# Evaluation of fishing gears modified to reduce ecological impacts in commercial fisheries

by

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# Abstract

To sustainably and responsibly harvest commercial aquatic species in the world's fisheries, consideration must be given towards the negative physical and biological effects that fishing gears place on marine ecosystems. Fish habitat degradation, bycatch of undersized and non-target species, carbon footprint, reductions in biodiversity and biomass are just some of the negative impacts of fishing gears. One novel method to reduce impacts while maintaining commercially viable catch rates of target species is through modification of fishing gears. Two experimental studies, conducted for this thesis, evaluated the catch characteristics of innovative, modified fishing gears designed to mitigate ecological concerns specific to each study's respective fishery. In the first study, the Newfoundland cod pot was modified in an attempt to target flatfish species while avoiding the capture of snow crab (*Chionoecetes opilio*). Major findings include the importance of artificial light and entrance shape in capturing American plaice (*Hippoglossoides platessoides*). Also, non-baited pots that contained only artificial light were successful in capturing plaice while greatly reducing the capture of snow crab. In the second study, at-sea catch characteristics of northern shrimp (*Pandalus borealis*) and non-targeted bycatch species were compared between two trawls, one containing a traditional rockhopper ground gear currently used in the northern shrimp fishery, the other containing an experimental ground gear designed to reduce seabed contact. Catch rates and size of shrimp were found to be comparable between trawls however the experimental trawl captured significantly more bycatch.

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# Co-authorship Statement

The author of this thesis contributed to the design of the experiments, collected/organized all of the data, analyzed and wrote all of the subsequent manuscripts. Dr. Scott Grant and Dr. Paul Winger contributed significantly to research proposals, experimental designs, and discussion of ideas and provided editorial reviews of all chapters. Rennie Sullivan contributed significantly to the data collection for Chapter 2.

Dr. Scott Grant and Rennie Sullivan are second and third authors for Chapter 2, respectively.

Dr. Scott Grant, Dr. Paul Winger, Jógvan Olsen, and Truong Nguyen are second, third, fourth, and fifth authors for Chapter 3, respectively.

It is anticipated that Chapters 2 and 3 will be submitted as separate manuscripts to scientific journals.

# Chapter 1. Introduction and overview

## 1.1 Impacts of fishing gears

Fishing provides many benefits to society. In addition to providing a source of food, employment, and recreation, fishing is strongly tied to many cultures and remains one of the greatest sources of protein for people all over the world (NOAA, 1998; Figure 1.1; FAO, 2012). In Newfoundland and Labrador, the seafood industry employs over 20,000 individuals, with 10,398 people employed in harvesting of capture fisheries, 467 employed in hatchery and grow-out of aquaculture, and 9,214 people involved in the processing of aquaculture and capture fisheries (DFA, 2013). Fishing remains an important economic driver in Newfoundland and Labrador. Overall, 251,952 tonnes of seafood was landed in capture fisheries in 2012 which had a total landed value of $575 million (DFA, 2013). While the benefits that fishing offer are vast, negative biological and physical impacts that fishing places on marine ecosystems must be considered and eliminated or at the very least mitigated where possible.

Widespread biological impacts from the use of fishing gears are commonplace in many fisheries throughout the world. The most frequent examples of negative biological impacts associated with fishing gears include: overfishing, destruction of the benthos (i.e., removal of sponges, corals, and benthic invertebrates), bycatch (i.e., the capture of marine organisms not directly targeted for fishing, including undersized fish of the target species, marine organisms discarded at sea, and the incidental capture of non-target species retained for their commercial value), and ghost fishing (i.e., lost fishing gear that continues to capture organisms). Adverse changes to a marine ecosystem can occur from removing large numbers of marine organisms, affecting the community structure and food chains of ecosystems (NOAA, 1998). Recovery of a marine ecosystem and commercial fish stocks will thus be more difficult and take much greater time if fishing gear and fishing effort is not managed and regulated appropriately.

Many static fishing gears such as gillnets, pots/traps, and longlines have low physical impact on the environment when compared to mobile fishing gears such as trawls and dredges, mainly due to their passive fishing nature. The magnitude of their physical impacts are primarily a result of their weight and contact area on the seabed, and the extent to which the gear drags on the seabed during setting and hauling (Fuller et al., 2008; Grieve et al., 2011). Depending on the size of the gear this can be very minimal impact. In contrast, mobile fishing gears such as bottom trawls (otter trawls and beam trawls) and dredges can have highly destructive physical impacts on the marine environment (Løkkeborg, 2005). Bottom trawling is a common fishing method that involves the towing of a large net by a fishing vessel on the seabed to capture groundfish and crustaceans that are located on or above the seabed (Figure 1.2; Winger et al., 2010). Beam trawls and dredges operate in much the same way but primarily target species that are on or partly buried below the seabed (Løkkeborg, 2005). Consequently, there are several factors that can affect the relative impacts of different gear types such as the gear’s design and mode of operation, weight, towing speed, and intensity of use (National Research Council, 2002).

The physical impacts on the marine environment associated with bottom trawling, beam trawling, and dredging have been documented in several studies (de Groot, 1984; Jones, 1992; Schwinghamer et al., 1998; Auster and Langton, 1999; Norse and Watling, 1999; Gilkinson et al., 2006). The most apparent physical impacts of mobile gears are scraping and ploughing of the substrate, as evidenced by the remains of trawl and dredge tracks present in bottom sediments. These tracks can take weeks or even years to recover to previous conditions depending on the habitat type and frequency of natural disturbance (e.g., wave action and storms) in the trawled area (Jones, 1992). The otter doors of a bottom otter trawl most commonly create furrows in the sediment whereas beam trawls and dredges cause a flattening of the bottom topography (Løkkeborg, 2005). The disturbance of trawling and dredging on the seabed can lead to reduced habitat complexity and loss of essential fish habitat (National Research Council, 2002).

Another physical effect from trawling and dredging that can have several negative biological implications is the resuspension of seabed sediments (Churchill, 1989). When a trawl or dredge comes into contact with the seabed, the sediments are disturbed and this typically results in the sediment being dispersed into the water column. The resuspension of large quantities of sediment can reduce the quality of available food for filter-feeders such as sponges and molluscs, smother spawning areas, negatively affect feeding and metabolic rates of fish and benthic invertebrates, and cause damage to the gills of marine organisms (National Research Council, 2002). Resuspended sediments can also uncover dormant toxic contaminants (i.e., mercury), and increase nutrients in the water column which can lead to eutrophication and phytoplankton blooms; ultimately creating hypoxic conditions unsuitable for many marine organisms. Further physical effects include: changes in grain size and sediment texture, and overturning of boulders (Messieh et al., 1991; Jones, 1992; National Research Council, 2002). Overall these physical impacts reduce the structural complexity of marine habitats and often lead to decreased species diversity and increased predation of young marine organisms (Norse and Watling, 1999), however, positive benefits have also been documented (van Denderen et al., 2013). Benthic hard bottom habitats with high abundances of corals and other sessile fauna are the most drastically affected by bottom trawling, while effects have been shown to be less impactful on soft bottoms that did not contain large sessile invertebrates such as sponges and corals (Løkkeborg, 2005). Furthermore, little is known about the impacts that trawling has on deep muddy habitats and soft bottoms (Løkkeborg, 2005; He and Winger, 2010). It is important to note that the topic of seabed impact due to bottom trawling is controversial and highly debated with studies contradicting each other and difficulties in designing and conducting experiments, and consequently interpreting results. Regardless, issues relating to the public perception of trawling are a significant consideration for the drive for seafood sustainability (e.g., Marine Stewardship Council (MSC) certification), and addressing these issues of consumer and public perception to trawling are of great concern.

It is important to understand the negative impacts of different fishing gears in order to reduce their potential for harm to marine ecosystems and in the process enhance their ability to target specific commercial species. While the mitigation of all adverse effects of fishing gears on the marine ecosystem are not expected to be resolved from gear modification alone, it is important that technologies developed significantly reduce biological and physical impact on marine ecosystems without resulting in reduced profitability of the fishing operation (Valdemarsen and Suuronen, 2003). Reducing physical and biological impacts can lead to healthier ecosystems which in turn will aid in increasing fishery yields (NOAA, 1998).

## 1.2 Methods to reduce the negative impacts of fishing

Fisheries management is one of the most important steps in reducing some of the negative impacts of fishing. Fisheries management regulates and establishes policies such as fishing quotas and total allowable catches (TAC) of many commercial species in fisheries worldwide in order to sustain fish stocks. When fish stocks decrease, management may mandate reduced fishing effort or fishing quotas in addition to area closures in order to protect stocks (DFO, 2007). The establishment of marine protected areas (MPAs) is another management measure that can be applied to protect and conserve commercial and non-commercial fishery resources and habitats as well as areas high in biodiversity or biological productivity (Campbell and Simms, 2009).

Fisheries management also regulates the types of fishing gears that can be used to harvest certain commercial species of fish. Management can set mandates such as the number and size of pots/traps that can be set, the mesh size of netting, mandatory use of biodegradable twine, use of bycatch reduction devices (BRDs), and more. Although fisheries management plays a vital role in setting acceptable policies and regulations to reduce the negative impacts of fishing, there is a great need for additional research and development of innovative fishing gears designed to reduce physical and biological impacts in marine ecosystems. These efforts will aid in creating more efficient and sustainable fisheries.

Several innovative modifications to fishing gears have been developed over the years to mitigate problems and concerns in many fisheries throughout the world. In fact, dozens of research institutes and universities have active research programs that undertake applied research and development of innovative fishing technologies (e.g., ICES, 2013). Some examples of gear modifications that have been applied to traditional fishing gears are described below.

Bycatch is a classic example of a commonly identified problem many bottom trawling fisheries face. Bycatch is defined as the capture of marine organisms that are not directly targeted for harvest during a commercial fishing operation. This includes undersized fish of the target species, non-target marine organisms discarded at sea, and incidentally captured non-target species retained for their commercial value. The use of BRDs in trawls, such as the Nordmøre grid in Canada's northern shrimp fishery to reduce the capture of fish, and the use of turtle excluder devices (TEDs) in the United States and Australian shrimp fisheries to reduce the capture of sea turtles, have helped to significantly reduce bycatch rates. The use of the Nordmøre grid has been shown to decrease bycatch by 60 to 95% without compromising the capture rate of commercial quantities of shrimp (Broadhurst, 2000). The Nordmøre grid precedes the codend of the trawl and serves to permit the passage of shrimp into the codend while directing anything larger than the bar spacings of the grid upwards and out of an opening in the top of the net. First developed in Norway to reduce the capture of fish in shrimp trawls, it was tested in Canada in the 1990s and proved to be highly effective (Hickey et al., 1993). This prompted fisheries management to require all inshore and offshore shrimp fishing vessels in Canada's northern shrimp fishery to use the Nordmøre grid, which has been mandated for use since 1992 (DFO, 2007; Fuller et al., 2008).

Turtle excluder devices are another bycatch reduction device which functions similar to the Nordmøre grid, but has been used primarily to reduce turtle bycatch in the United States' Gulf of Mexico tropical shrimp fisheries, and Australia's northern prawn fishery (Brewer et al., 2006; Eayrs, 2007). A TED is composed of a grid preceding the codend which allows shrimp to pass through while directing sea turtles out through a "trap door." The use of TEDs have significantly reduced the capture of sea turtles in these shrimp fisheries; in some cases TEDs have been shown to exclude up to 97% of sea turtles under test conditions (Watson, 1981). Their effectiveness can be lower in the field however

(NOAA, 1998) and reduction of  mortality rates in sea turtles while using TEDs can be variable with about a 20-40% reduction in sea turtle mortality estimated for the Gulf of Mexico (Cox et al., 2007).

Reducing seabed impacts is another important concern in bottom trawling fisheries. To address this concern, some studies have assessed the effectiveness of modifications to the ground gear components of bottom trawls designed to have reduced seabed contact. An example of modifications to reduce seabed impact include the use of semi-pelagic trawl doors.

Semi-pelagic doors, unlike demersal trawl doors, are designed to avoid contact with the seabed. Hydrodynamic forces generated by these high aspect trawl doors aid in spreading the trawl open without the trawl doors making contact with the seabed (He and Winger, 2010). Two studies (DeLouche and Legge, 2004; He et al., 2006) examined the feasibility of semi-pelagic trawl doors in northern shrimp fisheries of the Northwest Atlantic and found that there was no significant effect on the size range or catch rates of shrimp in comparison to catches made by a traditional shrimp trawl. It was concluded however that greater monitoring of trawl sensor equipment was necessary for this method to work effectively (He and Winger, 2010). While the Newfoundland shrimp fishery has not presently adopted semi-pelagic trawls in its fleets, primarily due to fisherman's preferences in fishing gear, semi-pelagic trawling is being used successfully in other shrimp fisheries all over the world, including the Northeast coast of the United States, Europe, India, and parts of Asia (pers. comm., P. Winger, Director of CSAR, Marine Institute of Memorial University, St. John's, Newfoundland, Canada). A study by Brewer et al. (1996) in Australia also displayed encouraging results for the application of semi-pelagic trawl doors, with no sacrifice in the catch rates of red snappers and reduced bycatch of non-target species in comparison to a traditional bottom trawl.

## 1.3 Objectives and overview of research

The objective of the research summarized in the following chapters was to evaluate the catch characteristics of new, innovative fishing gears designed to mitigate specific ecological concerns in Newfoundland and Labrador's fisheries. The gears tested were designed to capture commercial quantities of targeted species while reducing negative ecological impacts such as bycatch and habitat degradation (i.e., seabed impact) by fishing gears. In evaluating the effectiveness of these fishing gears it will add to the growing body of research investigating gear modifications to reduce ecological impacts on marine ecosystems and also assist in refining current gear designs to fish at optimal levels.

The first experimental chapter (Chapter 2) investigates the effectiveness of several modifications to the entrance of the Newfoundland cod pot to capture species of flatfish while avoiding snow crab. To reach this goal, a number of treatments were performed.

Specifically, the effects of pot entrance shape, fish retention device (FRD) trigger diameter, FRD trigger spacing, and artificial light were investigated. Two at-sea experiments were carried out to measure the effectiveness of these treatments on catch rates and body lengths of flatfish such as American plaice (*Hippoglossoides platessoides*) and Greenland halibut (*Reinhardtius hippoglossoides*). Experiment I used several combinations of the above treatments in baited pots while Experiment II assessed the effects of bait absence and presence on flatfish catch rates for the two different entrance shapes in the presence of artificial light. Results of Experiment I showed that presence/absence of artificial light and entrance shape significantly influenced catch rates of American plaice. Experiment II confirmed the importance of entrance shape as well as the ability of artificial light alone to capture American plaice which subsequently reduced snow crab capture. Overall, the results exhibit the importance of entrance shape and demonstrate novel findings with regard to the importance of artificial light on capture rates of American plaice.

The second experimental chapter (Chapter 3) examines and compares the catch characteristics of a bottom otter trawl with ground gear designed to have reduced seabed contact area over that of a standard trawl currently used in the Newfoundland inshore shrimp fishery. Comparative at-sea fishing trials were performed using the alternate haul technique to determine if the experimental trawl had comparable catch rates of shrimp, body sizes of shrimp, and bycatch of non-targeted species to the standard trawl. Results of the fishing trials demonstrated that catch rates and body size of shrimp were comparable

between both trawls, however catch rates of non-targeted species were higher in the experimental trawl. Flume tank testing of the experimental gear demonstrated reduced bottom contact area of the ground gear. However, at-sea observations of mud caked on the ground gear of the experimental trawl and mud in the catch provides evidence that the experimental trawl most likely dug into the seabed during several fishing tows. It is proposed that this increased disturbance to the seabed resulted in higher catch rates of non-targeted species. In conclusion, additional modifications to the ground gear of the experimental trawl are required in order to reduce potential seabed impacts, and catch rates of non-targeted species.

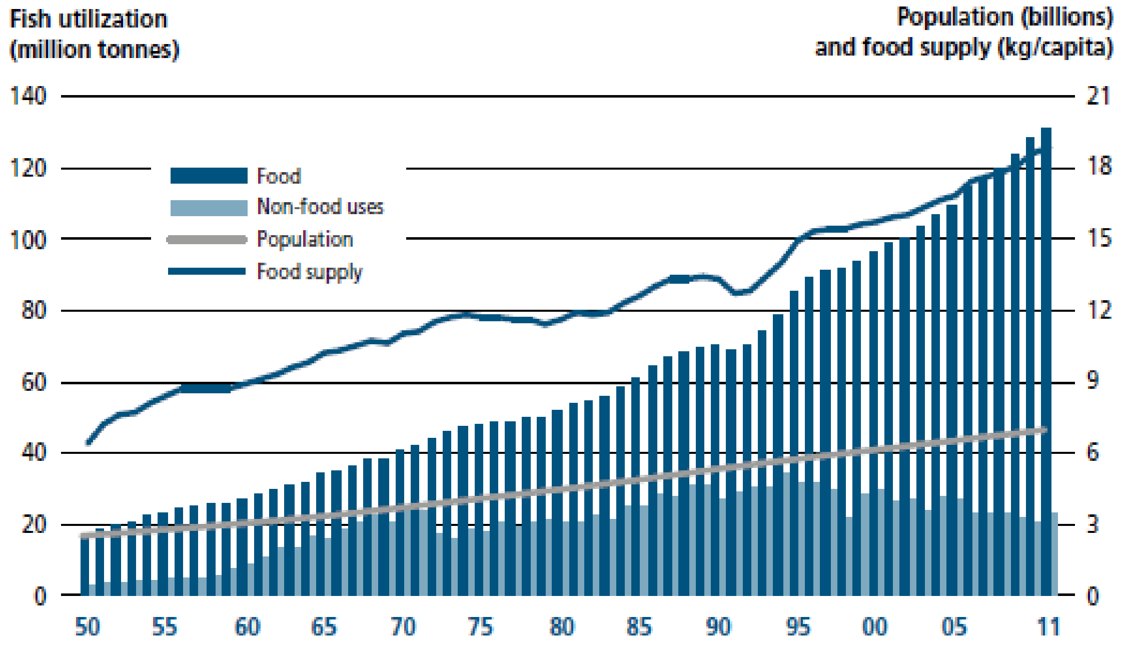


**Figure 1.1** Consumption and utilization of aquatic species in world capture fisheries and aquaculture (FAO, 2012).

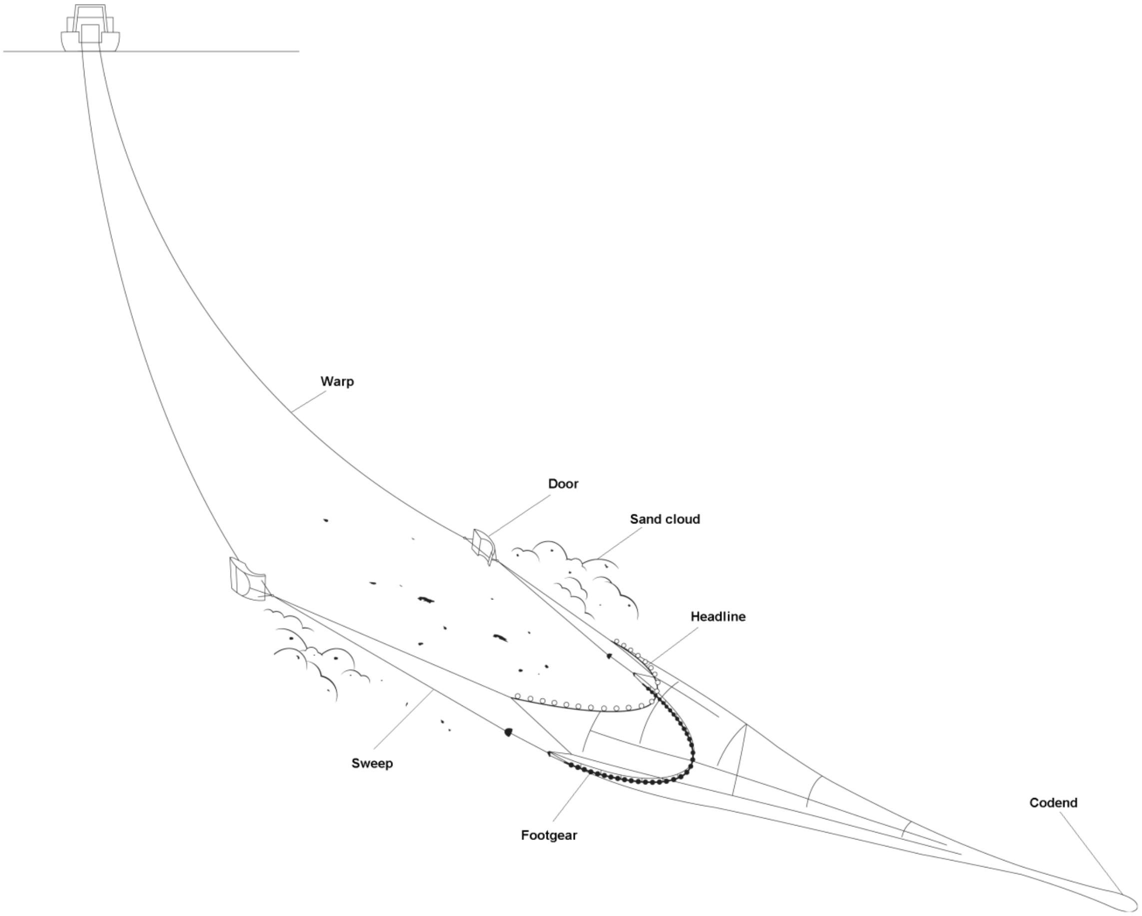


**Figure 1.2** Diagram of a bottom otter trawl outlining the major components of the gear. Some of the physical impacts of the trawl on the seabed are illustrated by the sand cloud produced from the doors and the sweeps of the trawl (Winger et al., 2010).

# Chapter 2. Modifying the Newfoundland cod pot to capture flatfish species while avoiding snow crab (*Chionoecetes opilio*).

## Abstract

Several years ago, a stewardship decision was made to voluntarily ban harvesting of Greenland halibut (*Reinhardtius hippoglossoides*) by gillnet in communities on the northeast coast of insular Newfoundland owing to a high incidence of snow crab bycatch. The development of a pot fishery to capture commercial quantities of this species would help small boat (<35′) fishermen regain access to this resource which has subsequently not been fished in over a decade. In the current study, the Newfoundland cod pot was modified in an effort to capture species of flatfish while attempting to reduce the incidental capture of snow crab (*Chionoecetes opilio*). Modifications to the entrance of the existing Newfoundland cod pot included entrance shape, fish retention device (FRD) trigger diameter, FRD trigger spacing, and presence/absence of an artificial fishing light within pots. Two at-sea experiments were carried out to assess the effectiveness of these treatments on flatfish capture. In Experiment I, combinations of the above treatments were employed with baited pots while Experiment II assessed the effects of bait absence and presence on catch rates of flatfish for two different pot entrance shapes in the presence of artificial light. Few Greenland halibut were captured throughout the experiments, however, captures of another commercial flatfish species, American plaice (*Hippoglossoides platessoides*), were substantial. Results of Experiment I indicate that presence/absence of artificial light and entrance shape significantly influenced catch rates

of American plaice, while in Experiment II entrance shape was significant in determining catch rates of American plaice. The results exhibit the overall importance of artificial light and entrance shape on capture rates of American plaice within the depths fished (340-530 m).

