without compromising commercial turbot catches compared to the traditional multifilament braided nylon gangion. Operationally, the 200 lb monofilament gangion would be better than the 100 lb or 50 lb as it is easier to work with due to its increased rigidity. Bycatch rates of Arctic skate did not differ between the experimental monofilament gangions and the traditional multifilament braided nylon gangions. Materials costs of monofilament and multifilament nylon are comparable (North Atlantic Marine, personal communication, May 16, 2012). The 200 lb monofilament gangion should be tested by Pangnirtung fishers on a commercial scale. The knowledge of the benefits using monofilament gangions should be shared with other communities in Baffin Island with plans to develop turbot longline fisheries.

4.2 Future Research

4.2.1 Inshore Newfoundland and Labrador northern shrimp trawl fishery

The next step in development of the aligned inshore shrimp trawl is to conduct at-sea comparative fishing trials with the traditional trawl at a commercial scale, using tow durations of 2-3 hr. For these trials it is recommended that a more reliable net mensuration system is used than what was used in this study to ensure the ability to calculate total area fished of each tow (i.e. wingspread, headline height and height of fishing line). It is recommended that under water cameras are used in these trials to allow observations of the seabed to confirm that the aligned trawl interacts with the seabed in the same way that was expected through flume tank testing. Without this, it will remain unknown whether the aligned trawl is actually low impact *in situ*. In addition cameras should be used to observe the behaviour of benthic bycatch species as they interact with the trawl, especially flatfish like turbot. Additionally, with the use of an inclinometer to calculate fishing line height, the cause of increased turbot catches may be possible through these fishing trials. Once the cause of the increased turbot catches is known, modifications to ameliorate the effect should be devised, and subsequently tested at sea.

4.2.2 Cumberland Sound turbot longline summer fishery

Severe entanglements involving Greenland shark and longline gear negatively affects both shark populations and the fishing industry. Severe entanglements decrease the probability of the shark surviving the capture as it places substantial stress on the body of the animal and can cause injuries. In addition, these entanglements render the hooked shark more vulnerable to fatal attacks from other sharks as it limits their mobility. Entanglements also negatively impact fishers as they increase fishing time, gear replacement costs and reduce commercial catch rates as entangled hooks no longer fish. This experiment demonstrated that the monofilament gangions can effectively reduce Greenland shark catch rates, without effecting turbot catches, however there was insufficient data to determine whether modified gangions affect entanglement rates and severity of entanglements (i.e. number of hooks) compared to traditional gangions. My hypothesis is that monofilament gangions will result in fewer entanglements and a reduction in the severity of entanglements compared to multifilament braided nylon gangions due to the physical properties of monofilament, allowing it to stretch with stress and weaken over time. To investigate this issue more experimental longline fishing trials with the 200 lb multifilament braided nylon and monofilament gangions are recommended to increase shark sample size.

APPENDICES

Appendix 1. Species captured incidentally (in numbers) per tow by the control trawl is illustrated. Miscellaneous fish include; witch flounder, eelpout and snakeblenny.

Paired tow no.	capelin	turbot	A. plaice	A. herring	redfish	sandlance	Benthic inverts.	misc. fish	Total
1	12	4	0	2	0	0	0	0	18
2	10	3	0	2	0	0	0	0	15
3	0	11	0	0	0	0	0	0	11
4	41	4	1	1	0	0	0	1	48
5	80	3	0	0	3	0	0	1	87
6	53	7	1	1	0	2	0	0	64
7	78	2	2	0	2	1	0	1	86
8	132	2	1	1	2	2	0	0	140
9	22	18	0	3	0	0	0	0	43
10	46	6	0	1	1	0	0	0	54
11	25	11	0	2	0	0	0	1	39
12	30	22	4	0	0	0	0	1	57
13	39	1	0	0	1	0	0	0	41
14	21	1	0	0	1	1	0	0	24
15	5	4	0	1	1	0	0	1	12
16	32	1	0	0	0	0	0	0	33
17	18	14	0	3	0	1	0	0	36
18	9	10	0	1	0	0	0	2	22
19	16	10	2	3	0	0	0	0	31
20	25	0	0	2	1	0	0	0	28
Total	694	134	11	23	12	7	0	8	889

Appendix 2. Species captured incidentally (in numbers) per tow by the experimental trawl is illustrated. Miscellaneous fish include; witch flounder, eelpout and alligator fish. Benthic invertebrates include the mud star and seapen.

Paired tow no.	capelin	turbot	A. plaice	A. herring	redfish	sandlance	Benthic inverts.	misc. fish	Total
1	35	29	1	0	0	2	1	1	69
2	21	6	0	1	0	0	0	1	29
3	23	17	0	0	0	0	0	0	40
4	77	17	1	0	3	1	0	2	101
5	32	4	1	3	0	0	0	0	40
6	43	7	0	0	0	1	0	1	52
7	78	4	0	1	2	1	0	0	86
8	290	7	1	0	9	3	0	1	311
9	169	1	2	3	1	0	0	0	176
10	45	15	2	1	1	0	0	1	65
11	16	16	4	4	0	0	0	0	40
12	53	16	4	4	1	0	0	0	78
13	37	4	0	1	3	0	0	1	46
14	19	4	2	1	1	0	0	0	27
15	2	7	0	0	0	0	0	0	9
16	30	23	1	0	1	0	1	0	56
17	12	10	4	2	0	0	0	0	28
18	23	30	6	1	1	0	0	5	66
19	41	6	0	0	0	0	0	0	47
20	20	5	0	2	0	0	0	1	28
Total	1066	228	29	24	23	8	2	14	1394

Appendix 3. Total biomass (kg) of turbot, capelin and shrimp captured in each tow for the control trawl. Additionally, turbot and capelin catches are expressed as percentages of total catch in terms of weight (kg).