## 2.1 Introduction

This study marks the first time that the Newfoundland cod pot has been modified to target a different species of groundfish. The Newfoundland cod pot, designed by Walsh and Sullivan (2008) was shown to be effective at capturing commercial quantities of Atlantic cod (*Gadus morhua*) with one fisherman in particular reporting a catch of over 100 cod at over 300 kg in a single pot for an overnight set. With success in capturing cod, and the capture of flatfish species in baited pots documented in previous studies (Carlile et al., 1997; Pinkham and Salerno, 2007), it was hypothesized that a select few modifications to the entrance as well as providing a visual stimulus (artificial light) would demonstrate the ability of the Newfoundland cod pot to capture additional species of commercial fish, specifically flatfish such as Greenland halibut (*Reinhardtius hippoglossoides*, also known locally as turbot) and American plaice (*Hippoglossoides platessoides*), hereafter referred to as plaice.

The entrance design is perhaps the most important component for facilitating fish entry into a pot. An easily accessible entrance as well as a large surface area to hold captured organisms inside the pot effectively increases catch rates (Munro, 1974; Miller, 1979; Furevik, 1994; Bagdonas et al., 2012). In the current study, rectangular and circular entrance frames which respectively created trapezoid and conical funnels were both tested to determine the entrance shape that was most effective at capturing flatfish.

One-way non-return devices, also known as fish retention devices (FRD) serve to reduce escapement of fish entering the pot. One example of an FRD are triggers which are slim, finger-like projections of steel that are mounted on the entrance of the pot and may be pushed inward with ease. However, they are unable to swing in the opposite direction, thereby preventing escapement from the pot. The effects of triggers have been documented in many studies on fish and crustacean capture and have been shown to enhance catch efficiency by preventing escapement (High and Ellis, 1973; Miller, 1979; Saulthaug, 2002; Pinkham and Salerno, 2007).

Species and size selectivity may be altered by modifying the diameter and spacing of the FRD triggers. For example, a greater trigger diameter and decreased spacing between triggers situated in a pot entrance serves to increase the resistance of an organism to enter the pot. Spacing in turn may also affect the escape rate of fish if they are able to locate and swim back through the trigger spacings in the entrance. Escape may also be influenced by fish size and behaviour (High and Ellis, 1973; Furevik, 1994; Carlile et al., 1997). Modifications to the diameter of the individual triggers as well as the spacing between triggers were assessed in this study to determine their importance in capturing different species and sizes of fish as well as different species of crustaceans.

The use of artificial lights for fishing has been documented in several studies (Stoner, 2003; Marchesan et al., 2005; Rose et al., 2005). Artificial light can serve as an attractant to lure the targeted organism to interact with a pot through the stimulus of the light intensity itself (i.e., phototaxis) or by luring bait fish to the area that the target fish may then prey on. Bait effectively increases the surrounding area that may attract fish to approach a pot (Thomsen et al., 2010) via the dispersal of biochemicals from the bait plume. Initially, fish will use long range chemosensory cues that aid them in seeking out the olfactory chemicals released by the bait source within a baited pot. This bait plume can travel from great distances, but only downstream with the water current and it will lose its effectiveness as an attractant over time as the chemicals from the bait plume disperse. Artificial light on the other hand is an omni-directional attractant which effectively creates a 360° zone of light that may also help fish to more easily locate the entrances to enter baited pots since fish behaviour switches to utilize visual and lateral line stimulation when in close proximity to pots (Marchesan et al., 2005; Thomsen et al., 2010) in order to locate bait in pots and traps at short ranges. In this study, the use of artificial light was tested in non-baited and baited pots alike to determine the effectiveness of artificial light as an attractant in facilitating the entry of flatfish into the pots.

Initially, Greenland halibut was targeted in the following experiments due to a long-standing stewardship decision by fishermen in the region of Notre Dame Bay (Located in NAFO Division 3K) to discontinue the use of gillnets to fish for Greenland halibut on the historical Greenland halibut fishing grounds in the deep water bays. This decision was made in order to reduce the incidental bycatch and mortality of commercially important snow crab. Subsequently the Greenland halibut resource has not been fished in over 15 years. Potting Greenland halibut would therefore allow inshore fishermen in the under 35′ fleet to once again access this resource. Greenland halibut is a commercially important groundfish species in the Newfoundland and Labrador region which comprised over 68% of the total landed value of all groundfish species landed in 2012; 10,823 tonnes were landed at a value of over $53 million (DFA, 2013).

Pots were selected as an alternate fishing gear to target Greenland halibut due to several favourable characteristics that they possess in comparison to other static fishing gears such as longlines and gillnets, or mobile fishing gears such as trawls and dredges. To begin, start-up costs for pots are generally low, pots are flexible and transportable, they have minimal seabed impact, and permit the live capture of marine organisms (especially important in times where retrieval of fishing gear is not possible, e.g., inclement weather). Furthermore, pots can be very selective for different species and sizes, fish captured in pots produce higher quality fillets when compared to longlines and gillnets, and non-targeted species captured in pots may be returned safely to the sea if handled quickly and carefully (Sainsbury, 1986; O’Brien and Dennis, 2006; Thomsen et al., 2010;

Suuronen et al., 2012). The latter attribute was an especially important factor for selecting pots as the alternative harvesting gear of flatfish in this study because it would aid in mitigating the mortality of snow crab captured as bycatch in the pots.

As with all fishing gears, there are limitations which must be considered. The greatest limitations to using pots include: ghost fishing of lost pots, and low capture efficiency of many fish species (Thomsen et al., 2010; Suuronen et al., 2012). Fortunately there are ways that these problems can be alleviated. Pots can be fitted with biodegradable twine (e.g., Legge et al., 2009) and escape vents (Winger and Walsh, 2007; 2011) to reduce the probability of fish and crustaceans being retained in lost pots. Low capture of fish species is an obstacle that this study is attempting to solve through several modifications to the original Newfoundland cod pot. The pots used in this study have two large accessible entrances for each pot with a large bottom area (1.98 m × 1.98 m) and a floating net bag to effectively increase the inner volume of the pot and allow greater fish capture.

This study aimed to quantify the effects of 1) entrance shape, 2) FRD trigger diameter, 3) FRD trigger spacing, and 4) presence/absence of artificial light on capture rates of flatfish species (Greenland halibut and American plaice). Two at-sea experiments were carried out during this study. Experiment I used several combinations of the above treatments while Experiment II used information from Experiment I to standardize various treatments before assessing the effects of bait absence and presence for the two different entrance shapes in the presence of artificial light. Unfortunately very few Greenland halibut were retained in pots throughout this study. Instead, encouraging numbers of American plaice were captured almost exclusively in the presence of artificial light. It is important to note that fish potting studies are still in their infancy but are attracting increased interest as a means to reduce ecological impacts. Therefore the information obtained in this study will help to contribute to future studies of the potential for artificial light as an attractant in capturing flatfish species as well as outline the most optimal pot configurations for flatfish capture.

## 2.2 Materials and Methods

### *2.2.1 Potting Technology (Modification of Newfoundland Cod Pot to Capture Flatfish Species: Greenland Halibut and American Plaice)*

The potting technology used in this study consisted of the Newfoundland cod pot (Walsh and Sullivan, 2008) with modifications made to the entrance shape, the diameter and spacing of the triggers on the fish retention device (FRD), and the presence or absence of artificial light. These modifications were carried out at the Centre for Sustainable Aquatic Resources (CSAR), Fisheries and Marine Institute of Memorial University. The frame of each of the collapsible cod pots (Figure 2.1) was constructed from 15.9 mm (5/8 inch) round stock steel and measured 1.98 m x 1.98 m x 1.02 m high. Standard 100 mm size (4 inch) green polyethylene mesh covered the top, bottom, and sides of the frame. Each pot had a large floating net bag which serves to increase catch rates. Additionally, the net bag may function as a large codend that assists in the landing and handling of the catch. A total of twelve pots were used in this study. One experimental pot modification was the shape of the entrance, with pots containing either rectangular entrances (60 cm × 20 cm) with trapezoid funnels or circular entrances (40 cm diameter) with conical funnels. Pot entrances were located on opposite sides of each pot and the funnels were made from 5.1 cm (2 inch) white knotless twine. The one-way fish retention devices allow organisms to enter the pot but prevent them from exiting the gear. Two different FRD trigger diameters (3 mm and 5 mm), and three different FRD trigger spacing (52 mm, 109 mm, and 166 mm) treatments were tested during this study. Space between the steel triggers of the FRD was easily altered by removing individual triggers. This effectively created three FRD trigger spacings: 1) 52 ± 3 mm, 2) 109 ± 4 mm, and 3) 166 ± 3 mm. Of the 12 pots used in the study, 6 had trapezoid entrances, 3 of which contained 3 mm diameter triggers, and 3 contained 5 mm diameter triggers. The other 6 pots had conical entrances, 3 of which contained 3 mm diameter triggers, and 3 contained 5mm diameter triggers. See Table 2.1 for full list of treatments.

The effect of the presence/absence of artificial light was also tested to observe if flatfish would respond to light as a stimulus to enter the pots. The artificial light source was commercially available fishing lights that did not possess an identifiable brand name. Each fishing light possessed two green LED lamps (532 nm peak wavelength, line width at $E_c/Z = 26$nm) situated within a waterproof housing containing a power source of two AA batteries (Figure 2.2). Using a light meter it was found that the fishing lights emitted a luminance of approximately 3.0 lux from a distance of 30 cm in air. These lights could function up to a maximum operating depth of 700 m. Lights were hung vertically from the centre of the pot, between the two entrances, with the light shining downward.

### *2.2.2 Gillnet Survey to Verify Presence of Greenland Halibut at the Study Site*

Two gillnets were deployed 12 days prior to the beginning of the potting experiments as well as on Day 5 of the experiments. All gillnets were deployed on the seabed within the study site. The gillnets used were 91 m (50 fathom) in length and consisted of 165 mm (6.5 inch) mesh throughout. Soak time for gillnets was two nights (48 hours) before being hauled.

### *2.2.3 Experimental Sea Trials*

Sea trials were conducted from September 17 to October 4, 2012, aboard the 34′11″ commercial fishing vessel *Ocean Breeze I.* The study site (Figure 2.3) was located within a deep water channel located between the community of Brighton and Long Island. Typically, pots were set for 24 hours before being hauled. However, for two of the sample periods, Day 6 and Day 9, inclement weather delayed pot retrieval for 48 hours. Refer to Table 2.1 for full list of treatments in Experiment I and Experiment II.

Pots were fished in depths ranging from approximately 340 m (185 fathom) to 530 m (290 fathom). Temperature data loggers were attached to pots to obtain bottom temperature within the study area. Experimental pots that were baited used a standardized bait regime of approximately 0.75 kg squid and 0.75 kg herring each cut into three pieces and placed in two bait bags. A bait bag was placed in front of each entrance. Pots were freshly baited after each haul back and used bait was disposed of outside the study area. Fish catches were grouped by species, weighed (± 10 g), and individual body lengths (± 1 mm) were recorded. In addition, body width (dorsal fin to anal fin) was recorded for flatfish with fins compressed against the side of the body. Crustaceans were grouped by species and weighed (± 10 g). Catch rates of a particular species were defined as the weight in kilograms of the species captured per pot haul (i.e., kg/pot haul). All organisms were released alive at the capture site. After the catch information was collected, the pots were re-baited and then returned to approximately the same location from which they had been hauled.

Two experiments were performed in this study. Experiment I observed the effects of entrance shape, FRD trigger diameter, FRD trigger spacing, and presence/absence of artificial light on catch rates. In Experiment II, information from Experiment I was used to standardize entrance shape and FRD treatments to allow more rigorous testing of the effects of bait presence/absence and artificial light on catch rates of fish and crustaceans (Table 2.1). Experiment II observed the effects of presence/absence of bait for each entrance shape on catch rates with 5 mm FRD trigger diameter, 166 mm FRD trigger spacing and artificial light present in all pots. The full list of treatments is summarized in Table 2.1.

### *2.2.4 Data Analysis*

Analysis of parametric data was performed in SPSS® Statistics Version 19 (IBM Corp., 2010). For Experiment I, analysis of American plaice catch weights included a three-way ANOVA which examined the effect of independent variables: entrance shape, trigger diameter, and trigger spacing on the dependent variable, plaice catch rate. Similarly, a three-way ANOVA was performed for plaice body length examining the effect of independent variables entrance shape, trigger diameter, and trigger spacing on the dependent variable, plaice body length. For Experiment II, a two-way ANOVA was used to examine the effect of independent variables entrance shape, and presence/absence of bait on dependent variable, plaice catch rate. Likewise, a two-way ANOVA was performed to examine the effect of independent variables entrance shape, and presence/absence of bait on dependent variable, plaice body length.

In analyzing snow crab catch rates for Experiment I, four-way, three-way, and two-way ANOVAs were employed to measure the effects of independent variables such as presence/absence of artificial light, entrance shape, FRD trigger diameter, and FRD trigger spacing on dependent variable snow crab catch rate. These ANOVAs however either violated Levene’s equality of variance test or had interaction terms and therefore independent-samples t-tests and one-way ANOVAs were carried out to analyze the effects of the independent variables separately on snow crab catch rates. These analyses were performed separately for each artificial light treatment as it was observed that snow crab catch rates were substantially higher when artificial light was present as opposed to light absent. I wanted to see if I could determine whether this result was due to light effectively increasing the area of attraction of the pot or if light facilitated the ability of the crab to enter the pot due to one or more of the other pot modifications (i.e., entrance shape, FRD trigger diameter, FRD trigger spacing). First, t-tests were performed comparing the effects of FRD trigger diameter on mean catch rates of snow crab across each entrance shape and FRD trigger spacing in the absence of artificial light and also when artificial light was present. One-way ANOVAs were performed assessing the effect of FRD trigger spacing on mean catch rates of snow crab across each entrance shape and FRD trigger diameter in the absence of artificial light and also when artificial light was present. Independent-samples t-tests were completed comparing the effect of FRD trigger diameter on the mean catch rate of snow crab for each entrance shape in the absence and presence of an artificial light source. Finally, t-tests were used to assess the effect of entrance shape on the mean catch rate of snow crab for each FRD trigger diameter when artificial light was absent and present. For Experiment II, an independent-samples t-test was used to compare the effect of bait presence/absence on mean catch rates of snow crab for each entrance shape.

Bonferroni's adjusted alpha level was used to control for family-wise error rate in multiple t-test comparisons. Significance level for all tests were set to Bonferroni's adjusted alpha level or 0.05. For each ANOVA performed, full factorial models examining the main effects and the interaction terms were completed. If interaction terms were observed to be statistically insignificant ($p > 0.05$) in the full factorial models than a reduced model examining only the main effects were completed in order to increase the power of the ANOVA tests and determine if there were any observed significant differences between treatments for the full factorial and reduced models. If no significant differences were observed in the reduced models then the results of the full factorial model were reported. Levene's equality of variances was used to validate homogeneity of variances for all ANOVAs. All catch weights were $\log_{10}(n+1)$ transformed and body lengths $\log_{10}$ transformed to improve on normality and homogeneity of variances.

## 2.3 Results

### *2.3.1 Gillnet Surveys: Verification of Greenland Halibut Presence in Study Area*

Two gillnets hauled back on September 7, 2012 were set at 366 m and 521 m. The gillnet set deployed at 366 m captured nine Greenland halibut with total lengths ranging from 38-46 cm (Mean = 40.8 cm). The gillnet set at 521 m captured eight Greenland halibut with total lengths ranging from 38-51 cm (Mean = 44.3 cm). Only information on Greenland halibut were collected in these pre-potting gillnet sets.

Two gillnets were also deployed on Day 5 of the potting experiments. Once again Greenland halibut were captured in both gillnets. The first gillnet was set at a depth of approximately 360 m and captured four Greenland halibut with total body lengths ranging from 44-50 cm (Mean = 47.2 cm). This gillnet also captured 13 Atlantic cod, six redfish, and nine snow crab. The second gillnet was set at a depth of approximately 520 m and captured 10 Greenland halibut with total body lengths ranging from 41-48 cm (Mean = 44.8 cm). Additionally, two American plaice, one eelpout, and 18 snow crab were captured in this net. A total of five Greenland halibut were euthanized and dissected for stomach content analysis. The stomachs were all found to be empty. It is unclear whether the Greenland halibut were not feeding prior to being captured or if evacuation of the stomach contents occurred following capture in the net.

### *2.3.2 General Observations and Total Catch of Potting Experiments*

Overall, for both experiments, American plaice dominated the fish captures followed by Atlantic cod, redfish, Greenland halibut, spotted wolffish, and miscellaneous fish (grenadier, eelpout, and sculpin) (Table 2.2). Snow crab dominated the crustacean captures, followed by toad crab (Table 2.2). Vemco temperature data loggers logged a consistent bottom temperature of 3 °C throughout the study.

Artificial light proved to be a very important factor influencing the capture of American plaice. Individual plaice were captured almost exclusively with light present (i.e., 99%) as opposed to light absent treatments in Experiment I; 85% of pots that contained artificial light captured plaice in contrast to only 4% of pots with light absent (Table 2.2). Noting the large discrepancy in abundance of plaice between light treatments, Experiment II was designed to examine the effectiveness of artificial light in pots with bait present and absent. Also, during Experiment I, although the same percentage of pots were occupied by Atlantic cod, a greater number of cod were captured in pots containing artificial light. Further, throughout Experiment I, a greater biomass of snow crab was captured in the presence of artificial light with 1.7× more snow crab captured in pots containing artificial light (Table 2.2).

Artificial light was also found to be important in the capture of plaice during Experiment II with more plaice captured overall in pots containing artificial light and no bait, as opposed to pots containing artificial light and bait. Overall, 1.75× more plaice were captured in pots containing artificial light and no bait (Table 2.2). Although few Atlantic cod were captured during Experiment II, five out of six were captured in pots containing light and no bait. Conversely, snow crab were captured more often and total catches were 5× higher in pots containing light and bait (Table 2.2).

### *2.3.3 Experiments I and II*

#### *2.3.3.1 American Plaice*

As was previously outlined, artificial light was very important in the successful capture of American plaice with approximately 99% of plaice captured in pots containing an artificial light source during Experiment I. Subsequently, parametric analyses of plaice catch rates and total body lengths were restricted to pots where artificial light was present.

Results of a full factorial three-way ANOVA analyzing the effects of pot entrance shape, FRD trigger diameter, and FRD trigger spacing on mean catch rates of American plaice captured in Experiment I (Table 2.3) indicated entrance shape ($F_{1,48} = 11.111$, $p = 0.002$) and FRD trigger spacing ($F_{1,48} = 3.601$, $p = 0.035$) significantly influenced catch rates, while there was no effect of FRD trigger diameter ($F_{1,48} = 0.995$, $p = 0.324$; Table 2.3). A reduced model three-way ANOVA with the interaction terms removed was performed sequentially; however there were no significant changes to the p-values of the source variables. Overall, pots with trapezoid entrances (Mean = 1.263 ± 0.148 kg/pot haul (±1 SE)) captured a significantly greater biomass of plaice (1.8× more plaice) over the pots with conical entrances (Mean = 0.697 ± 0.165 kg/pot haul (±1 SE)) ($t_{58} = 3.112$, $p= 0.003$; Figure 2.4).

The relationship between body length and width of plaice captured in both conical and trapezoid pots throughout the study is illustrated in Figure 2.5. A full factorial three-way ANOVA analyzing the effects of entrance shape, FRD trigger diameter, and FRD trigger spacing on mean plaice body lengths indicated no interactions. Therefore a reduced model three-way ANOVA examining only the main effects was used and indicated that both FRD trigger spacing ($F_{2,247} = 3.318$, $p = 0.038$) and FRD trigger diameter ($F_{1,247} = 8.396$, $p = 0.004$) were significant (Table 2.4). The mean body lengths of plaice were subsequently analyzed for each FRD trigger spacing of the 3 and 5 mm FRD trigger diameters. Mean body lengths of plaice varied without trend for each FRD trigger spacing containing the 3 mm FRD trigger diameter, while mean body lengths of plaice decreased with increasing FRD trigger spacing containing the 5 mm trigger diameter (Table 2.5). Next, mean body lengths of plaice were analyzed by grouping data from both the FRD trigger diameters and entrance shapes to verify the differences between mean body lengths. Through this analysis it was determined that mean body lengths of plaice varied without trend between the FRD trigger spacing treatments (Table 2.6). Post-hoc analysis identified two homogeneous subsets with the 52 mm and 166 mm trigger spacing forming one subset and the 166 mm and 109 mm trigger spacing forming the second subset. The maximum difference between treatments however was minor, at 2.72 cm (Table 2.6). The percent frequency plot for individual American plaice for each of the three FRD trigger spacings (Figure 2.6) indicates that the 52 mm FRD trigger spacing captured the greatest frequency of undersize (<30 cm) plaice followed by the 166 mm, and 109 mm FRD trigger spacing.

With regard to Experiment II, a two-way ANOVA indicated entrance shape had a significant effect ($F_{1,36} = 6.793$, $p = 0.014$) on American plaice catch rates while presence/absence of bait had no significant effect ($F_{1,36} = 0.210$, $p = 0.650$; Table 2.7). Removing the interaction term and running a reduced two-way ANOVA model did not significantly affect this result. Trapezoid pots which contained light and no bait captured substantially (1.6-1.7×) more plaice than conical pots for both bait treatments as well as 1.4× more plaice than trapezoid pots containing bait (Figure 2.7).

A two-way ANOVA indicated that the bait treatments had a significant but small effect ($F_{1,150} = 4.083$, $p = 0.045$) on the mean body length of American plaice while entrance shape had no effect ($F_{1,150} = 1.651$, $p = 0.201$; Table 2.8). Running a reduced two-way ANOVA model did not change this result. Plaice captured in pots that did not possess bait exhibited a mean body length of $28.3 \pm 0.7$ cm (±1 SE) while plaice captured in pots containing bait exhibited a mean body length of $30.8 \pm 1.0$ cm (±1 SE). The mean difference in body length therefore was 2.5 cm between bait treatments. Similar to Experiment I, undersized ($< 30$ cm) plaice were well represented (Figure 2.8).

Partially eaten, deceased American plaice were observed in pots throughout both experiments. This displayed evidence of snow crab predation on small American plaice, which occurred in 31% of pot sets where both species were captured together.

#### *2.3.3.2 Snow Crab*

Homogeneity of variance was violated for a four-way ANOVA analyzing the effect of pot entrance shape, FRD trigger diameter, FRD trigger spacing, and presence/absence of artificial light on mean catch rates of snow crab. Further, homogeneity of variance was violated on a three-way ANOVA analyzing the effects of pot entrance shape, FRD trigger diameter, and FRD trigger spacing on mean catch rates of snow crab captured in pots with artificial light present, while interaction effects among main terms were observed in treatments with artificial light absent for Experiment I. Due to the inconsistencies in the three-way ANOVAs, a series of full factorial and reduced two-way ANOVAs were performed on the above variables to determine if any of these variables were statistically significant or had significant interaction terms. Many of these tests violated Levene's equality of variances which prompted analyses examining the effect of each of the pot modifications on snow crab catch rates separately for each light treatment. The purpose of this was to determine if there were differences among snow crab catch rates and/or observable trends between and within different pot entrance shapes, FRD trigger diameter, and FRD trigger spacing treatments for Experiment I.

FRD trigger diameter did not have a significant effect on mean catch rates of snow crab in the absence of artificial light among FRD trigger spacings for both the conical and trapezoid entrance pots (Table 2.9). However, conical pots fitted with 3 mm diameter triggers captured substantially lower biomass (2.1-11.6× less) of snow crab at all FRD trigger spacing treatments compared to the trapezoid pots (Table 2.9). Analysis of the effect of FRD trigger diameter on snow crab catch rates in the presence of artificial light revealed that the conical entrance with 166 mm trigger spacing captured significantly less snow crab in the 3 mm diameter FRD trigger treatment than the 5 mm diameter FRD trigger treatment ($t_{10} = 5.201$, $p = 0.001$; Table 2.10). Once again, conical entrance pots fitted with 3 mm diameter FRD triggers captured substantially fewer (3-7× less) snow crab than those fitted with 5 mm diameter FRD triggers (Table 2.10).

Next, the effect of FRD trigger spacing on snow crab catch rates was analyzed within the trigger diameter treatments for each entrance shape. The analyses revealed that there were no significant differences found between trigger spacing in the absence (Table 2.11) or presence (Table 2.12) of an artificial light source. These results for the FRD trigger diameter and FRD trigger spacing treatments indicate that FRD treatments can be combined across FRD trigger spacing to investigate the effects of FRD trigger diameter for each entrance shape (Table 2.13) as well as the effect of entrance shape for each FRD trigger diameter (Table 2.14) on snow crab catch rates. There were significant differences in mean snow crab catch rates between FRD trigger diameters for the conical entrance in the absence ($t_{22} = 2.614$, $p = 0.016$) and presence of artificial light ($t_{28} = 3.273$, $p = 0.003$; Table 2.13). The 5 mm diameter trigger captured over 5× more crab in the absence of light and over 4.5× more crab when light was present in the pots (Table 2.13). There were no significant differences in mean snow crab catch rates for the trapezoid entrance between FRD trigger diameters in either the absence or presence of artificial light (Table 2.13).

With regard to the effect of entrance shape for each FRD trigger diameter on snow crab catch rates, there were significant differences in mean snow crab catch rates found between entrance shapes in the 3 mm diameter FRD trigger treatments in the absence ($t_{22}$ = 4.199, p = <0.001) and presence of artificial light ($t_{28}$ = 3.328, p = 0.002; Table 2.14). In both cases, trapezoid entrances captured approximately 4.5× more crab than conical entrances (Table 2.14). Conversely, no significant differences in mean snow crab catch rates were found between entrance shapes in the 5 mm diameter FRD trigger treatments in the absence ($t_{22}$ = 0.628, p = 0.536) or presence of artificial light ($t_{16}$ = 1.012, p = 0.327; Table 2.14). Overall, conical pots were found to capture more snow crab in pots with 5 mm diameter FRD triggers, and trapezoid pots captured significantly more crab with the 3 mm diameter FRD triggers (Table 2.14).

Regarding Experiment II, homogeneity of variance was violated for a two-way ANOVA analyzing the effects of pot entrance shape and presence/absence of bait on snow crab catch rates. Therefore the effect of bait presence/absence was analyzed separately for each pot entrance shape. A significant effect of bait absence/presence on mean catch rates of snow crab was found for crab captured in conical pots ($t_{16}$ = 6.502, p = <0.001) but not in trapezoid pots ($t_{16}$ = 1.191, p =0.251, Table 2.15). Over 50× more crab were captured in the conical entrance with bait as opposed to no bait, while 1.6× more crab were captured in the trapezoid entrance with bait as opposed to no bait (Figure 2.9).

#### *2.3.3.3 Greenland Halibut*

Overall, only five Greenland halibut were captured in pots throughout the course of this study, with all captures occurring in Experiment I when the artificial light source was absent. Four of the Greenland halibut were captured alive and ranged in length from 35-42 cm (Mean = 37.5 cm) while the fifth Greenland halibut was partially eaten by snow crab. Four of the five Greenland halibut were captured in pots with trapezoid entrances.

## 2.4 Discussion

This study aimed to capture flatfish species such as Greenland halibut and American plaice while avoiding snow crab through modifications to the entrance of the Newfoundland cod pot design, as well as the application of an artificial light lure. Several treatments such as pot entrance shape, FRD trigger diameter, FRD trigger spacing, and presence/absence of artificial light were examined in Experiment I while the effect of presence/absence of bait on the capture of organisms for each pot entrance shape using artificial light, 5 mm FRD trigger diameter, and 166 mm FRD trigger spacing in all pots was examined in Experiment II. Overall, these experiments demonstrated the importance of entrance shape and artificial light in the capture of American plaice. The application of artificial light as a potential lure for fish to enter pots has not been well studied. Therefore the results obtained in these experiments are quite novel and are valuable information moving forward in the development of potting technology and techniques to capture fish species.

Observed abundances of flatfish captured in this study were greater than observed abundances of flatfish captured by baited pots in a previous study conducted by Pinkham and Salerno (2007). They targeted winter flounder (*Pseudopleuronectes americanus*) with their pots and captured a total of 26 winter flounder over three seasons (i.e., summer, winter, and spring; 1,160 traps hauled over 33 trips) of potting trials. These flounder ranged in size from 15 to 42 cm with half (13) of the flounder being at or above the minimum legal landing size of 30.5 cm. In comparison, five Greenland halibut and 422 plaice were captured over twelve fishing days in the current study. The plaice ranged in size from 18 to 47 cm and 168 individual plaice (approximately 40% of all plaice captured) were either at or above the minimum legal landing size of 30 cm.

The presence of an artificial light source in the pots was found to be an essential factor influencing catch rates of American plaice in this study. Plaice were captured almost exclusively when artificial light was present making it a significant factor for targeting plaice when using potting gear. Plaice behaviour in relation to artificial light has not been studied before so these are novel findings. American plaice commonly inhabit depths of

20-180 m (Iglesias et al., 1996) which is shallow enough for natural light to penetrate. This may explain the willingness of plaice to enter pots containing a relatively high intensity (3.0 lux) green light source in the fairly deep depths of the study site (~340-530 m).

Pot entrance shape proved to be another important factor influencing American plaice catch rates. Plaice were captured in the trapezoid entrance pots in greater quantities as opposed to the conical entrance pots in both experiments. I hypothesize that this is due to the flattened entrance and funnel of the trapezoid pots which would conceivably be more conducive for a flatfish such as plaice to rest upon before pushing past the triggers and entering into the pot in contrast to the rounded funnel of the conical entrance.

In Experiment II, the effect of the absence and presence of bait on catches of plaice and crab were examined. Baiting pots and traps serves to increase the rate of entry until the bait odour is exhausted, after which time the rate of entry decreases (Thomsen et al., 2010). During Experiment II, catches of plaice were found to be significantly greater (2.3× more) in the trapezoid entrances over the conical. I believe that this difference is again related to the preferred movement of American plaice over the more flattened funnel of the trapezoid entrance. Interestingly, substantially more plaice were captured in both entrance shapes with bait absent and only light present. Conversely, less snow crab biomass was captured in both entrance shapes with bait absent and only light present.

During the study it was observed that a number of pots showed evidence of snow crab predation on American plaice. This was determined by the appearance of partially eaten, deceased plaice in pots containing large numbers of snow crab. It is a possibility that there were more plaice captured in pots when bait was absent due to fewer snow crab being captured in non-baited pots. Plaice were perhaps more willing to enter pots containing fewer numbers of snow crab in order to reduce the possibility of predation by snow crab. There are however several other reasons why a fish or crustacean may enter a pot in the absence of bait such as: random movements, inhabiting a pot as a residence or shelter, curiosity, intraspecific social behaviour, or locating prey (High and Beardsley, 1970).

A high percentage of plaice captured in this study were juveniles that would be considered undersized (< 30 cm) in a commercial fishery. It was observed that there was mud on pots that were hauled up from the seabed for a number of pot hauls, indicating a muddy bottom habitat. Walsh and Brodie (1988) found that most catches of juvenile American plaice found on the southern Grand Bank were located in areas of a large mud deposit. It is believed that muddy bottoms may serve as nursery areas for juveniles that feed on small infaunal invertebrates in these habitats and they may more efficiently avoid predators by burying themselves in the sediment (Walsh, 1991). The study area for these experiments may be an important nursery ground for juvenile plaice which would explain the large numbers of juveniles captured in this study. To reduce the capture of juvenile plaice in pots, the mesh-size in the bag of the pot could be increased to allow the escapement of undersized fish as the pot is hauled to the surface. The 110 mm mesh used throughout the pot stretches to approximately a 55-60 mm opening which corresponded to the smallest body width of American plaice captured during the study (Figure 2.5). An increased mesh size that could create an approximate 100 mm opening when stretched would allow for juveniles to escape through the meshes while legal sized (≥30 cm) adult plaice could be captured (Figure 2.5).

The only pot entrance modification that was found to have a significant effect on the catch rates of snow crab in Experiment I was FRD trigger diameter. There were no significant effects of entrance shape or FRD trigger spacing, and no significant effect of absence/presence of artificial light on snow crab catch rates. However it is worth noting 1.5× more snow crab were captured in the presence of both bait and artificial light during Experiment I which would be a substantial improvement for fishermen targeting snow crab with baited pots.

In the conical entrance pots, snow crab catches were much lower for the 3 mm diameter FRD trigger over the 5 mm diameter FRD trigger. It was discovered during the experiments that the length of individual 3 mm diameter triggers in the conical entrance pots were too long for this narrow gauge of steel. The triggers in these pots were easily bent and sometimes became entangled in the mesh of the funnel and thus would not be easily manipulated by fish and crustaceans attempting to push past them. The 3 mm FRD triggers for the trapezoid entrances on the other hand were at an appropriate size where they were not easily bent and did not become entangled in the mesh of the funnel, which is perhaps what allowed for more comparable catches with the 5 mm FRD triggers.

As expected, less snow crab were captured in pots with bait absent versus pots with bait present in Experiment II. Snow crab are more olfactory than visual predators and without a bait plume to help guide them towards the pot from a distance (Vienneau et al., 1993) and fresh bait to entice them to enter the pot, there were significant decreases in snow crab catch rates in pots without bait. The presence of artificial light in all the pots for Experiment II still however attracted snow crab to enter the pots. It is possible that snow crab entered the pots to feed on any other fish (i.e., American plaice) that were already captured. No significant difference in mean catch rates of snow crab between entrance shapes was found. However, the conical entrance pots with bait present captured significantly more (over 50× more) snow crab than conical pots with bait absent and more snow crab was captured overall in the trapezoid baited pots over the trapezoid non-baited pots.

Greenland halibut were present in the study area as indicated by exploratory gillnets set prior to and during the experiments. The degree of Greenland halibut densities within the study area however was not determined. Traditional ecological knowledge of Greenland halibut densities within the study area by fishermen indicated that historically, Greenland halibut were present in large quantities. However, very few Greenland halibut were captured in pots throughout the study. A study by Valdemarsen (1975) showed similar results where he tested collapsible pots on fishing grounds for Greenland halibut but he was not able to capture any of the target species. However, on the same fishing grounds using longlines he found the catches to be much more substantial.

The five Greenland halibut that were captured during the current study were captured only in Experiment I when artificial light was absent. No previous studies have observed the response of Greenland halibut to artificial light; nevertheless it is probable that Greenland halibut avoided the light source due to its high intensity (3.0 lux) and/or wavelength (green - 532 nm peak wavelength) which may have been too bright for them at such depths. A previous study by Machesan et al. (2005) found that green colored light induced strong repulsion in European seabass. Other studies (Imamura, 1958; 1959) have found that many fish species prefer to aggregate in dim areas just outside the brightest areas of a pot. Also, Greenland halibut are visual predators that are more attracted to moving as opposed to stationary prey, similar to another flatfish species, the winter flounder (Macdonald, 1983). Greenland halibut are adapted to hunt at low light to no light conditions in great depths of water (400-1,500 m). Young (age 1-2) juvenile Greenland halibut have been observed to migrate up through the water column, but only at night, and particularly around midnight which is in contrast to older juveniles and adult Greenland halibut that have been documented to remain close to the ocean floor during the day and night (Jorgensen, 1997) all under low light conditions. The illuminance of a full moon on a clear night can be from 0.27-1.00 lux (Bunning and Moser, 1969) which is a much lower intensity of light in comparison to the artificial lights used throughout this study (i.e., 3 lux). It is conceivable that Greenland halibut were sensitive and not well adapted to the relatively high illuminance of the artificial light source and perhaps remained on the dimly lit periphery of the illuminated zone of the artificial light. American plaice were captured almost exclusively in the presence of artificial light while no Greenland halibut were captured in pots containing artificial light which would suggest a considerable difference in each flatfish species' level of attraction toward the light source. If the illuminance of the light used in the experiment could be diminished or placed in an area of the pot where the light illuminating the entrances appeared dimmer perhaps more Greenland halibut would enter the pots. For example, if the light was attached to the float connected to the net bag that rises several meters off the seabed then it is possible Greenland halibut may be more attracted to enter the pot.

Since Greenland halibut are more visual predators, perhaps the use of an artificial mobile bait inside pots would increase catch rates of Greenland halibut. Experiments with Atlantic halibut (*Hippoglossus hippoglossus*) raised in captivity have demonstrated they will only enter pots when the bait was gently moved to simulate movement of their prey (pers. comm., S. Grant, Research Scientist, Marine Institute of Memorial University, St. John's, Newfoundland, Canada). Similarly, wild Greenland halibut held under laboratory conditions would not feed on capelin until they were moved about on a fishing line throughout the water column (pers. comm., Y. Lambert, Research Scientist, Maurice

Lamontagne Institute, Mont-Joli, Quebec, Canada). In the current study, bait was immobile and concealed in bait bags. These observations suggest future Greenland halibut potting studies should consider adding moving bait such as a pendulum mounted artificial bait inside pots to entice Greenland halibut to enter in addition to reducing the intensity of the illuminance of the artificial light source.

Atlantic cod catch rates were found to be greatest in treatments with artificial light present with 65% of cod in Experiment I captured in treatments with an artificial light source and bait present and 83% of cod captured in Experiment II occurring in pots with artificial light only. These results demonstrate the important role that artificial lights could have on improving catch rates of cod in pots and it is recommended that more experiments be performed using artificial light in pots to target Atlantic cod.

At one time the American plaice fishery was the largest fishery for flatfish in the Newfoundland region. This resource was greatly overfished though, and declining catches in the mid-1980s and 1990s brought about a moratorium in 1995 banning all fishing of American plaice stocks (Morgan et al., 2001) which continues to this day. Stratified random bottom surveys completed by DFO have indicated that there have been increases in the abundance and biomass of plaice since 2002 in Div. 2J3K (region of the study area). Yet, the current biomass and abundance is still far lower than averages of the mid-1980s at 10% and 25% respectively (DFO, 2012).

The goal of this study was to capture commercial quantities of flatfish species while avoiding the capture of snow crab in modified fish pots. I believe that some of the findings in this study were important in attempting to mitigate this problem. One of the most important results of this study was that both American plaice and snow crab are attracted to pots that contain an artificial light source, however, few crab will enter a pot absent an olfactory stimulus (i.e., bait) while American plaice will enter a pot containing only artificial light as the stimulus. In targeting American plaice and avoiding the capture of snow crab with pots, the results suggest that the presence of an artificial light source and absence of olfactory bait is a viable option, as mean catch rates of plaice in pots containing light and no bait were actually greater (1.4× more) than mean catch rates of plaice in pots containing artificial light and bait. In future studies targeting American plaice, it is recommended that pots be tested within the preferred depth range (i.e., 20-180 m) of American plaice (Iglesias et al., 1996).

Even though the target fish species in this study, Greenland halibut, was not captured in commercial quantities, these experiments were still a success in the fact it was demonstrated that the Newfoundland cod pot design with some minor modifications was able to capture fish species that differ in morphology, such as American plaice. The behaviour of plaice to actively enter a pot containing only artificial light is a new, important finding which opens the door for more research using artificial lights in fish pots. It is recommended that future studies using pots to target Greenland halibut be conducted in areas where known commercial quantities of this species exists. Also, future studies working with fish pots should make use of artificial lights with different intensities and wavelengths of light. Studies by Marchesan et al. (2005) and Widder et al. (2005) have shown that changing these two variables can result in various levels of attraction or aversion to light as a stimulus in fish. Furthermore, is recommended that a mobile, artificial bait that sways with the bottom currents be placed in the pots as another possible attractant to entice fish to enter into the pot while avoiding the capture of snow crab.

**Table 2.1** Full list of treatments for Experiment I and II. Twelve pots were fished per day. Six pots were utilized for each entrance type with three replicates for each trigger diameter (Experiment I) or bait (Experiment II) treatment. Numbers in the columns correspond to the three trigger spacing treatments (52 ± 3 mm, 109 ± 4 mm, and 166 ± 3 mm) used in Experiment I. All pots used in Experiment I contained bait. All pots in Experiment II were equipped with artificial light, 5 mm diameter triggers, and 166 ± 3 mm trigger spacing.

| | | **Conical Entrance** | | **Trapezoid Entrance** | |
|---|---|---|---|---|---|
| **Experiment #** | **Day** | **3 mm Diameter Trigger** | **5 mm Diameter Trigger** | **3 mm Diameter Trigger** | **5 mm Diameter Trigger** |
| **Experiment I** | **1** | *No Light & 52 mm* | *No Light & 52 mm* | *No Light & 52 mm* | *No Light & 52 mm* |
| | **2** | *Light & 52 mm* | *Light & 52 mm* | *Light & 52 mm* | *Light & 52 mm* |
| | **3** | *Light & 109 mm* | *Light & 109 mm* | *Light & 109 mm* | *Light & 109 mm* |
| | **4** | *No Light & 109 mm* | *No Light & 109 mm* | *No Light & 109 mm* | *No Light & 109 mm* |
| | **5** | *No Light & 166 mm* | *No Light & 166 mm* | *No Light & 166 mm* | *No Light & 166 mm* |
| | **6** | *Light & 166 mm* | *Light & 166 mm* | *Light & 166 mm* | *Light & 166 mm* |
| | **7** | *Light & 109 mm* | *Light & 109 mm* | *Light & 109 mm* | *Light & 109 mm* |
| | **8** | *No Light & 109 mm* | *No Light & 109 mm* | *No Light & 109 mm* | *No Light & 109 mm* |
| | **9** | *Light & 166 mm* | *Light & 166 mm* | *Light & 166 mm* | *Light & 166 mm* |
| | | **Conical Entrance** | | **Trapezoid Entrance** | |
| **Experiment II** | **10** | *Bait* | *No Bait* | *Bait* | *No Bait* |
| | **11** | *No Bait* | *Bait* | *No Bait* | *Bait* |
| | **12** | *Bait* | *No Bait* | *Bait* | *No Bait* |

**Table 2.2** Summary of the total catches for Experiment I and II. Numerical values indicate the total number of individuals captured in pots for the most commonly captured fish and miscellaneous fish species (i.e., grenadier, eelpout, and sculpin) while values for snow crab and toad crab indicate kilograms (kg) of species captured. The number of pot hauls for each treatment is indicated by (n) while percentages in parentheses indicate the percentage of pot hauls a species was captured in for each corresponding treatment.

| Species | Total for Exp. I and Exp. II | Total for Exp. I | | Total for Exp. II | |
|---|---|---|---|---|---|
| | | Light absent (n=48) | Light present (n=60) | Bait absent (n=18) | Bait present (n=18) |
| American plaice | 422 | 3<br>(4%) | 265<br>(85%) | 98<br>(89%) | 56<br>(83%) |
| Greenland halibut | 5 | 5<br>(8%) | 0<br>(0%) | 0<br>(0%) | 0<br>(0%) |
| Atlantic cod | 32 | 9<br>(17%) | 17<br>(17%) | 5<br>(17%) | 1<br>(6%) |
| Redfish spp. | 9 | 4<br>(8%) | 3<br>(5%) | 1<br>(6%) | 1<br>(6%) |
| Spotted wolfish | 4 | 4<br>(8%) | 0<br>(0%) | 0<br>(0%) | 0<br>(0%) |
| Miscellaneous fish | 6 | 3<br>(6%) | 2<br>(3%) | 1<br>(6%) | 0<br>(0%) |
| Snow crab | 1,802 | 556<br>(96%) | 948<br>(95%) | 49<br>(67%) | 249<br>(89%) |
| Toad crab | 12.6 | 1.6<br>(13%) | 7.3<br>(42%) | 2.0<br>(33%) | 1.7<br>(33%) |

**Table 2.3** Experiment I: Summary of three-way ANOVA to test the effect of pot entrance shape, FRD trigger diameter, and FRD trigger spacing on mean catch rates of American plaice captured in baited pots containing an artificial light source.

| Source | df | SS | MS | F- statistic | p-value |
|---|---|---|---|---|---|
| Entrance | 1 | 0.311 | 0.311 | 11.111 | 0.002* |
| Trigger diameter | 1 | 0.028 | 0.028 | 0.995 | 0.324 |
| Trigger spacing | 2 | 0.201 | 0.101 | 3.601 | 0.035* |
| Entrance × Trigger diameter | 1 | 0.018 | 0.018 | 0.633 | 0.430 |
| Entrance × Trigger spacing | 2 | 0.020 | 0.010 | 0.349 | 0.707 |
| Trigger diameter × Trigger spacing | 2 | 0.105 | 0.052 | 1.873 | 0.165 |
| Entrance × Trigger diameter × Trigger spacing | 2 | 0.008 | 0.004 | 0.144 | 0.866 |
| Error | 48 | 1.343 | 0.028 | | |

*Significantly different at $p<0.05$.

**Table 2.4** Experiment I: Summary of a reduced model three-way ANOVA to test the effect of pot entrance shape, FRD trigger diameter, and FRD trigger spacing on mean body length of American plaice captured in baited pots containing an artificial light source.

| Source | df | SS | MS | F- statistic | p-value |
|---|---|---|---|---|---|
| Entrance | 1 | 0.000 | 0.000 | 0.043 | 0.836 |
| Trigger diameter | 1 | 0.077 | 0.077 | 8.396 | 0.004* |
| Trigger spacing | 2 | 0.061 | 0.031 | 3.318 | 0.038* |
| Error | 247 | 2.280 | 0.009 | | |

*Significantly different at $p<0.05$.