Paired tow No.	Turbot (kg)	Capelin (kg)	Shrimp (kg)	Total catch (kg)	% catch turbot	% catch capelin
1	0.26	0.49	143.52	144.26	0.18	0.34
2	0.08	0.13	105.00	105.21	0.07	0.13
3	0.17	0.35	100.00	100.51	0.17	0.34
4	0.16	0.79	103.00	103.95	0.15	0.76
5	0.13	0.45	107.00	107.58	0.13	0.42
6	0.48	0.71	53.00	54.19	0.88	1.31
7	0.30	0.68	112.00	112.98	0.26	0.60
8	0.07	0.66	87.00	87.72	0.08	0.75
9	1.01	0.26	163.20	164.47	0.62	0.16
10	0.37	0.51	116.00	116.89	0.32	0.44
11	0.42	0.20	148.50	149.12	0.28	0.13
12	1.10	0.35	141.48	142.93	0.77	0.24
13	0.02	0.45	76.00	76.47	0.02	0.59
14	0.01	0.24	154.80	155.04	0.00	0.15
15	0.28	0.06	144.90	145.24	0.19	0.04
16	0.03	0.37	129.00	129.40	0.02	0.29
17	0.93	0.24	154.20	155.37	0.60	0.15
18	0.60	0.23	108.00	108.83	0.55	0.21
19	1.22	0.37	153.00	154.59	0.79	0.24
20	0.00	0.26	183.40	183.66	0.00	0.14
Mean	0.38	0.39	124.15	124.92	0.30	0.37

Appendix 4. Total biomass (kg) of turbot, capelin and shrimp captured in each tow for the experimental trawl. Additionally, turbot and capelin catches are expressed as percentages of total catch in terms of weight (kg).

Paired tow No.	Turbot (kg)	Capelin (kg)	Shrimp (kg)	Total catch (kg)	% catch turbot	% catch capelin
1	2.09	0.17	114.0	116.26	1.79	0.15
2	0.45	0.28	118.0	118.74	0.38	0.24
3	1.27	0.00	105.0	106.27	1.20	0.00
4	0.78	0.61	137.5	138.88	0.56	0.44
5	0.16	0.71	173.6	174.47	0.09	0.41
6	0.36	0.58	156.2	157.14	0.23	0.37
7	0.55	0.72	159.6	160.87	0.34	0.45
8	0.44	0.63	132.0	133.07	0.33	0.48
9	0.02	0.61	144.0	144.63	0.01	0.42
10	0.65	0.50	159.6	160.75	0.40	0.31
11	0.89	0.29	173.6	174.79	0.51	0.17
12	0.96	0.59	189.0	190.56	0.50	0.31
13	0.20	0.44	109.0	109.65	0.19	0.40
14	0.51	0.24	193.2	193.95	0.26	0.13
15	0.89	0.04	147.6	148.53	0.60	0.02
16	1.50	0.34	160.8	162.65	0.92	0.21
17	0.93	0.14	132.0	133.07	0.70	0.10
18	1.65	0.09	153.6	155.34	1.06	0.06
19	0.64	0.20	212.8	213.63	0.30	0.09
20	0.28	0.31	195.3	195.89	0.14	0.16
Mean	0.76	0.37	153.32	154.46	0.53	0.25

Appendix 5. Number of trawl geometry measurements (n) for wingspread and headline height per trawl type and tow. Bolded numbers indicate where there was at least 25% of the maximum number of measurements (147 for wingspread and 308 for headline height) for that parameter recorded for both tows in a pair. Underlined numbers indicate a tow that met the arbitrary data requirement; however the other tow in the pair did not, thus neither was included in analysis.

Pair #	Control wingspread	Experimental wingspread	Control headline height	Experimental headline height
1	32	2	**279**	**184**
2	<u>118</u>	11	<u>246</u>	16
3	**147**	**47**	<u>265</u>	10
4	**120**	**47**	<u>268</u>	7
5	<u>137</u>	0	<u>285</u>	44
6	<u>109</u>	2	<u>190</u>	41
7	**123**	**75**	<u>223</u>	0
8	**79**	**45**	<u>111</u>	31
9	0	<u>94</u>	<u>255</u>	13
10	0	27	<u>244</u>	49
11	0	1	<u>256</u>	5
12	0	13	<u>196</u>	28
13	1	<u>94</u>	<u>302</u>	29
14	1	<u>138</u>	<u>308</u>	21
15	0	1	0	6
16	0	<u>50</u>	0	28
17	0	10	<u>304</u>	10
18	0	0	<u>263</u>	37
19	<u>89</u>	0	<u>178</u>	55
20	2	0	**268**	**103**