**Table 2.5** Experiment I: Summary of mean body lengths of American plaice captured for each FRD trigger spacing among baited pots containing 3 mm trigger diameter and 5 mm trigger diameter. All pots additionally contained an artificial light source.

| FRD Trigger diameter (mm) | FRD Trigger spacing (mm) | No. of pots | Body length (cm) | |
|---|---|---|---|---|
| | | | Mean | SE |
| 3 | 52 | 29 | 25.72 | 0.890 |
| | 109 | 42 | 28.98 | 1.059 |
| | 166 | 50 | 25.98 | 0.734 |
| 5 | 52 | 11 | 30.45 | 2.577 |
| | 109 | 54 | 30.35 | 0.903 |
| | 166 | 66 | 28.98 | 0.819 |

**Table 2.6** Experiment I: Summary of mean body lengths of American plaice captured for each FRD trigger spacing among baited pots containing an artificial light source. Homogeneous subsets are identified (i.e., A and B).

| FRD Trigger spacing (mm) | No. of individuals captured | Body length (cm) | |
|---|---|---|---|
| | | Mean | SE |
| 52 | 40 | 27.03 A | 1.00 |
| 109 | 96 | 29.75 B | 0.69 |
| 166 | 116 | 27.69 AB | 0.58 |

**Table 2.7** Experiment II: Summary of two-way ANOVA to test the effect of pot entrance shape and presence/absence of bait on mean catch rates of American plaice captured in pots. All pots were fished with artificial light, 5 mm diameter FRD triggers, and 166 mm FRD trigger spacing.

| Source | df | SS | MS | F-statistic | p-value |
|---|---|---|---|---|---|
| Entrance | 1 | 0.272 | 0.272 | 6.793 | 0.014* |
| Bait | 1 | 0.008 | 0.008 | 0.210 | 0.650 |
| Entrance × Bait | 1 | 0.020 | 0.020 | 0.500 | 0.485 |
| Error | 32 | 1.283 | 0.040 | | |
| Total | 36 | 4.349 | | | |

*Significantly different at $p<0.05$.

**Table 2.8** Experiment II: Summary of two-way ANOVA to test the effect of pot entrance shape and presence/absence of bait on the mean body length of American plaice captured in pots. All pots were fished with artificial light, 5 mm diameter FRD triggers, and 166 mm FRD trigger spacing.

| Source | df | SS | MS | F-statistic | p-value |
|---|---|---|---|---|---|
| Entrance | 1 | 0.018 | 0.018 | 1.651 | 0.201 |
| Bait | 1 | 0.045 | 0.045 | 4.083 | 0.045* |
| Entrance × Bait | 1 | 0.005 | 0.005 | 0.438 | 0.509 |
| Error | 146 | 1.603 | 0.011 | | |
| Total | 150 | 318.217 | | | |

*Significantly different at p<0.05.

**Table 2.9** Experiment I: Summary of independent-samples t-tests comparing the effect of FRD trigger diameter on the mean catch rate of snow crab captured in baited pots across each entrance shape, and FRD trigger spacing in the absence of an artificial light source. No significant differences in mean catch rates of plaice were found using Bonferroni's adjusted alpha level (α = 0.0167).

| Entrance shape | FRD Trigger spacing (mm) | FRD Trigger diameter (mm) | No. of Pots | Catch rate (kg/pot haul) | | Analysis | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Mean | SE | df | t-statistic | p-value |
| Conical | 52 | 3 | 3 | 4.27 | 3.92 | 4 | 0.577 | 0.595 |
| | | 5 | 3 | 9.27 | 6.45 | | | |
| | 109 | 3 | 6 | 3.68 | 1.50 | 10 | 2.071 | 0.065 |
| | | 5 | 6 | 17.80 | 4.07 | | | |
| | 166 | 3 | 3 | 2.20 | 0.97 | 4 | 1.487 | 0.211 |
| | | 5 | 3 | 25.60 | 16.58 | | | |
| Trapezoid | 52 | 3 | 3 | 13.17 | 4.91 | 4 | 1.849 | 0.138 |
| | | 5 | 3 | 3.63 | 1.70 | | | |
| | 109 | 3 | 6 | 16.45 | 6.65 | 10 | 0.006 | 0.995 |
| | | 5 | 6 | 13.10 | 3.64 | | | |
| | 166 | 3 | 3 | 17.03 | 2.26 | 4 | 1.733 | 0.158 |
| | | 5 | 3 | 7.97 | 3.37 | | | |

**Table 2.10** Experiment I: Summary of independent-samples t-tests comparing the effect of FRD trigger diameter on the mean catch rate of snow crab captured in baited pots across each entrance shape, and FRD trigger spacing in the presence of an artificial light source.

| Entrance shape | FRD Trigger spacing (mm) | FRD Trigger diameter (mm) | No. of Pots | Catch rate (kg/pot haul) Mean | SE | Analysis df | t-statistic | p-value |
|---|---|---|---|---|---|---|---|---|
| Conical | 52 | 3 | 3 | 3.00 | 1.86 | 4 | 0.456 | 0.672 |
| | | 5 | 3 | 15.10 | 13.92 | | | |
| | 109 | 3 | 6 | 3.87 | 2.01 | 10 | 1.567 | 0.148 |
| | | 5 | 6 | 12.97 | 4.59 | | | |
| | 166 | 3 | 6 | 4.83 | 2.38 | 10 | 5.201 | 0.001* |
| | | 5 | 6 | 33.83 | 5.38 | | | |
| Trapezoid | 52 | 3 | 3 | 8.20 | 5.01 | 4 | 1.653 | 0.174 |
| | | 5 | 3 | 16.10 | 1.30 | | | |
| | 109 | 3 | 6 | 21.88 | 5.14 | 10 | 0.030 | 0.977 |
| | | 5 | 6 | 18.00 | 2.67 | | | |
| | 166 | 3 | 6 | 19.70 | 6.94 | 10 | 1.059 | 0.315 |
| | | 5 | 6 | 21.73 | 3.03 | | | |

*Significantly different at Bonferroni's adjusted alpha level (p<0.0167).

**Table 2.11** Experiment I: Summary of one-way ANOVAs comparing the effect of FRD trigger spacing on the mean catch rate of snow crab captured in baited pots across each entrance shape, and FRD trigger diameter in the absence of an artificial light source. No significant differences in mean catch rates of snow crab were found (i.e., p>0.05).

| Entrance shape | FRD Trigger diameter (mm) | FRD Trigger spacing (mm) | No. of Pots | Catch rate (kg/pot haul) |  | Analysis |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  | Mean | SE | df | F-statistic | p-value |
| Conical | 3 | 52 | 3 | 4.27 | 3.92 | 2,9 | 0.034 | 0.967 |
|  |  | 109 | 6 | 3.68 | 1.50 |  |  |  |
|  |  | 166 | 3 | 2.20 | 0.97 |  |  |  |
|  | 5 | 52 | 3 | 9.27 | 6.45 | 2,9 | 0.398 | 0.683 |
|  |  | 109 | 6 | 17.80 | 4.07 |  |  |  |
|  |  | 166 | 3 | 25.60 | 16.58 |  |  |  |
| Trapezoid | 3 | 52 | 3 | 13.17 | 4.91 | 2,9 | 0.271 | 0.769 |
|  |  | 109 | 6 | 16.45 | 6.65 |  |  |  |
|  |  | 166 | 3 | 17.03 | 2.26 |  |  |  |
|  | 5 | 52 | 3 | 3.63 | 1.70 | 2,9 | 2.225 | 0.164 |
|  |  | 109 | 6 | 13.10 | 3.64 |  |  |  |
|  |  | 166 | 3 | 7.97 | 3.37 |  |  |  |

**Table 2.12** Experiment I: Summary of one-way ANOVAs comparing the effect of FRD trigger spacing on the mean catch rate of snow crab captured in baited pots across each entrance shape, and FRD trigger diameter in the presence of an artificial light source. No significant differences in mean catch rates of snow crab were found (i.e., p>0.05).

| Entrance shape | FRD Trigger diameter (mm) | FRD Trigger spacing (mm) | No. of Pots | Catch rate (kg/pot haul) | | Analysis | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Mean | SE | df | F-statistic | p-value |
| Conical | 3 | 52 | 3 | 3.00 | 1.86 | | | |
| | | 109 | 6 | 3.87 | 2.01 | 2,12 | 0.163 | 0.851 |
| | | 166 | 3 | 4.83 | 2.38 | | | |
| | 5 | 52 | 3 | 15.10 | 13.92 | | | |
| | | 109 | 6 | 12.97 | 4.59 | 2,12 | 3.091 | 0.083 |
| | | 166 | 3 | 33.83 | 5.38 | | | |
| Trapezoid | 3 | 52 | 3 | 8.20 | 5.01 | | | |
| | | 109 | 6 | 21.88 | 5.13 | 2,12 | 0.744 | 0.496 |
| | | 166 | 3 | 19.70 | 6.94 | | | |
| | 5 | 52 | 3 | 16.10 | 1.30 | | | |
| | | 109 | 6 | 18.00 | 2.67 | 2,12 | 0.711 | 0.511 |
| | | 166 | 3 | 21.73 | 3.03 | | | |

**Table 2.13** Experiment I: Summary of independent-samples t-tests comparing the effect of FRD trigger diameter on the mean catch rate of snow crab captured in baited pots for each entrance shape, both in the absence and presence of an artificial light source.

| | | | | Catch rate (kg/pot haul) | | Analysis | | |
|---|---|---|---|---|---|---|---|---|
| Light | Entrance shape | FRD Trigger diameter (mm) | No. of pots | Mean | SE | df | t-statistic | p-value |
| No | Conical | 3 | 12 | 3.46 | 1.14 | 22 | 2.614 | 0.016* |
| | | 5 | 12 | 17.62 | 4.60 | | | |
| | Trapezoid | 3 | 12 | 15.78 | 3.41 | 22 | 1.542 | 0.137 |
| | | 5 | 12 | 9.45 | 2.25 | | | |
| Yes | Conical | 3 | 15 | 4.08 | 1.23 | 28 | 3.273 | 0.003* |
| | | 5 | 15 | 21.74 | 4.44 | | | |
| | Trapezoid | 3 | 15 | 18.27 | 3.64 | 16 | 1.428 | 0.172 |
| | | 5 | 15 | 19.11 | 1.66 | | | |

*Significantly different at Bonferroni's adjusted alpha level (p<0.025).

**Table 2.14** Experiment I: Summary of independent-samples t-tests comparing the effect of entrance shape on the mean catch rate of snow crab captured in baited pots for each FRD trigger diameter, both in the absence and presence of an artificial light source.

| Light | FRD Trigger diameter (mm) | Entrance shape | No. of pots | Catch rate (kg/pot haul) | | Analysis | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Mean | SE | df | t-statistic | p-value |
| No | 3 | Conical | 12 | 3.46 | 1.14 | 22 | 4.199 | <0.001* |
| | | Trapezoid | 12 | 15.78 | 3.41 | | | |
| | 5 | Conical | 12 | 17.62 | 4.60 | 22 | 0.628 | 0.536 |
| | | Trapezoid | 12 | 9.45 | 2.25 | | | |
| Yes | 3 | Conical | 15 | 4.08 | 1.23 | 28 | 3.328 | 0.002* |
| | | Trapezoid | 15 | 18.27 | 3.64 | | | |
| | 5 | Conical | 15 | 21.74 | 4.44 | 16 | 1.012 | 0.327 |
| | | Trapezoid | 15 | 19.11 | 1.66 | | | |

*Significantly different at Bonferroni’s adjusted alpha level (p<0.025).

**Table 2.15** Experiment II: Summary of independent-samples t-tests comparing the effect of bait presence/absence on the mean catch rate of snow crab captured in pots. All pots were fished with artificial light, 5 mm diameter FRD triggers, and 166 mm FRD trigger spacing.

| Entrance shape | Presence of bait | No. of pots | Catch rate (kg/pot haul) |  | Analysis |  |  |
|---|---|---|---|---|---|---|---|
|  |  |  | Mean | SE | df | t-statistic | p-value |
| Conical | No bait | 9 | 0.38 | 0.22 | 16 | 6.502 | <0.001* |
|  | Bait | 9 | 19.59 | 4.15 |  |  |  |
| Trapezoid | No bait | 9 | 5.07 | 3.13 | 16 | 1.191 | 0.251 |
|  | Bait | 9 | 8.10 | 2.77 |  |  |  |

*Significantly different at $p<0.05$.

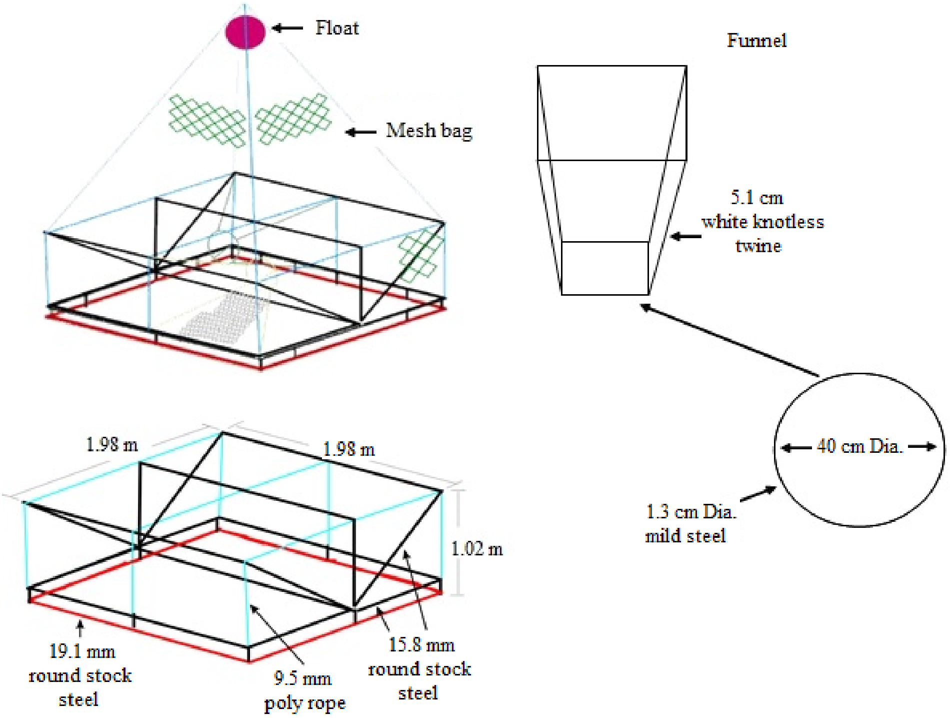
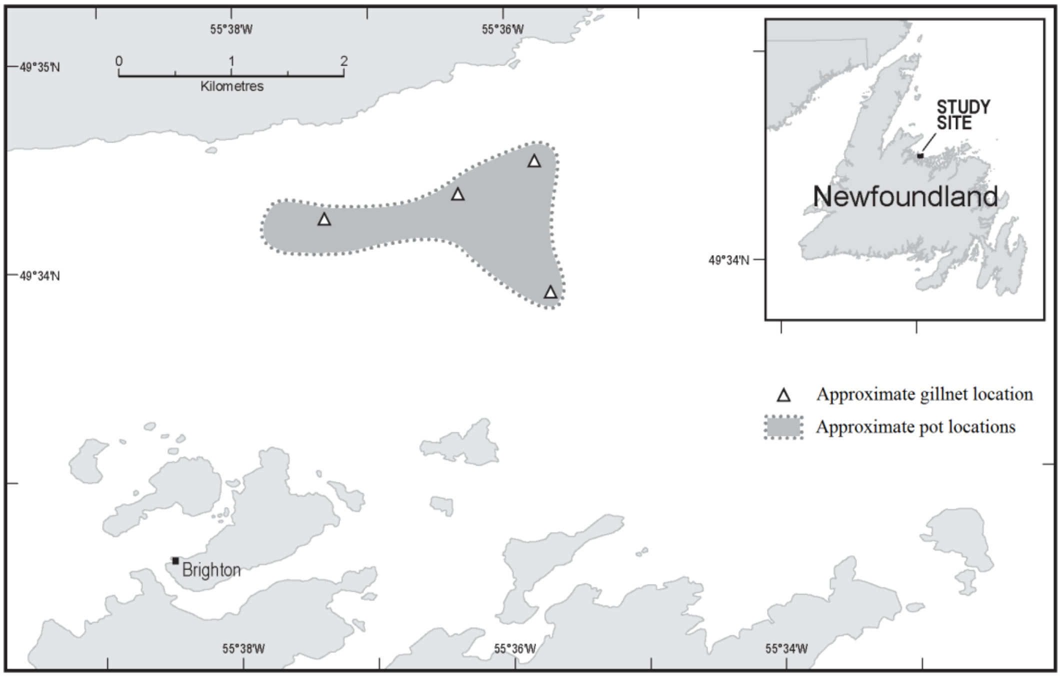


**Figure 2.1** Diagram of the Newfoundland cod pot. Conical entrance pot is illustrated (Walsh and Sullivan, 2008).

**Figure 2.2** Photos of a battery powered artificial light that was hung vertically between fish pot entrances for pots undergoing light treatment. Both photos are of the same fishing light with the photo on the right taken in the dark.



Map prepared in the Map Room, Queen Elizabeth II Library Memorial University, March 2013.

**Figure 2.3** Map of study site in Notre Dame Bay illustrating pot locations for all twelve pots used throughout Experiments I and II. Approximate locations of exploratory gillnets to survey the study area are also displayed.

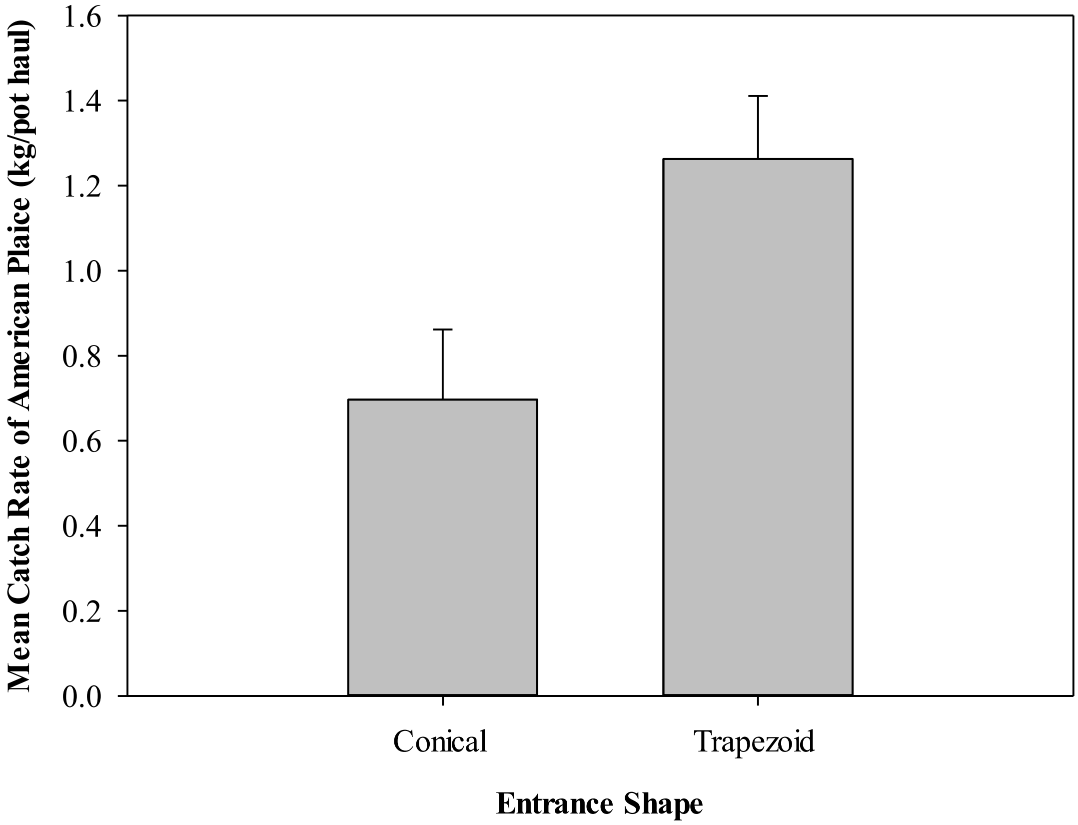


**Figure 2.4** Experiment I: Comparison of mean catch rate of American plaice captured in baited pots in the presence of an artificial light source for pots fitted with conical and trapezoid entrance shapes. Error bars indicate standard error of the mean values.

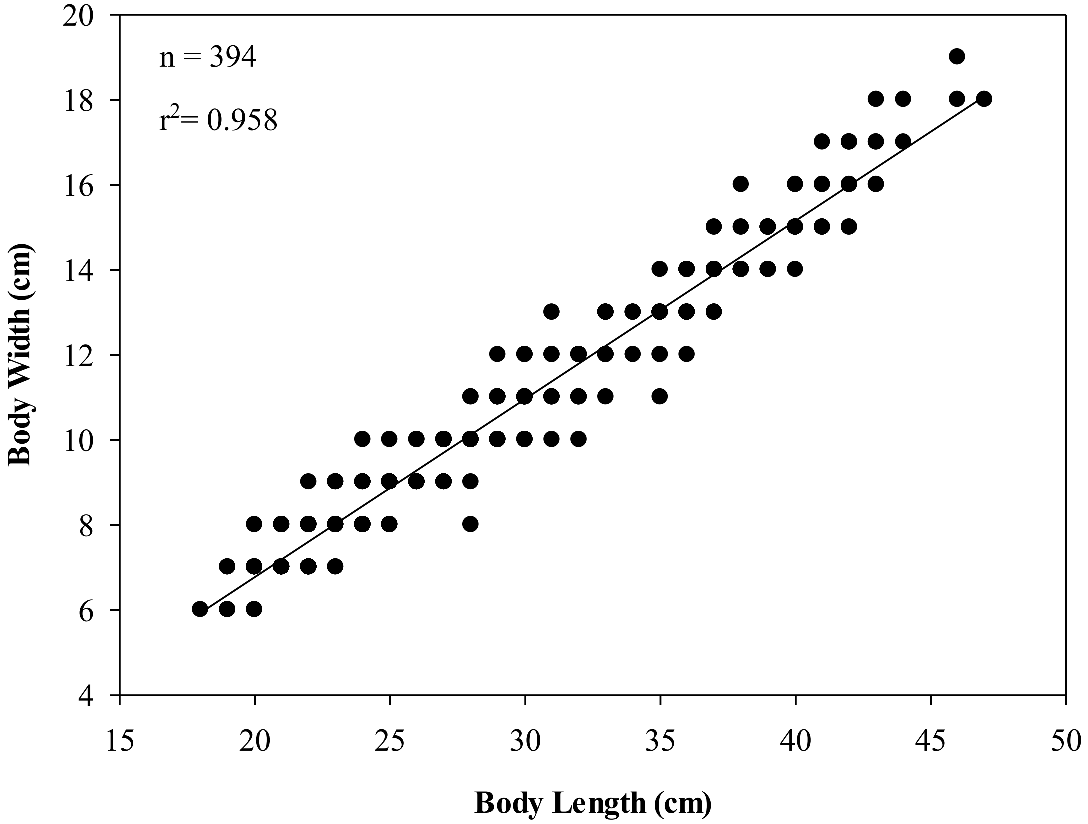


**Figure 2.5** Length-width relationship of American plaice captured in pots. Number of American plaice measured (n), coefficient of determination ($r^2$), and line of best fit are illustrated.

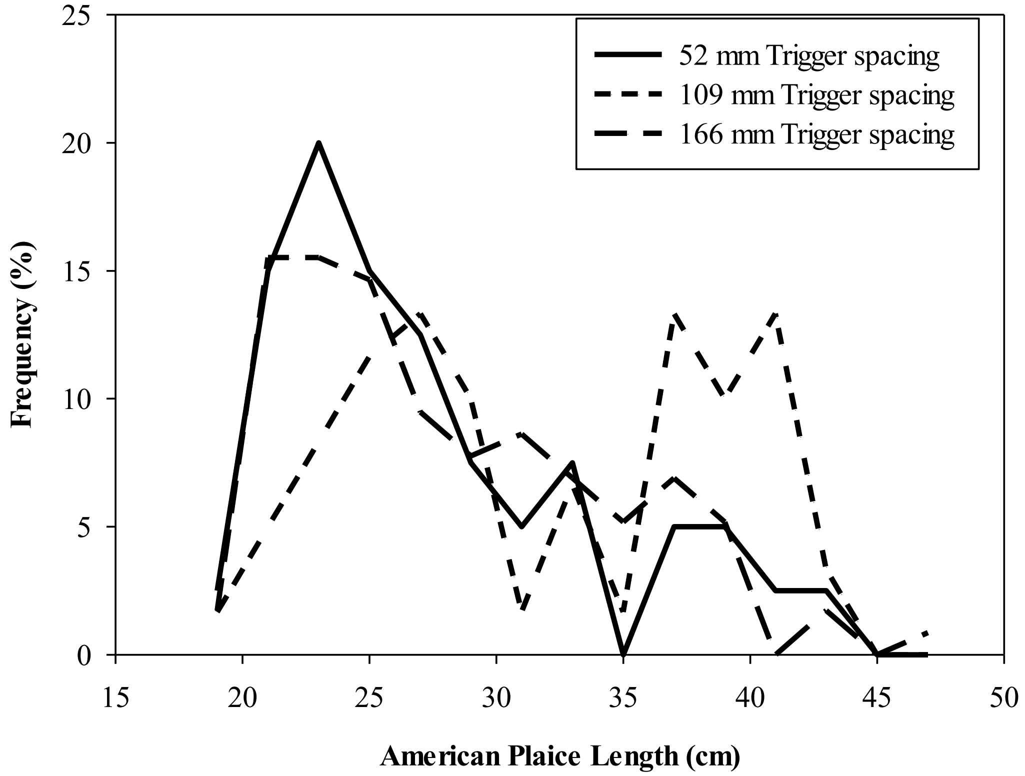


**Figure 2.6** Experiment I: Body length frequency distribution of American plaice captured in baited pots with three different FRD trigger spacings (52 ± 3 mm, 109 ± 4 mm, and 166 ± 3 mm).

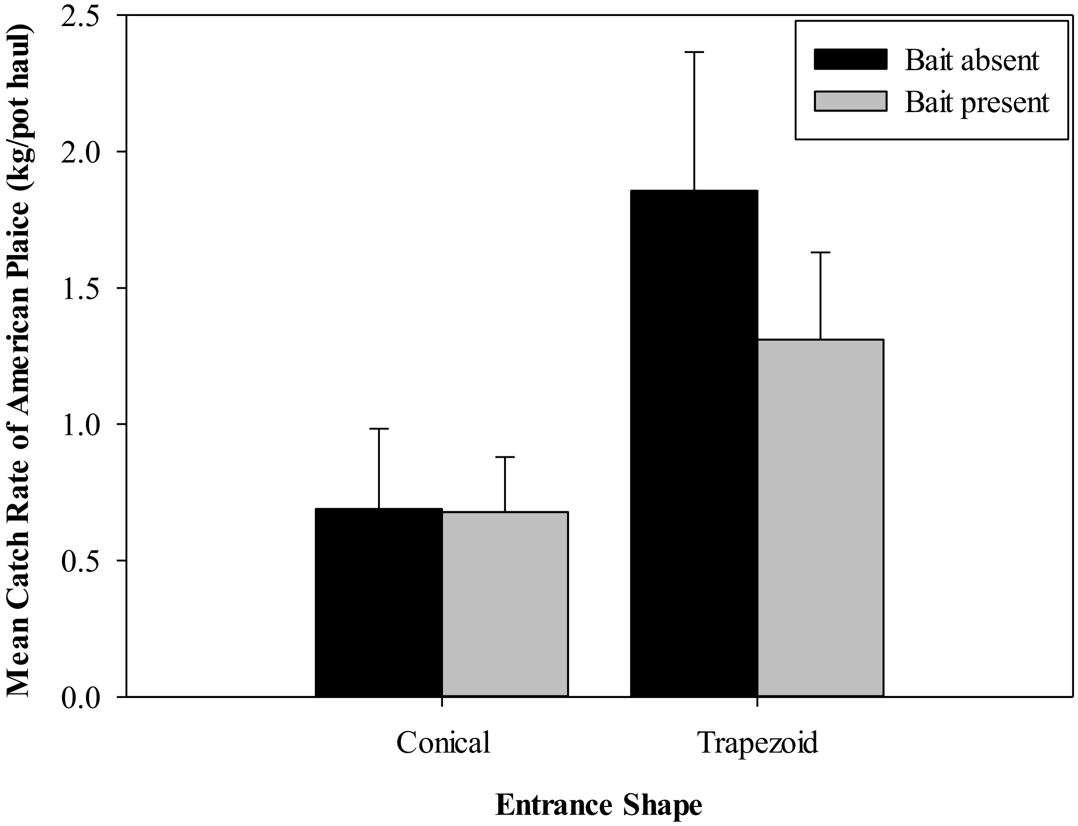


**Figure 2.7** Experiment II: Summary of the effect of presence/absence of bait on the mean catch rate of American plaice captured in conical and trapezoid entrance pots. All pots were fished with artificial light, 5 mm diameter FRD triggers, and 166 mm FRD trigger spacing. Error bars indicate the standard error of the mean values.

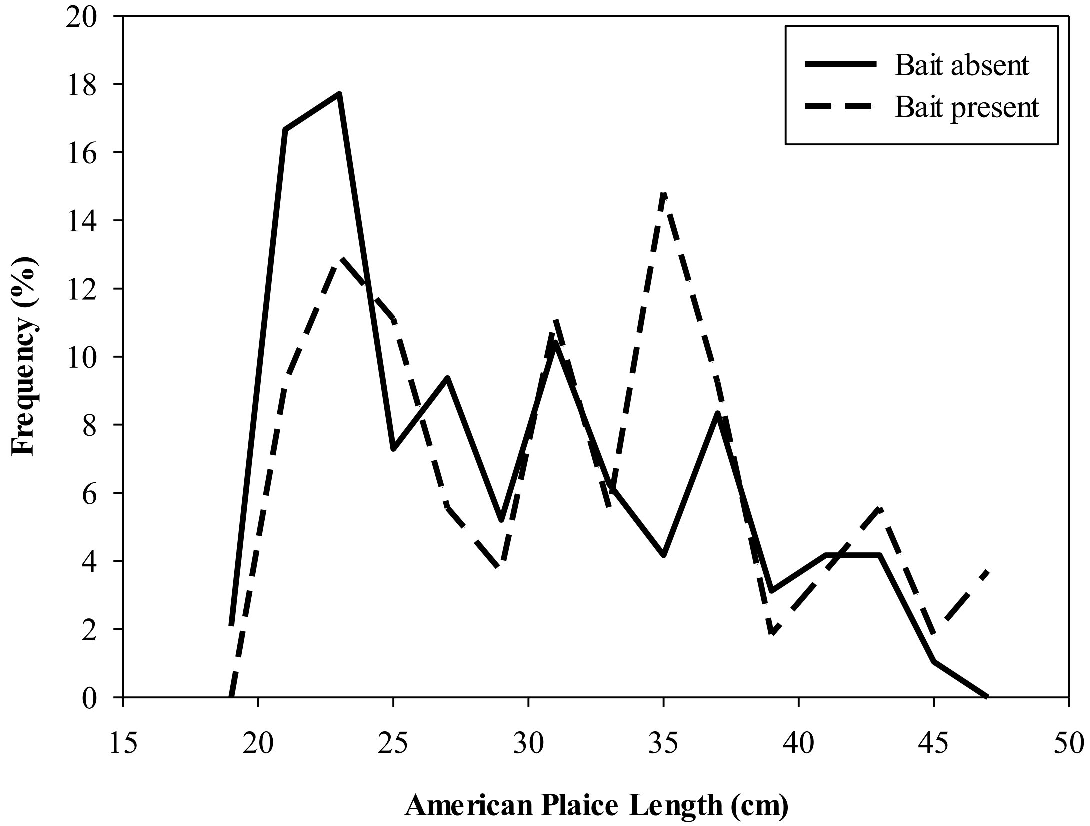


**Figure 2.8** Experiment II: Body length frequency distribution of American plaice captured in conical and trapezoid entrance pots with bait absent and bait present. All pots were fished with artificial light, 5 mm diameter FRD triggers, and 166 mm FRD trigger spacing.

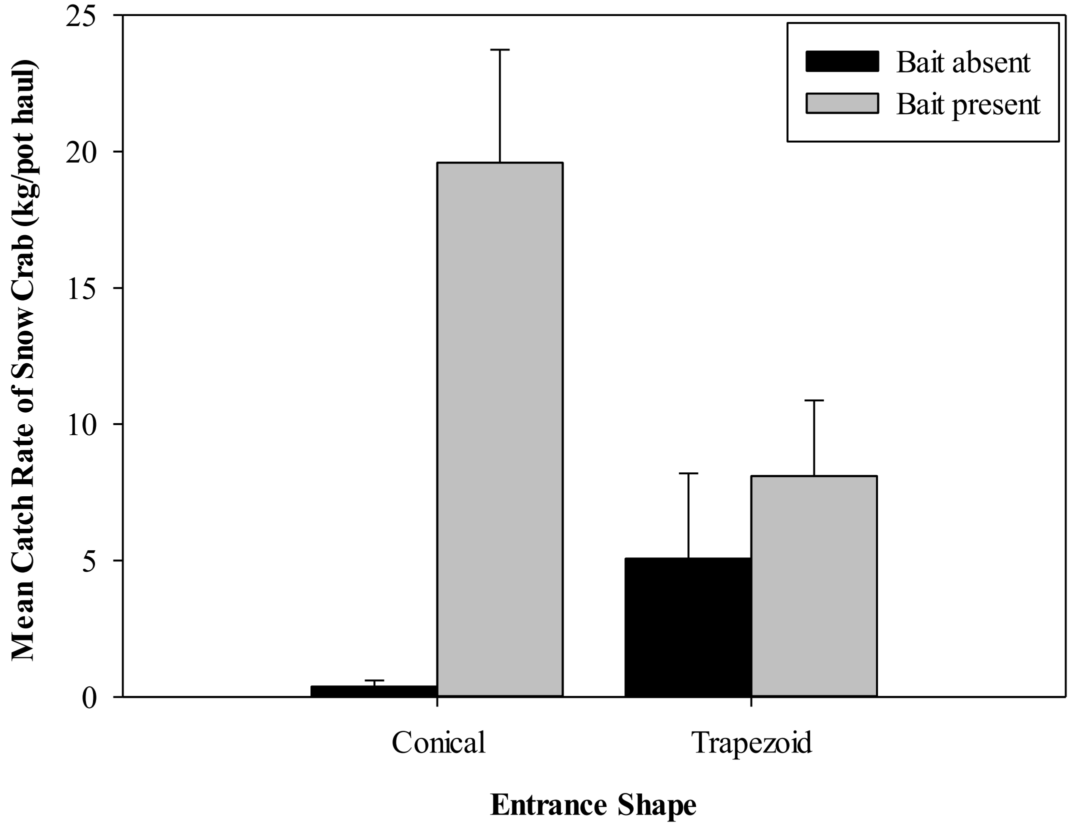


**Figure 2.9** Experiment II: Summary of the effect of presence/absence of bait on the mean catch rate of snow crab captured in conical and trapezoid entrance pots. All pots were fished with artificial light, 5 mm diameter FRD triggers, and 166 mm FRD trigger spacing. Error bars indicate the standard error of the mean values.

# Chapter 3. Gear modifications to a shrimp trawl to reduce seabed impacts in the Atlantic Canada inshore shrimp fishery.

## Abstract

The ground gear of bottom trawls can have detrimental impacts to structurally complex seabed ecosystems. As a result, bottom trawling fisheries are facing increasing restrictions, area closures, and bans in many regions around the world which all proves very challenging to the fishing industry. Canada is one of the world's leading producers of cold water shrimp, particularly northern shrimp (*Pandalus borealis*), and bottom trawling is currently the only economical means to harvest this species to meet market demand. If restrictions or bans were placed on this fishing method than the shrimp fishing industry would suffer greatly along with the many other bottom trawl fisheries in Atlantic Canada. The goal of the current study was to determine if modifications to the ground gear of a bottom otter trawl designed to reduce seabed contact area could maintain catch rates and body size of shrimp, while not increasing bycatch of non-targeted species. The ground gear of an experimental trawl was designed to have a 48% reduction in seabed contact area compared to the ground gear of a standard shrimp trawl currently used in the fishery. Results of comparative at-sea fishing trials of both the experimental and standard trawls demonstrate that catch rates and size of shrimp were comparable between both trawls, however the experimental trawl captured a greater abundance of non-target species. The presence of mud on the ground gear of the experimental trawl and mud found in the catch provides evidence that the experimental trawl likely dug into the

seabed for several fishing tows. The experimental ground gear appears to hold promise, however additional modifications will be required to reduce seabed impacts and bycatch rates.

## 3.1 Introduction

Northern shrimp (*Pandalus borealis*) is the primary cold water shrimp species fished in the North Atlantic Ocean (DFO, 2007). In the northwest Atlantic they occur from West Greenland (75°N) southward to Georges Bank (42°N) (Parsons and Fréchette, 1989; Squires, 1990). Northern shrimp are found most abundantly at water temperatures of 1 to 6 °C (DFO, 2013) and prefer seabed environments with soft, silty, and muddy substrates, but they may also be found in areas with sand and gravel (Williams, 1984; DFO, 2013). This species of shrimp is concentrated at depths of 150-600 m resulting in a vast area of suitable habitat in deep water channels and banks throughout Atlantic Canada (DFO, 2007; 2013).

The northern shrimp fishery has developed considerably over the past three and a half decades (DFA, 2012). Presently the fishery consists of two operating fleets, the offshore fleet (vessels >100′) and the inshore fleet (vessels <65′). In recent years the inshore fleet has landed its quota more often than the offshore fleet (Figure 3.1; DFA, 2012). Shifts in environmental conditions favoring northern shrimp (e.g., colder water temperature) and swift decreases in groundfish predators from declines in Newfoundland and Labrador’s groundfish stocks in the early 1990s resulted in rapid growth of northern shrimp populations (DFO, 2007). Increases in northern shrimp provided fishermen with an opportunity to partially fill the void that the collapse of groundfish stocks created and as a result many fishermen switched over to harvesting shrimp. This gave rise to an inshore fishery for northern shrimp in 1997 to take advantage of the growth in the shrimp resource (DFA, 2012).

The shrimp fishery is very important to Canada which is one of the world's leading producers of cold water shrimp, particularly northern shrimp. The inshore shrimp fishery in the region of Newfoundland and Labrador is a lucrative enterprise employing approximately 1,600 harvesters on over 325 fishing vessels and 2,151 plant workers in 12 inshore shrimp plants for on-shore operations totalling a value of $72 million for 50,223 t of shrimp landed in 2011 (DFA, 2012). Similarly, landings of shrimp in 2012 were greater than 85 thousand tonnes with a landed value of just over $191 million for both inshore and offshore shrimp fisheries (DFA, 2013). Bottom trawling is currently the only economical means to harvest large quantities of shrimp and if restrictions or bans were placed on this fishing method than the shrimp fishing industry would suffer greatly along with the many other bottom trawl fisheries in Atlantic Canada. Reducing seabed impacts of bottom trawls would help change attitudes of environmental groups and seafood buyers that are against the idea of trawling since it is a move towards more sustainable fishing practices.

The northern shrimp fishery was actually the first fishery in Canada to receive Marine Stewardship Council (MSC) certification which certifies that the fishery is fished and managed in a sustainable manner. In order to be MSC certified, a fishery must be conducted in a manner which does not lead to overexploitation of the fishery resource, fishing activities must aim to reduce impact on the ecosystem, and the fishery must be managed effectively respecting all local, national, and international laws and standards. Implementing the use of trawls that reduce seabed impacts would help the fishery to maintain this certification.

While trawling is a method that is very efficient at capturing northern shrimp, there are several negative impacts associated with the many components of the trawl gear that must be considered along with their effects on marine ecosystems (Grant, 2012). Bycatch, for example, can be a significant problem as a result of trawling activities. Bycatch not only includes marine organisms that are not directly targeted for harvest during a commercial fishing operation, but also includes undersized fish of the target species, non-target marine organisms discarded at sea, and incidentally captured non-target species retained for commercial value. Unfortunately, many marine organisms that are captured in trawls and hauled to the surface will die when returned to the ocean (Davis, 2002; Surronen, 2005). High removals of non-commercial species can change the dynamics of marine ecosystems which may lead to impacts on other non-commercial and commercial species alike.

To help solve this problem of bycatch in shrimp trawls, some fisheries add bycatch reduction devices (BRDs) to trawling gears. An example of a BRD modification that has reduced the bycatch of non-targeted species in shrimp trawls is the Nordmøre grid. Since 1992, the Nordmøre grid has been mandated for use on all shrimp fishing vessels in the Canadian northern shrimp fishery in order to reduce the capture of fish species (DFO, 2007). The grid precedes the codend of the trawl and serves to permit the passage of shrimp into the codend while directing anything larger than the bar spacings of the grid upwards and out of an opening in the top of the net. This significantly reduces the capture of adult groundfish. However, juveniles and fish species small enough to pass through the grid continue to be captured (Graham, 2006; Fuller et al., 2008).

The physical impacts that bottom trawls have on the seabed is another point worth considering when discussing the impacts of trawling. For example, bottom trawls are typically rigged with ground gear such as bobbins and rockhopper disks that allow the trawl to make contact with the seabed. These components aid in preventing damage to the trawl net when encountering rough bottoms with sharp rocks, boulders or other obstacles in the path of the trawl. Consequently, bobbins and rockhopper gear can exert a great deal of pressure on the seabed depending on their weight as well as the extent of area they make contact with. These components of the ground gear can leave imprints in the seabed but may also scrape and dig in to the sediment. Additionally, they may cause mortality to fish and invertebrates that collide with the gear.

The heavy trawl doors that precede the ground gear and trawl net are also responsible for impacting the seabed. The doors function in spreading the net open laterally and creating sediment plumes that are essential in herding certain groundfish species such as Atlantic cod (*Gadus morhua*) towards the mouth of the trawl (Winger et al., 2010). This component of the trawl inflicts arguably the most damage to the seabed as it is rigged to penetrate into the sediment. In some cases trawl doors can penetrate as deep as 20 cm (Schwinghamer et al., 1998), however depth of penetration is largely dependent on sediment type. Trawl doors displace benthic organisms such as molluscs, crabs, and polychaetes; sometimes damaging or destroying these organisms, all the while leaving visible trawl marks that can take weeks and sometimes years to return to previous conditions, depending on the type of habitat (Jones, 1992). The bridles of the trawl which connect the doors to the ground gear also create sediment plumes or sand clouds by sweeping over and digging into the seabed. There are several other physical impacts which ground gear, doors, and bridles have on the seabed including the removal of major habitat structures (i.e., corals), reduction of habitat complexity, and changes in the seabed structure (Norse and Watling, 1999). These impacts, in turn, can lead to decreased species diversity and increased predation of young marine organisms that feed and seek shelter in biogenic structures such as coral reefs, kelp holdfasts, shells, tubes, and tunnels that are damaged or destroyed by trawls (Løkkeborg, 2005).

Fortunately, many studies have been carried out to address the issue of gear modification to reduce seabed impacts of bottom trawls (Ramm et al., 1993; Brewer et al., 1996; Ball et al., 2003; DeLouche and Legge, 2004; He et al., 2006; Rose et al., 2006; DEGREE, 2008). Some examples of modifications to reduce seabed impact include the use of semi-pelagic trawl doors, off-bottom bridles, and reductions in the weight and number of contact points of the ground gear (Valdemarsen et al., 2007; He and Winger, 2010). These examples are discussed in more detail below.

Semi-pelagic doors are designed to function above the seabed in comparison to demersal doors. Through the use of high aspect trawl doors, the trawl is spread open from hydrodynamic forces alone (He and Winger, 2010). Two studies have examined the feasibility of the semi-pelagic trawl in the northern shrimp fishery and found that there was no significant effect on the size range or catch per unit effort of shrimp in comparison to a traditional shrimp trawl fishing on the same grounds (DeLouche and Legge, 2004; He et al., 2006). These results are understandable as shrimp do not herd toward the mouth of the net in the presence of sediment plumes created by trawl doors like some species of groundfish (Watson, 1989; Hannah et al., 2003). This method however requires consistent monitoring of door height and active adjustment of warp length to achieve optimum results (He and Winger, 2010) and necessitates further testing to improve upon the trawl design. Semi-pelagic trawling has not been fully accepted in Newfoundland and Labrador fisheries due to fishermen's preferences for more traditional fishing gears, however, it has been successful in other global shrimp fisheries such as the northeast coast of the United States, Europe, India, and parts of Asia (pers. comm., P. Winger, Director of CSAR, Marine Institute of Memorial University, St. John's, Newfoundland, Canada).

In another gear modification study, Rose et al. (2010) experimented with modified sweeps to reduce contact with the seabed in the Alaskan flatfish trawl fisheries. To raise the sweeps off the bottom they experimented with various sized disk clusters on the cable. For two out of the three configurations they observed no significant reduction in capture of flatfish species. Moreover, sonar operations of the sweeps in operation and seafloor after trawl passage indicated a substantial reduction in direct seafloor contact by the modified sweeps (Rose et al., 2010).

Another method to minimize bottom impacts of trawling on the seabed is through a reduction in the weight and number of contact points of the ground gear. This can be accomplished by limiting the number and size of ground gear components such as rockhopper disks and bobbins. This concept was tested by He and Foster (2000) who assessed the performance of an offshore shrimp trawl that decreased and spread out the number of bobbins on the trawl foot rope from 31 to nine. In doing so, the weight of the ground gear was minimized from 2,984 kg to 1,306 kg and the area encountered by the trawl was reduced by 70 percent. The shrimp catch was not negatively affected by these modifications. The biggest downside to these modifications however was that the ground gear and trawl were more prone to damage from having fewer bobbins in contact with the seabed. This research is similar in principle to the experiment completed in this thesis chapter.

In the current study, a trawl designed to reduce seabed impacts (hereinafter referred to as the experimental trawl) was developed by industry for the inshore northern shrimp fishery of Atlantic Canada. This trawl was designed to have an approximate 48% reduction in contact area of the ground gear on the seabed compared to the ground gear of a standard trawl currently being used in the commercial inshore shrimp fishery. Physical impacts of the two trawls on the seabed were not assessed in the study due to time and monetary constraints. The objective of this study was instead to evaluate and compare the catch characteristics of each trawl type. Comparative at-sea trials were performed between the two trawls to determine if the experimental trawl had comparable 1) catch rates of shrimp, 2) size composition of shrimp, and 3) bycatch composition, to the standard trawl. If the experimental trawl is comparable in its catch characteristics to that of the standard trawl, it is possible that consideration will be taken by the shrimp fishing industry to adopt this trawl design in their inshore fleets.

## 3.2 Materials and Methods

### *3.2.1 Trawl Specifications*

The trawls manufactured and tested in this study were designed by the staff at Vónin Ltd. and Vónin Canada Ltd. with assistance from the staff at Marine Institute's Centre for Sustainable Aquatic Resources (CSAR). The trawls were manufactured in the company's factory located in Port de Grave, Newfoundland.

The standard trawl ground gear consisted of 28 rockhopper disks with a diameter of 35.6 cm, 38 disks with a diameter of 30.5 cm, and two 35.6 cm diameter steel bobbins linked together by a 13 mm footgear chain, a 10 mm travel chain, and a 10 mm weight chain (Figure 3.2). By comparison the experimental trawl contained "double wheeled" ground gear which consisted of six 35.6 cm diameter rockhopper disks located near the mouth of the trawl and 12 double wheeled (i.e., two rockhopper disks combined) 30.5 cm diameter rockhopper disks positioned on the wings of the trawl linked together by 13 mm chains (Figure 3.2). The toggle chain heights for both trawls were 72 cm to comply with toggle chain height regulations. Trawl model testing in the Marine Institute's flume tank using 1:4 scale models revealed that the double wheeled ground gear had a 48% reduction in bottom contact area compared to the standard ground gear (Figure 3.3). The trawl nets for both the standard and experimental trawls employed the "Vónin 2007" design. "Sparrow" trawl doors designed to remain in contact with the seabed were used for both trawl treatments. Each trawl door weighed approximately 800 kg. The weight of the standard and experimental ground gears were not obtained as there was considerable difficulty in weighing the full scale components of each ground gear effectively.

Prior to at-sea testing, quality control measurements were performed on the trawls at the trawl factory located in Port de Grave, Newfoundland. The number of meshes for each of the primary trawl panels as well as the size of 60 individual meshes for each of the trawl panels were measured in accordance with established protocols (DFO, 1998). A standard Nordmøre grid with 22 mm bar spacing was used in both trawls.

### *3.2.2 Experimental Sea Trials*

Sea trials were conducted aboard the commercial fishing vessel *Newfie Pride* from August 22 to August 26, 2012. The study site was located within a deep water channel located several kilometers from the community of Port au Choix on the west coast of the island of Newfoundland (Figure 3.4).

Temperature data loggers were attached to the belly section of the trawl to record bottom temperature of the fishing area. MaxSea® marine navigation software was used on board the fishing vessel to provide digital charts and maps for navigation and recording of the tracks that the trawls were towed over. Trawl geometry data relating to the doorspread, wingspread, and headline height of both trawls was recorded from the bridge of the vessel for each tow using Netmind® and eSonar® trawl sensors. Only tows that had measurements of at least 25% of the maximum number of measurements recorded for a particular trawl type were analyzed.

Trawls were deployed and fished in depths ranging from 232-284 m. Fishing took place during the daylight period between one hour of sunrise and sunset. The alternate haul method was used to compare the catches between the two trawl types. This involved trawling an area with one of the trawls before returning back to fish the adjacent area in a parallel track with the other trawl. This method of sampling allows the investigator to sample similar abundances of marine life and environmental conditions in space and time that was sampled from the first tow (DFO, 1998). Standard and experimental trawl tows were paired in order to make legitimate comparisons regarding trawl catches and a standardized fishing regime of AB-BA – BA-AB (i.e., A = Standard trawl, B = Experimental trawl) was employed. Distance between paired tows was approximately 100-300 m. Four paired tows were completed for each fishing day. Twenty paired tows were completed in total. The amount of time the trawl spent on the seabed was determined as the time when the winches of the warp cable locked to the time haul back was initiated. Paired tows 1-12 had a bottom time of approximately 20 minutes while paired tows 13-20 had a bottom time of approximately 15 minutes. This change in bottom time was necessary to avoid exceeding the shrimp quota for the study.

When the trawl was hauled back, the catch was placed in 20 L (± 1 L) baskets. A hanging dial scale was used to obtain catch weights (± 0.25 kg), a fish measuring board was used to obtain lengths of fish (± 1 mm), and a digital caliper was used to obtain carapace lengths of shrimp (± 0.1 mm). All fish captured as bycatch were grouped by species and weighed and individual body lengths were also recorded. Five full baskets were randomly selected for weighing and for each of the five baskets a 750 ml volumetric subsample of shrimp was taken for individual shrimp carapace length and shrimp count per kg analyses. All other baskets were tallied. The total weight of shrimp captured from a trawl tow was calculated by multiplying the mean weight of the first five full baskets by the total number of baskets of shrimp captured. Any basket observed to be less than full was recorded as a percentage. If less than five full baskets of shrimp were captured in a tow, the number of subsamples would reflect the number of baskets. Shrimp catch rate for each trawl tow was calculated as the total weight of shrimp captured divided by the time the trawl was on the seabed (i.e., kg of shrimp/min). A carapace is the chitinous shell that covers the head and thorax of the shrimp and carapace length is the standard measurement for shrimp-like decapods (Squires, 1990). Individual shrimp carapace lengths were a linear measure made with digital calipers from the posterior edge of the orbit to the posterior edge of the carapace (Squires, 1990). Carapace length was measured for all shrimp in each subsample of an individual tow. Shrimp count/kg measurements were completed on land using a digital balance (± 0.1 g) and was performed on all subsamples for each individual tow. Shrimp count/kg is a common index used by industry to gauge shrimp size. Due to the industrial relevance of this study it is included in addition to individual shrimp carapace length measurements. Percent contribution of total catch weight for bycatch species was performed by dividing the weight of a species by the total weight of the catch and multiplying by 100. The hanging dial scale provided inaccurate weights of bycatch species due to their relatively low weights and the rolling and pitching of the vessel. Therefore weights of each of the major bycatch species (capelin, Greenland halibut, and redfish) were restructured from length-weight relationship equations obtained from other studies (Bowering and Stansbury, 1984; Hurtubise, 1993; Wigley et al., 2003) to provide more accurate species' weights.

### *3.2.3 Data Analysis*

All parametric data analyses were performed in IBM® SPSS® Statistics Version 19.0 (IBM Corp., 2010). Separate independent-samples t-tests were carried out to assess the effect of trawl type (independent variable) on mean shrimp catch rates, and mean shrimp count/kg (dependent variables). A nonparametric Mann-Whitney U-test was performed to assess the effect of trawl type (independent variable) on mean shrimp carapace lengths (dependent variable) because the data did not exhibit normal distribution. Also, the effect of trawl type (independent variable) on mean percent of total catch weight of bycatch species (dependent variable) was completed using an independent-samples t-test. All subsequent testing of mean percent of total catch weight of individual bycatch species (capelin, Greenland halibut, redfish, miscellaneous species) were completed in the same manner. Individual independent-samples t-tests were also performed for the major bycatch species (capelin, Greenland halibut, redfish) assessing the effect of trawl type (independent variable) on mean total length (dependent variable) of each respective species. A one-way ANOVA was performed to assess the effect of trawl type (independent variable) on dependent variable, mean headline height, for the standard and experimental trawl. Significance level for all tests were set to 0.05. Levene's equality of variances was used to validate homogeneity of variances for all ANOVAs. All catch weights were $\log_{10}(n+1)$ transformed and body lengths were $\log_{10}$ transformed to improve on normality and homogeneity of variances. Percentage of total catch weight data was arcsin square root transformed prior to analyses.

## 3.3 Results

### *3.3.1 Quality Control Analysis of Trawl Nets*

Quality control analyses were performed on the netting of both trawls. Results revealed that the number of meshes for each trawl panel was equal for both trawls. The differences between mean mesh size for each section of both trawls were found to be negligible, with most panels having less than 1% difference in mean mesh size between trawls (Table 3.1). This indicates that the trawl nets are comparable based on number of meshes and mesh size and therefore the different ground gear between the two trawls should be the only factor that will affect the performance of the trawls while fishing at-sea.

### *3.3.2 Northern Shrimp Analysis*

Catch rates of shrimp did not differ significantly between the standard and experimental trawl ($t_{38} = 0.502$, $p = 0.619$; Table 3.2). High variability was observed within and between the two trawl designs (Figure 3.5).

Count per kg of shrimp was not significantly different between the standard and experimental trawl ($t_{38} = 0.406$, $p = 0.687$; Table 3.2), and varied considerably within and between trawls (Figure 3.6). The standard trawl captured shrimp within a range of ~190 - 290 shrimp/kg while the experimental trawl captured within a range of ~190 - 300 shrimp/kg (Figure 3.6).

The carapace length of shrimp did not differ significantly between the standard and experimental trawl ($U_{38}$ = 177.50, p = 0.543; Table 3.2), and shrimp length frequency distributions were comparable between trawls (Figure 3.7). The range of carapace lengths of shrimp captured were from 9.0 - 28.5 mm with the greatest frequency of shrimp carapace length occurring from 15.0 - 19.0 mm (Figure 3.7).

### *3.3.3 Bycatch Analysis*

#### *3.3.3.1 Catch Rates*

Overall, capelin (*Mallotus villosus*) dominated the fish bycatch species in terms of abundance for both trawls followed by Greenland halibut (*Reinhardtius hippoglossoides*), and redfish (*Sebastes spp.*) (Figure 3.8). Miscellaneous fish species which were less abundant and less prevalent included Atlantic cod (*Gadus morhua)*, eelpouts (family Zoarcidae), skates (family Rajidae), grey sole (*Glyptocephalus cynoglossus*), silver hake (*Merluccius bilinearis*), Atlantic mackerel (*Scomber scombrus*), sandlance (*Ammodytes americanus*), eels (order Anguilliformes), alligatorfish (*Aspidophoroides monopterygius*), and lanternfishes (family Myctophidae) (Figure 3.8). A small benthic soft coral cnidarian, the sea pen (order Pennatulacea), was also captured in both trawls, but occurred more often in catches of the experimental trawl (Figure 3.8). Due to the greater frequency of capture for capelin, Greenland halibut, and redfish, they were considered the major bycatch species and were analyzed separately, while the miscellaneous fish bycatch species were analyzed collectively, due to their lesser frequency in both trawl catches. For all bycatch species, the experimental trawl captured a greater abundance of individuals of each species or species grouping (Figure 3.8).

There was only a minor increase in catch rates of capelin in the experimental trawl over the standard trawl (2.5%; Figure 3.8). However, the amount of Greenland halibut captured in the experimental trawl was almost two fold (1.94× more) that of the standard trawl (Figure 3.8). Likewise, the catch rate of redfish was slightly greater than two fold (2.02× more) in the experimental trawl (Figure 3.8). Bycatch of miscellaneous fish was nearly 3× greater (2.94× more) while sea pen catch was more than 10× greater in the experimental trawl over that of the standard trawl (Figure 3.8). Sea pens were also more prevalent in the experimental trawl, occurring in 10 of the 20 tows compared to 2 of 20 tows made with the standard trawl (Figure 3.9). In the two paired tows where both trawls captured sea pens, the experimental trawl also captured a greater number of sea pens (Figure 3.9).

#### *3.3.3.2 Bycatch as a Percentage of the Total Catch Weight*

When bycatch is expressed as a percentage of the total catch weight it may be used to combine all bycatch species for analysis. An independent-samples t-test indicated that, overall, the experimental trawl was found to capture a significantly greater mean percentage of bycatch ($t_{38} = 2.138$, $p = 0.039$; Table 3.3). The percentage of total catch weight that was made up of bycatch species was 1.5× greater on average for the experimental trawl in comparison to the standard trawl (Table 3.4). This prompted further analyses of the major and miscellaneous fish bycatch species.

The experimental trawl captured a greater mean percentage of all bycatch species or species groups over the standard trawl, capturing 1.15× more capelin, 1.5× more Greenland halibut, 2.0× more redfish, and 1.7× more miscellaneous fish (Table 3.4). Each major bycatch species and miscellaneous bycatch species exhibited a high degree of variability both within trawl treatments and between tows (Figure 3.10; 3.11; 3.12; 3.13). Independent-samples t-test analyses comparing the effect of trawl type on the mean percentage of total catch weight of each of the major bycatch species as well as the miscellaneous fish bycatch species however revealed no significant differences (Table 3.4). Within the study site, the mean percentages that each of the major bycatch species and the collective miscellaneous fish bycatch species contributed to the total catch weight among both trawls was fairly low overall, ranging from 0.06% to 0.86% (Table 3.4).

#### *3.3.3.3 Total Length of Bycatch Species*

No statistically significant differences were detected in the mean total length of the major bycatch species between trawl types (Table 3.5). Both trawls captured the same size ranges with a similar percent frequency for each species. Capelin ranged from 10.0-17.0 cm with a mode of 14.0 cm (Figure 3.14), Greenland halibut ranged from

10.0-60.0 cm with a mode of 21.0 cm (Figure 3.15), and redfish ranged from 3.0-18.0 cm with a mode of 9.0 cm (Figure 3.16). Miscellaneous fish were not analyzed due to low catch rates and the large variety of species morphologies.

### *3.3.4 Trawl Geometry Data*

Vemco temperature data loggers logged a consistent bottom temperature of 5 °C throughout the study. Unfortunately the trawl sensors were not functioning optimally during the comparative fishing trials for both trawls and returned no valuable measurement data for trawl doorspread. However, some useful data was obtained from the sensors for headline height and wingspread (Table 3.6). Results of a one-way analysis of variance comparing the effect of trawl type on mean headline height found no significant difference in headline height between the trawls ($F_{1,17} = 0.326$, $p = 0.575$; Table 3.7). There was only an approximate 2% increase in headline height of the standard trawl as compared to the experimental trawl (Table 3.7). Overall the headline height for both trawls was approximately 5.10 m (Table 3.7). Analysis of trawl wingspread data was not completed due to the few number of eligible tows (3 of 20 paired tows) that could be analyzed in the experimental trawl.

### *3.3.5 Observations of Trawl Disturbance to the Seabed*

During haul back and landing of the catch, it was observed that components of the trawl ground gear, trawl net, and the catch were caked in mud. This appears to have resulted from the trawl digging into the seabed and displacing sediment into the trawl net. Although data was not recorded, the general consensus among the vessel's crew and research team was that there was a greater incidence of mud in the tows with the experimental trawl.

## 3.4 Discussion

The experiments performed in this study sought to analyze and compare the catch characteristics of a new, innovative trawl ground gear designed to have reduced seabed contact area over that of a standard trawl ground gear commonly used by fishermen in the present day northern shrimp fishery of Atlantic Canada. The ground gear of the experimental trawl was designed to have far less surface contact (~48% less) with the bottom substrate than the standard trawl. Less surface contact in turn would conceivably decrease impacts on the seabed.

Although physical impacts to the seabed were not measured during this study observations suggest that the experimental ground gear may have had greater physical impact than intended. Specifically, several of the tows made with the experimental trawl were observed to have mud on the trawl net, ground gear, and within the catch during haul back. It appears that one or more of the components of the trawl ground gear dug into the seabed, causing muddy sediment to become caked on to the trawl ground gear and mud to become resuspended into the trawl net. I suspect that the long horizontal steering chains that connected each double wheel assembly may have been digging into the seabed. While this was not observed during flume tank evaluations, it is possible that the close proximity of chains to the seabed caused them to dig into the sediment and function in perhaps the same manner as a tickler chain when attached to the ground gear of a trawl. Tickler chains are used in many flatfish bottom trawling fisheries throughout the world and are designed to penetrate the upper few centimeters of the sediment and displace flatfish and other targeted species upwards from the sediment into the mouth of the trawl net (Løkkeborg, 2005; He and Winger, 2010).

The quality control assessments performed on the trawls prior to at-sea testing indicates that differences in the trawl nets and Nordmøre grid were negligible; each trawl had the same number of meshes for each trawl panel and comparable mesh sizes for the trawl net as well as the same bar spacing of the Nordmøre grid. This is important to clarify as the differing ground gears for each trawl were the only factors that should have affected catch rates of shrimp and other bycatch species.

Unfortunately, the trawl geometry sensors did not perform well for many of the tows, and only half the number of paired tows could be used to provide comparisons of trawl headline height. Headline height was subsequently not found to be significantly different between trawl types. The wingspread for the experimental trawl had only 3 tows out of 20 that were eligible for analysis which presumably would not give an accurate measure of actual mean wingspread throughout the 20 paired tows. Consequently, wingspread data was not analyzed. Also, doorspread sensors had too few measurements to accurately evaluate doorspread. Headline height, wingspread, and doorspread measurements are important to identify during a fishing operation as the swept area of a trawl largely determines the amount of shrimp that will be captured (Watson, 1989; Hannah et al., 2003). A greater spread of these trawl components in theory will allow greater capture of shrimp and bycatch species as the trawl may sample a larger area.

Catch rates were variable among tows and may be due in part to variable abundances of shrimp in the area that was sampled. The alternate haul technique which was employed for sampling in this study involves trawling immediately and directly adjacent to the site that was towed earlier thereby sampling roughly the same abundances of marine life and environmental conditions in space and time that was sampled from the first tow (DFO, 1998). In this way, valid comparisons between catch characteristics of different trawls may be made. Northern shrimp are known to aggregate and it is possible that some areas trawled during this study had lower abundances of shrimp than others. In such cases the opportunity to capture shrimp would be decreased and would not necessarily reflect similar catch characteristics among trawls. I am confident however that the catch characteristics of both trawls were well represented from the 20 paired tows performed during this study. Furthermore, the DFO protocol for performing bottom trawl comparison studies using the alternate haul method cite 20 paired tows as an acceptable number of replicates to make inferences about trawl catch characteristics (DFO, 1998).

As expected, the carapace length of shrimp captured in both trawls were very similar. Both trawls had the same trawl net design with comparable mesh size throughout and a standard Nordmøre grid with 22 mm bar spacing. When shrimp enter the mouth of the trawl net, the carapace length of shrimp retained in the codend as catch is a function of trawl mesh size and Nordmøre grid bar spacing and it is therefore highly unlikely that a difference in ground gear would alter that.

Count per kg of shrimp was also very similar among the two trawls. A lower count per kg of shrimp is indicative of larger shrimp (i.e., greater carapace length) or proportionately more gravid females and is more profitable for fishermen to land over a higher count per kg of shrimp (i.e., smaller shrimp). On average, the standard trawl captured less than four more shrimp per kg than the experimental trawl which would not affect the landed value. Once again, count/kg was not expected to be noticeably affected by a difference in ground gear type since count per kg is affected by similar factors as carapace length such as trawl mesh size and bar spacing in the Nordmøre grid.

In terms of bycatch of fish species, the experimental trawl was observed to capture substantially more individuals of each major fish species as well as miscellaneous fish species. While the number of capelin captured between the two trawls was fairly similar, the experimental trawl captured nearly twice as many Greenland halibut and redfish, and three times as many miscellaneous fish. Capelin is a pelagic schooling fish species which makes it vulnerable to capture in large quantities, especially when they are concentrated near the seabed during trawling activities. Juvenile Greenland halibut exhibit bathypelagic behaviour (de Groot, 1970) but during daylight hours have been found to be captured almost exclusively near the bottom (Jorgensen, 1997), which is perhaps why Greenland halibut were a major bycatch species captured throughout this study. Redfish are often distributed in clumped aggregations and exhibit diel vertical migrations which can result in higher daytime catches in bottom trawls (Atkinson, 1989). The experimental trawl also captured significantly more sea pens in this study with ten times the number of sea pens being captured in the experimental trawl over that of the standard trawl. It was observed that the sea pens were not uprooted but appeared to be cut or sheared off by the chains and cables of the experimental trawl ground gear.

Although percent contribution to the total catch weight for each major bycatch species and miscellaneous fish species groups did not differ significantly, the experimental trawl did capture a higher percentage of fish that resulted in a significant difference when all bycatch species were combined. The mean percentage of the total catch weight for all bycatch species was 1.55% for the standard and 2.31% for the experimental trawl. All shrimp vessels fishing in Canadian waters are required by law to use sorting grates such as the Nordmøre grid to reduce bycatch levels. This requirement has significantly reduced bycatch levels in the northern shrimp fishery in Atlantic Canada, which currently averages less than 2% bycatch in relation to the total shrimp catch (DFO, 2007). This level of bycatch is much lower than many other large-scale shrimp fisheries (Alverson et al., 1994). I believe that this result from the study provides further evidence that the experimental trawl likely dug into the sediment as it captured more groundfish bycatch species that live on and within the sediment over that of the standard trawl.

Mean total length of the major bycatch species were comparable between the two trawls. This again relates back to the mesh size of the trawl net and the bar spacings of the Nordmøre grid as well as the comparable size distributions of these species in the path of the trawls. Only fish that are small enough to pass through the Nordmøre grid will be retained as catch in the codend of the trawl and fish smaller than a particular mesh should pass through the net and not be captured. In this way, the trawl selects a particular size range of bycatch which are commonly either small, juvenile fish, or small fish species. Capelin are a small pelagic fish that will fit through the Nordmøre grid of a trawl without difficulty as an adult or juvenile. Additionally, many of the Greenland halibut captured in this study were from 20.0-30.0 cm in length and are considered juveniles (Bowering, 1983). Similarly, most redfish captured were from 8.0-12.0 cm in length and are considered juveniles (Ni and Templeman, 1985). Fish were considered juveniles if they were documented in the literature as being less than the mean length at which 50% of individuals attain sexual maturity.

The results of this study found that both trawls fished similarly in terms of targeting northern shrimp, however, the mean percent contribution of total catch weight of all bycatch species combined was statistically higher in the double wheeled experimental trawl. It is important that the experimental trawl had comparable catch rates, carapace lengths, and count per kg of northern shrimp to the standard trawl and was a success in that respect. Significantly greater levels of bycatch and bycatch catch rates above average rates documented in the fishery are not acceptable however due to several factors. Firstly, many of the fish captured as bycatch in trawls are severely injured or killed in the landing process (Davis, 2002; Surronen, 2005). This removes large numbers of animals from the marine environment and can harm the dynamics of marine ecosystems where all species are interacting with one another. Bycatch will also reduce recruitment of commercial species to the fishery as many of the bycatch species captured in trawls are juveniles (NOAA, 1998). Secondly, more bycatch equates to more time spent sorting and removing bycatch by fishermen. Thirdly, any bycatch missed during sorting that is landed at the dock can be deducted from the fisherman’s profit. I hypothesize that the increase in bycatch in the experimental trawl may be due to the trawl possibly digging in to the seabed and functioning somewhat as a tickler chain, displacing fish into the mouth of the trawl net. This would also result in high volumes of sediment being resuspended that would create a herding effect for groundfish (Rose et al., 2010) and make it difficult for fish to locate the escape region between the ground gear and the fishing line of the trawl, resulting in higher levels of bycatch.

Physical impacts on the seabed were not measured in this study as time and resources did not permit, so it is not conclusive whether the experimental ground gear did indeed dig in to the seabed more than the standard trawl. Observations of mud on the components of the trawl and in the trawl catch as well as the high incidence of sea pens and increased levels of groundfish bycatch retained in the experimental trawl however do suggest that increased disturbance to the seabed by the experimental ground gear is quite possible. Even though the experimental ground gear had far fewer contact points than the standard ground gear, the presence and location of the horizontal steering chains which connected the double wheeled ground gear may have inadvertently dragged along the seabed which would increase the impact of the ground gear more than previously thought.

I recommend modifications to reduce the amount of chains and wires on the experimental ground gear which was used in this study. This would conceivably reduce the chances of components of the ground gear from digging in to the sediment. If further modifications are to be performed on this ground gear, the use of underwater cameras is recommended to determine if the ground gear is truly digging into the seabed. For future studies, I would also recommend the use of equipment to assess and quantify physical impacts on the seabed such as underwater video, side scan sonar, or hydro acoustics.

**Table 3.1** Results of the trawl quality control analysis performed prior to at-sea fishing trials to compare measurements of mesh size for both the standard and experimental trawl nets. 36 trawl panel measurements are included.

| Trawl section | Standard trawl | Experimental trawl | % Difference |
|---|---|---|---|
| Upper Wing Starboard | 92.3 | 91.5 | + 0.87 |
| Upper Wing Port | 92.1 | 91.6 | + 0.54 |
| Upper Bunt Wing Starboard | 46.1 | 45.5 | + 1.32 |
| Upper Bunt Wing Port | 45.5 | 45.8 | - 0.30 |
| Lower Wing Starboard | 91.9 | 91.5 | + 0.44 |
| Lower Wing Port | 91.7 | 92.1 | - 0.44 |
| Lower Bunt Wing Starboard | 45.7 | 45.6 | - 0.22 |
| Lower Bunt Wing Port | 46.0 | 46.4 | - 0.86 |
| Codend Top | 42.5 | 43.7 | - 2.78 |
| Codend Bottom | 43.4 | 43.7 | - 0.69 |
| Side Panel 1 Starboard | 44.9 | 45.2 | - 0.69 |
| Side Panel 1 Port | 46.2 | 45.7 | + 1.09 |
| Side Panel 2 Starboard | 45.2 | 45.7 | - 1.09 |
| Side Panel 2 Port | 45.8 | 46.4 | - 1.29 |
| Side Panel 3 Starboard | 45.5 | 46.0 | - 1.09 |
| Side Panel 3 Port | 45.5 | 45.6 | - 0.22 |
| Side Panel 4 Starboard | 44.6 | 45.5 | - 1.98 |
| Side Panel 4 Port | 44.9 | 45.0 | - 0.22 |
| Side Panel 5 Starboard | 45.6 | 46.1 | - 1.09 |
| Side Panel 5 Port | 45.6 | 45.3 | + 0.66 |
| Side Panel 6 Starboard | 43.9 | 44.2 | - 0.68 |
| Side Panel 6 Port | 44.7 | 44.6 | + 0.22 |
| First Upper Belly | 45.8 | 45.5 | + 0.66 |
| First Lower Belly | 43.5 | 43.2 | + 0.46 |
| Second Upper Belly | 45.9 | 45.8 | + 0.22 |
| Second Lower Belly | 45.1 | 46.0 | - 1.96 |
| Third Upper Belly | 45.4 | 45.2 | + 0.44 |
| Third Lower Belly | 45.2 | 46.0 | - 1.74 |
| Fourth Upper Belly | 44.7 | 45.1 | - 0.89 |
| Fourth Lower Belly | 44.8 | 44.7 | + 0.22 |
| Extension Piece Top | 43.5 | 42.6 | + 2.11 |
| Extension Piece Bottom | 43.1 | 45.2 | - 4.65 |
| Grid Section Top | 44.1 | 44.5 | - 0.90 |
| Grid Section Bottom | 43.1 | 42.9 | + 0.47 |
| Extension Top | 42.0 | 42.7 | - 1.64 |
| Extension Bottom | 42.6 | 42.5 | + 0.24 |

**Table 3.2** Summary of data analyses comparing the effect of trawl type on the mean catch rate of northern shrimp, count per kg of shrimp, and carapace length of shrimp. Independent-samples t-tests were performed for catch rate and count per kg analyses while a nonparametric Mann-Whitney U-test was performed for carapace length analysis. No significant effects of trawl type on catch rate, count per kg, or carapace length of shrimp were found (i.e., p>0.05).

| | | | | | Analysis | | |
|---|---|---|---|---|---|---|---|
| Source | Trawl type | No. of tows | Mean | SE | df | t-statistic/ U-statistic | p-value |
| Catch rate (kg/min) | Standard | 20 | 10.92 | 0.87 | 38 | 0.502 | 0.619 |
| | Experimental | 20 | 10.63 | 0.98 | | | |
| Count per kg (#/kg) | Standard | 20 | 241.51 | 6.03 | 38 | 0.406 | 0.687 |
| | Experimental | 20 | 237.80 | 6.86 | | | |
| Carapace length (mm) | Standard | 20 | 18.06 | 0.11 | 38 | 177.50 | 0.543 |
| | Experimental | 20 | 18.21 | 0.13 | | | |

**Table 3.3** Summary of independent-samples t-test comparing the effect of trawl type on the mean percent contribution of total catch weight of all bycatch species combined.

| | | Percent of total catch weight (%) | | Analysis | | |
|---|---|---|---|---|---|---|
| Trawl type | No. of tows | Mean | SE | df | t-statistic | p-value |
| Standard | 20 | 1.55 | 0.25 | 38 | 2.138 | 0.039* |
| Experimental | 20 | 2.31 | 0.34 | | | |

*Significantly different at $p<0.05$.

**Table 3.4** Summary of independent-samples t-test comparing the effect of trawl type on the mean percent contribution of total catch weight of the major bycatch species (Greenland halibut, capelin, redfish) and miscellaneous species (Atlantic cod, eelpouts, skates, grey sole, silver hake, Atlantic mackerel, sandlance, eels, alligator fish, and lantern fish). No significant effects of trawl type on percent of total catch weight of major bycatch species or miscellaneous bycatch species were found (i.e., p>0.05).

| | | | Percent of total catch weight (%) | | Analysis | | |
|---|---|---|---|---|---|---|---|
| Species | Trawl type | No. of tows | Mean | SE | df | t-statistic | p-value |
| Capelin | Standard | 20 | 0.47 | 0.08 | 38 | 0.617 | 0.541 |
| | Experimental | 20 | 0.58 | 0.11 | | | |
| Greenland halibut | Standard | 20 | 0.57 | 0.11 | 38 | 1.747 | 0.089 |
| | Experimental | 20 | 0.86 | 0.15 | | | |
| Redfish | Standard | 20 | 0.06 | 0.01 | 30 | 1.333 | 0.193 |
| | Experimental | 20 | 0.12 | 0.03 | | | |
| Misc. fish | Standard | 20 | 0.44 | 0.17 | 38 | 1.815 | 0.077 |
| | Experimental | 20 | 0.76 | 0.21 | | | |

**Table 3.5** Summary of independent-samples t-test comparing the effect of trawl type on the mean total length of the major bycatch species. No significant effects of trawl type on total length of each species were found (i.e., p>0.05).

| | | | Total length (cm) | | Analysis | | |
|---|---|---|---|---|---|---|---|
| Species | Trawl type | No. of tows | Mean | SE | df | t-statistic | p-value |
| Capelin | Standard | 20 | 13.59 | 0.07 | 38 | 1.645 | 0.108 |
| | Experimental | 20 | 13.82 | 0.12 | | | |
| Greenland halibut | Standard | 20 | 21.98 | 0.74 | 38 | 0.086 | 0.932 |
| | Experimental | 20 | 21.93 | 0.84 | | | |
| Redfish | Standard | 20 | 8.88 | 1.23 | 38 | 0.593 | 0.556 |
| | Experimental | 20 | 8.04 | 0.66 | | | |

**Table 3.6** Number of trawl sensor measurements of headline height and wingspread for both the standard and experimental trawl during at-sea comparative fishing trials. Only tows that had measurements of at least 25% of the maximum number of measurements recorded for a particular trawl type were analyzed. Values in bold indicate tows where the number of measurements were at least 25% of the maximum number recorded for that trawl type. N/A denotes tows where no useable measurements were obtained.

| | Headline height (m) | | Wingspread (m) | |
|---|---|---|---|---|
| Paired Tow # | Standard | Experimental | Standard | Experimental |
| | | | | |
| 1 | 35 | **141** | 18 | N/A |
| 2 | **238** | **107** | 6 | N/A |
| 3 | 49 | 140 | 1 | N/A |
| 4 | **256** | **268** | 2 | N/A |
| 5 | **184** | **101** | 42 | **145** |
| 6 | **321** | 3 | 4 | 3 |
| 7 | **150** | 64 | **152** | 3 |
| 8 | **339** | 2 | N/A | 4 |
| 9 | N/A | **293** | N/A | 23 |
| 10 | 2 | **279** | N/A | **72** |
| 11 | **204** | 4 | N/A | 2 |
| 12 | N/A | **226** | N/A | 7 |
| 13 | N/A | **203** | **180** | N/A |
| 14 | 5 | **271** | **126** | 15 |
| 15 | 4 | 10 | N/A | 10 |
| 16 | N/A | 2 | **130** | 20 |
| 17 | **281** | 4 | **126** | N/A |
| 18 | **220** | 5 | **98** | N/A |
| 19 | **228** | 6 | **108** | 32 |
| 20 | N/A | 3 | N/A | **58** |

**Table 3.7** Summary of one-way ANOVA comparing the effect of trawl type on the mean headline height (m) of the standard and experimental trawl. No significant differences in mean headline heights were found (i.e., p>0.05).

| | | Headline height (m) | | Analysis | | |
|---|---|---|---|---|---|---|
| Trawl type | No. of tows | Mean | SE | df | F-statistic | p-value |
| Standard | 10 | 5.17 | 0.09 | 1, 17 | 0.326 | 0.575 |
| Experimental | 9 | 5.09 | 0.08 | | | |

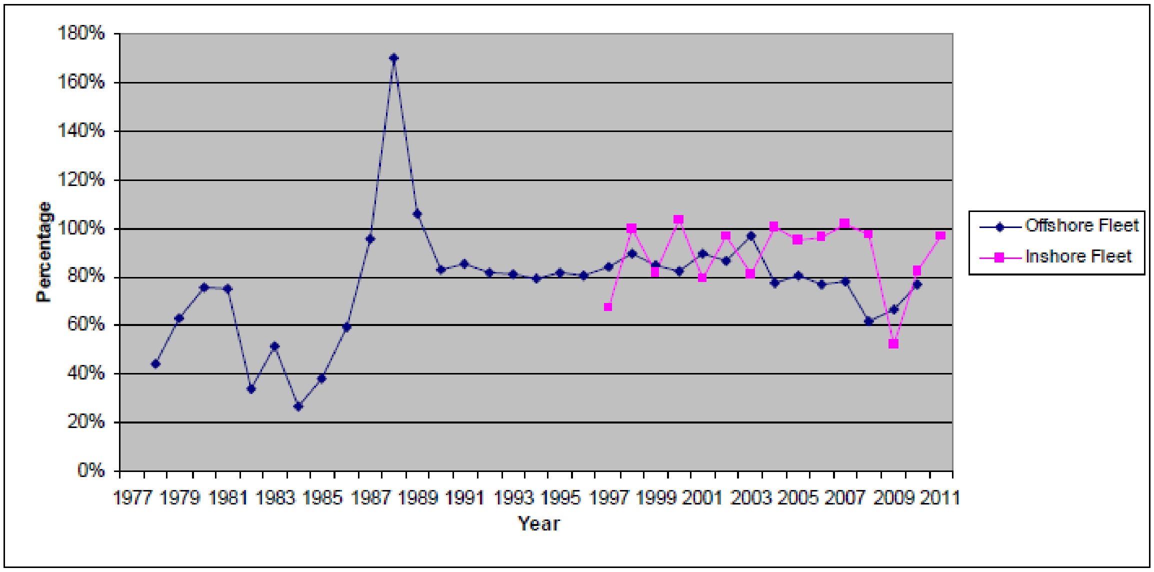


**Figure 3.1** Northern shrimp quota usage by the inshore and offshore fleets from 1977 to 2011 (DFA, 2012).

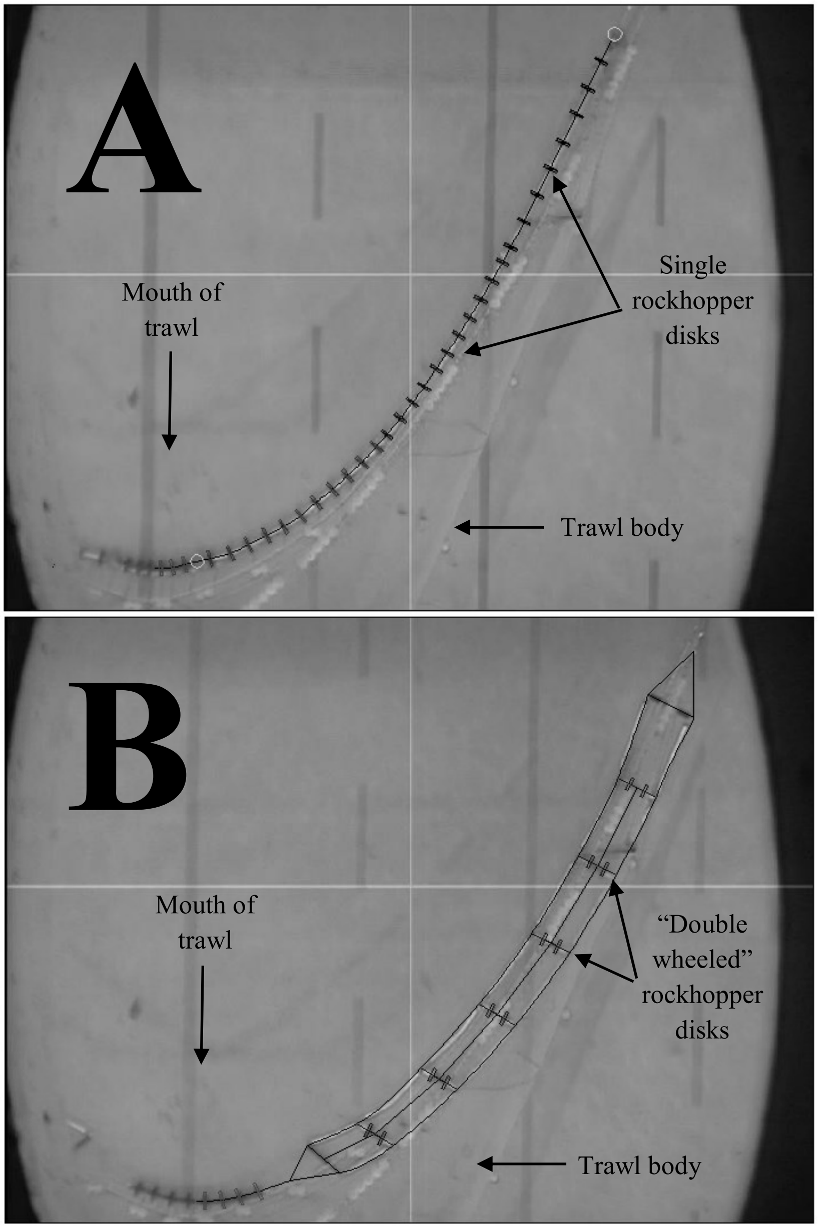


**Figure 3.2** Overhead view showing the right half of the standard (Panel A) and experimental (Panel B) trawl ground gears being tested in the flume tank of the Marine Institute. The standard trawl can be seen to have several more rockhopper disks than the experimental trawl.

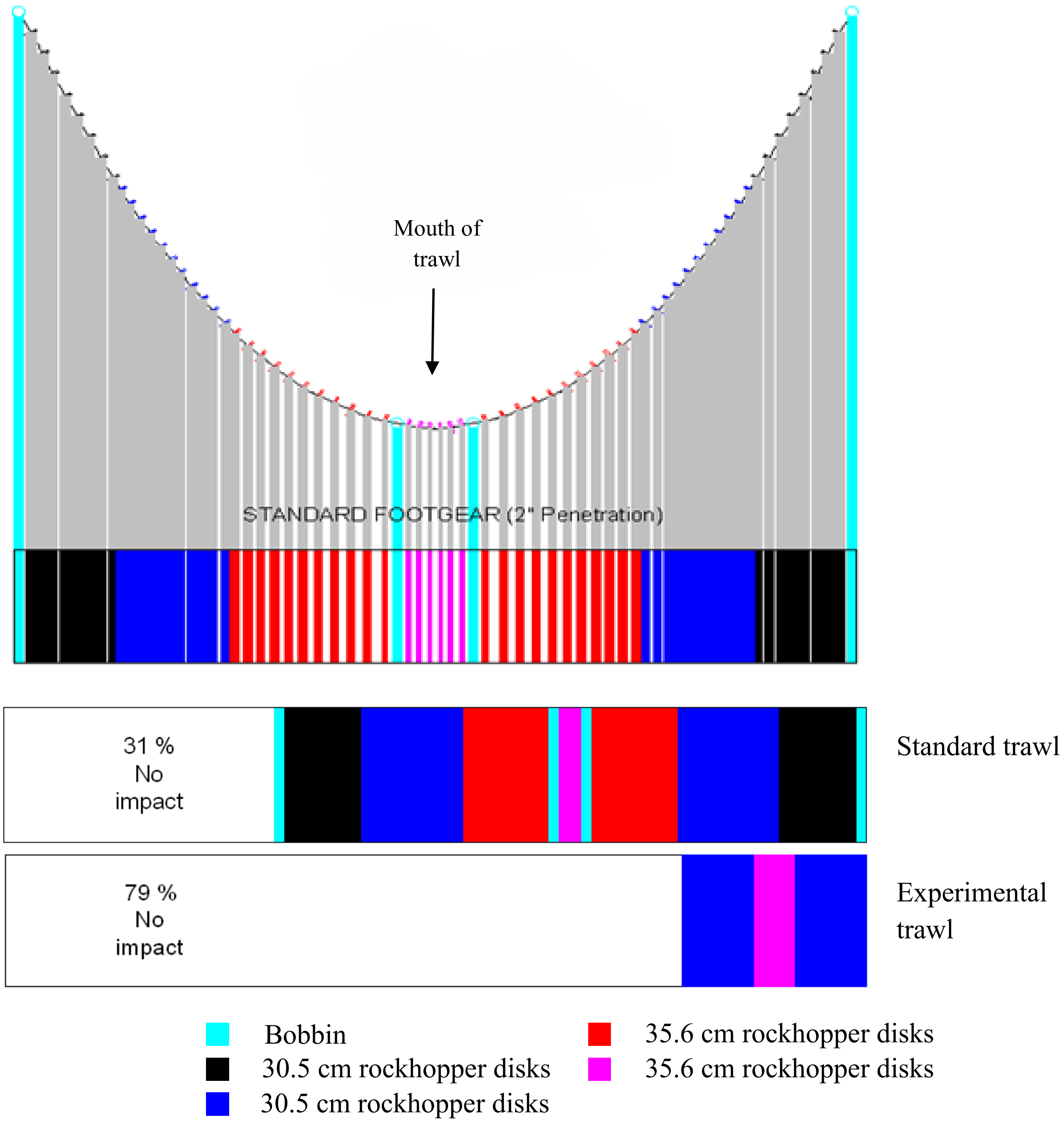
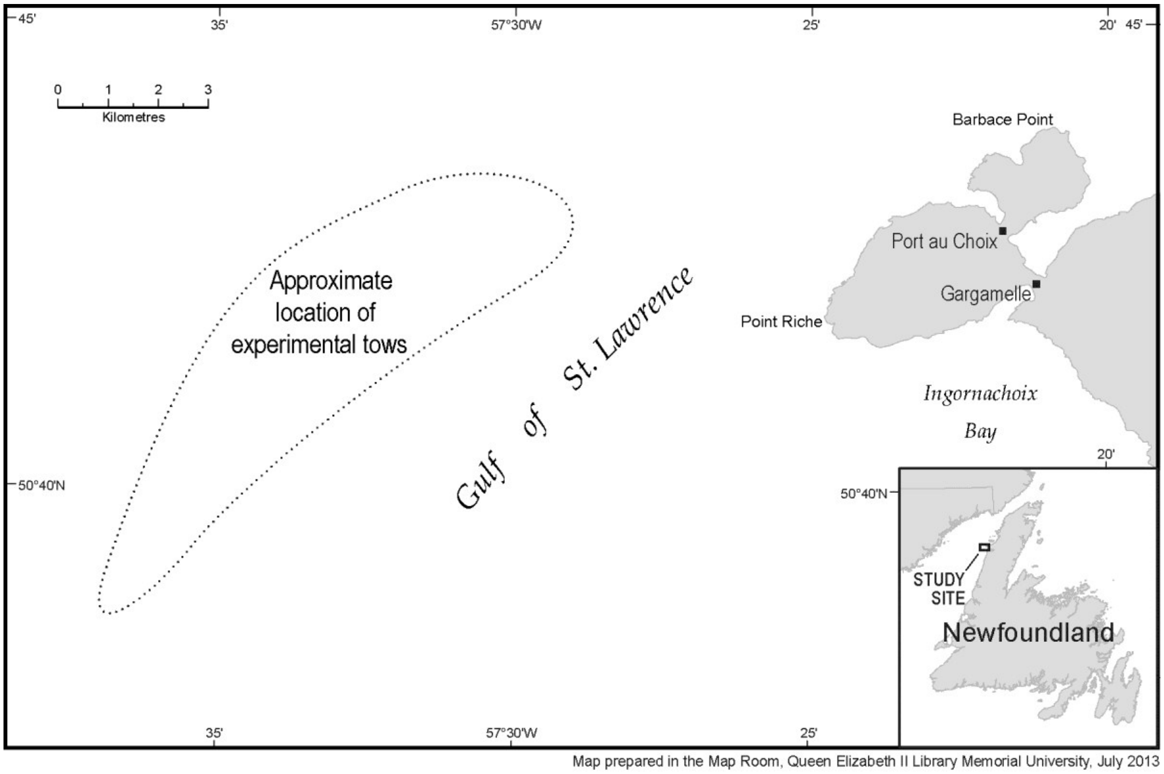


**Figure 3.3** Trawl ground gear schematic illustrating some of the components of the ground gear and the area of the seabed that the ground gear makes contact with in flume tank trials. The experimental trawl can be seen to have substantially less (79% - 31% = 48%) bottom contact area than the standard trawl. This schematic was designed from flume tank tests of 1:4 scale model trawls. The standard trawl ground gear is illustrated.



Map prepared in the Map Room, Queen Elizabeth II Library Memorial University, July 2013

**Figure 3.4** Map of the northeast region of the Gulf of St. Lawrence illustrating the approximate tow locations for 20 comparative paired tows from the at-sea fishing trials of the standard and experimental trawl.

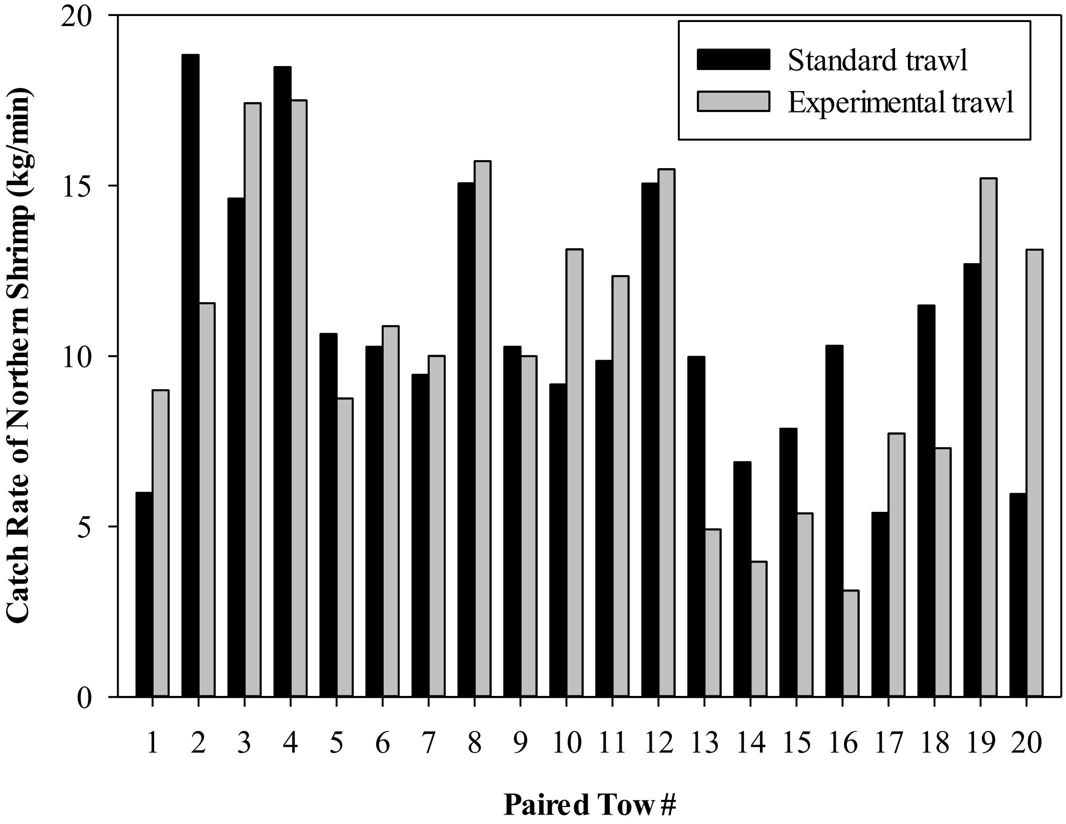


**Figure 3.5** Catch rates of northern shrimp across 20 paired tows of the standard and experimental trawl.

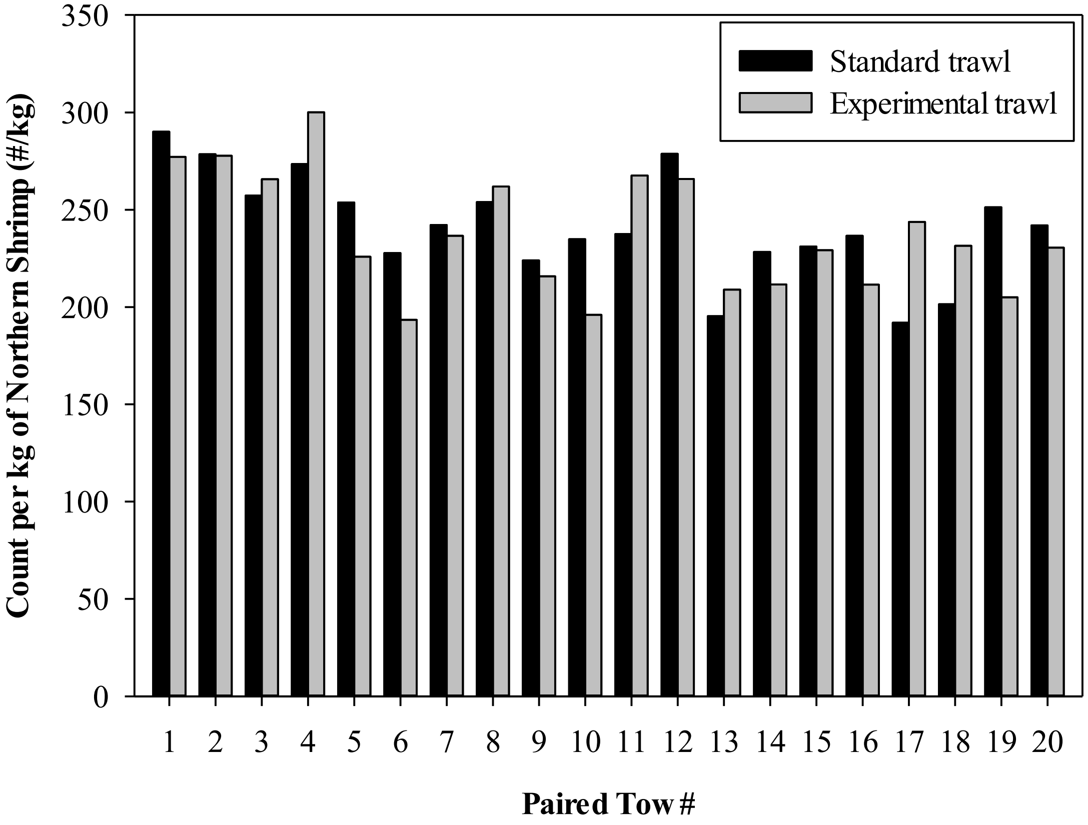


**Figure 3.6** Count per kg of northern shrimp captured across 20 paired tows of the standard and experimental trawl.

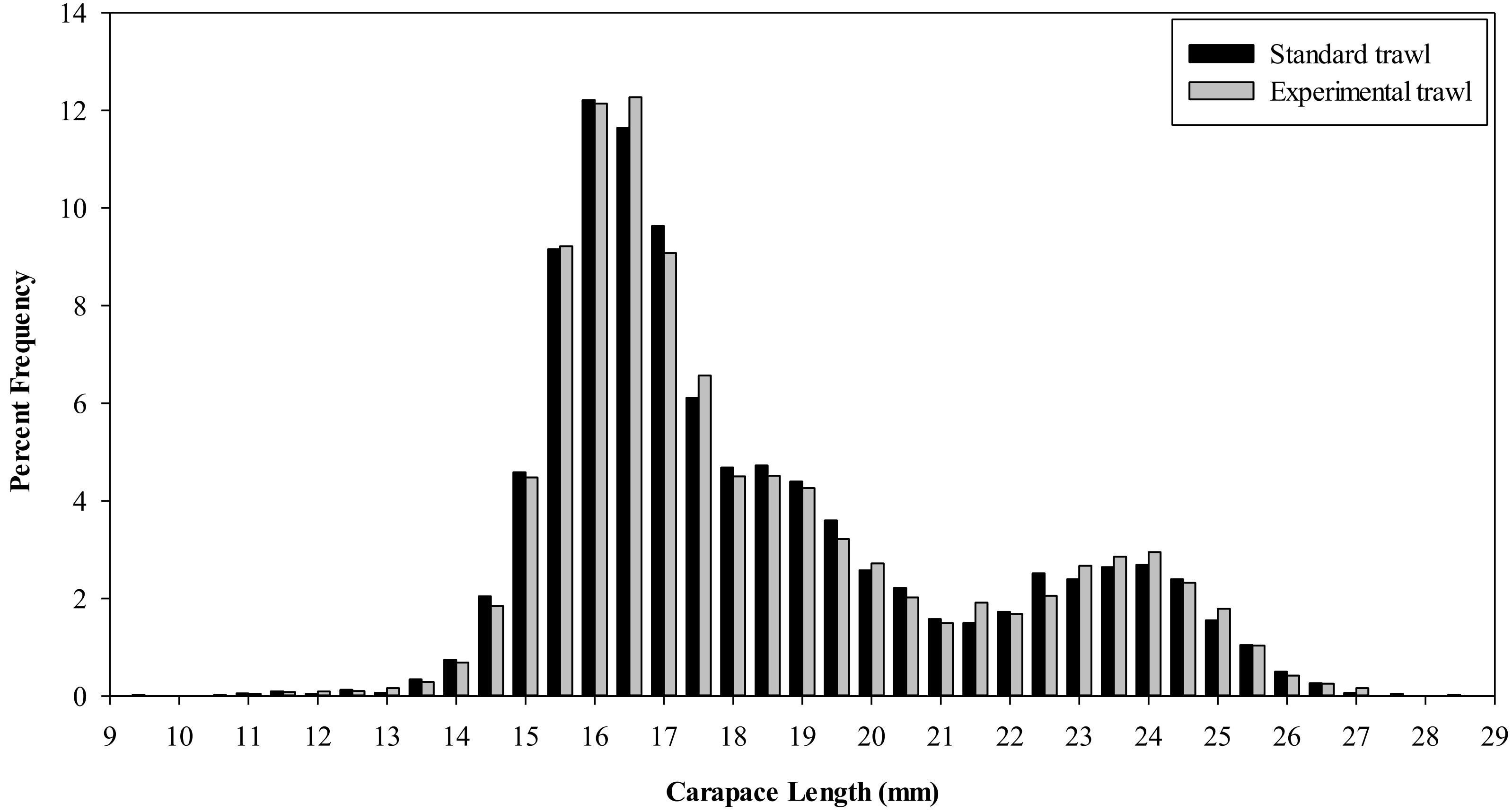


**Figure 3.7** Percent frequency distribution of northern shrimp carapace lengths across 20 paired tows of the standard and experimental trawl.

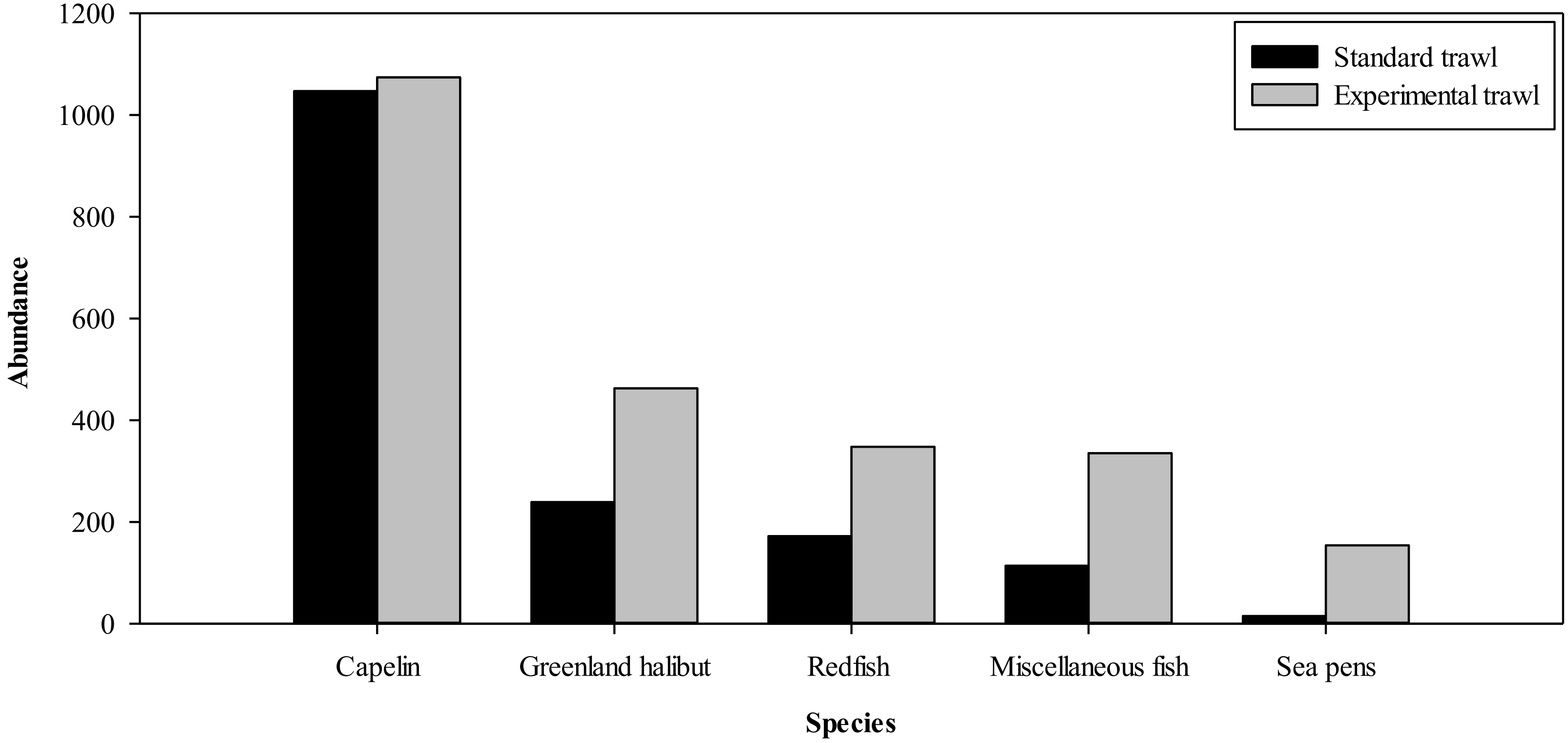


**Figure 3.8** Total abundances of non-targeted bycatch species captured in the standard and experimental trawl. The abundances of the three major bycatch species (capelin, Greenland halibut, and redfish) and the miscellaneous fish species (Atlantic cod, eelpout, skate, grey sole, silver hake, Atlantic mackerel, sandlance, eel, alligator fish, and lantern fish) as well as the major soft coral captured, the sea pen, are illustrated.

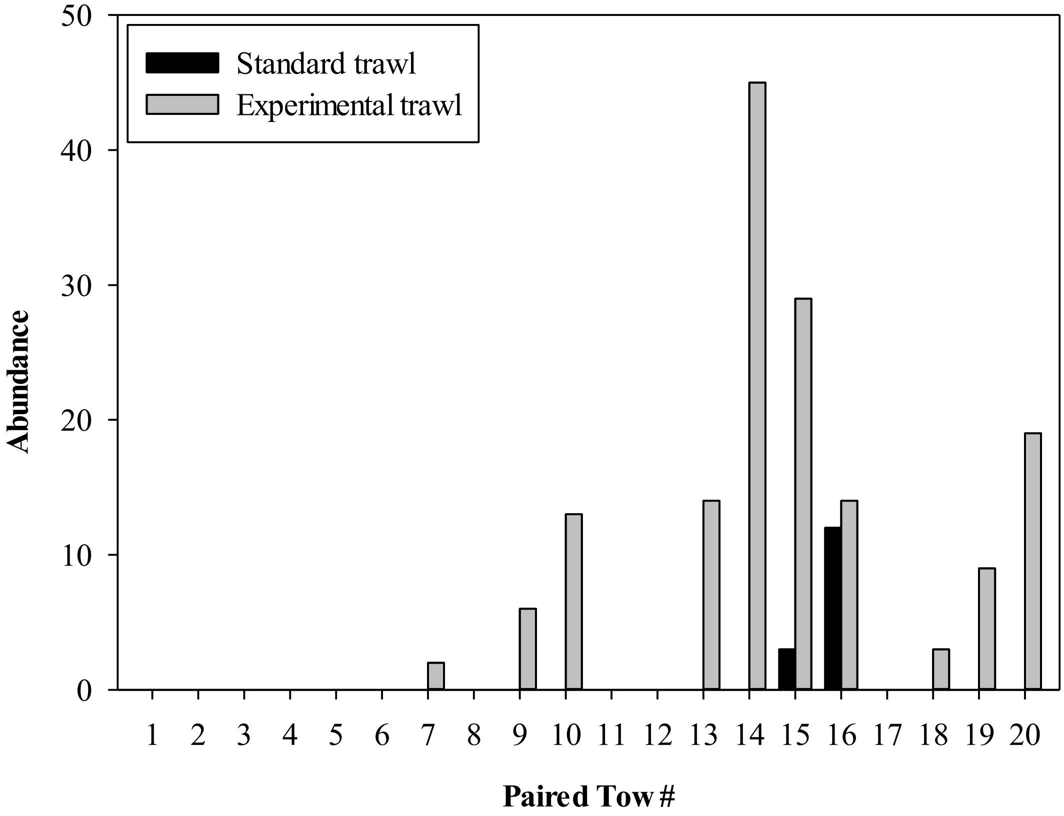


**Figure 3.9** Abundance of sea pens captured across 20 paired tows of the standard and experimental trawl.

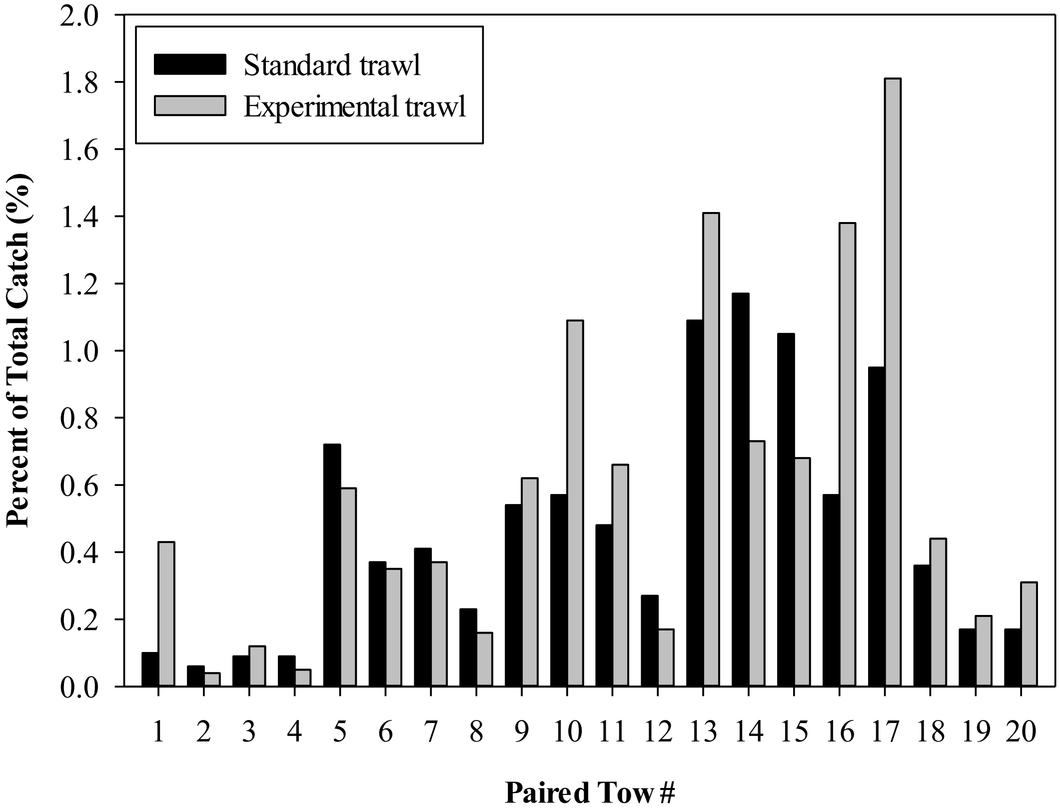


**Figure 3.10** Percent contribution of capelin to the total catch weight across 20 paired tows of the standard and experimental trawl.

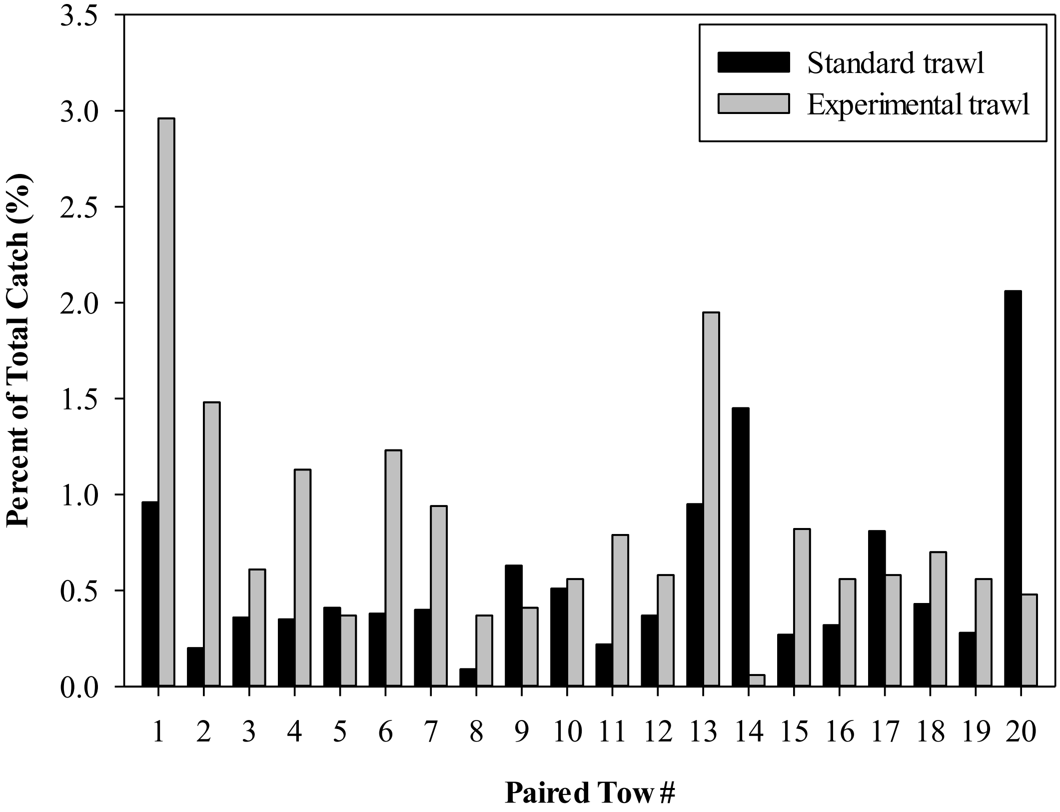


**Figure 3.11** Percent contribution of Greenland halibut to the total catch weight across 20 paired tows of the standard and experimental trawl.

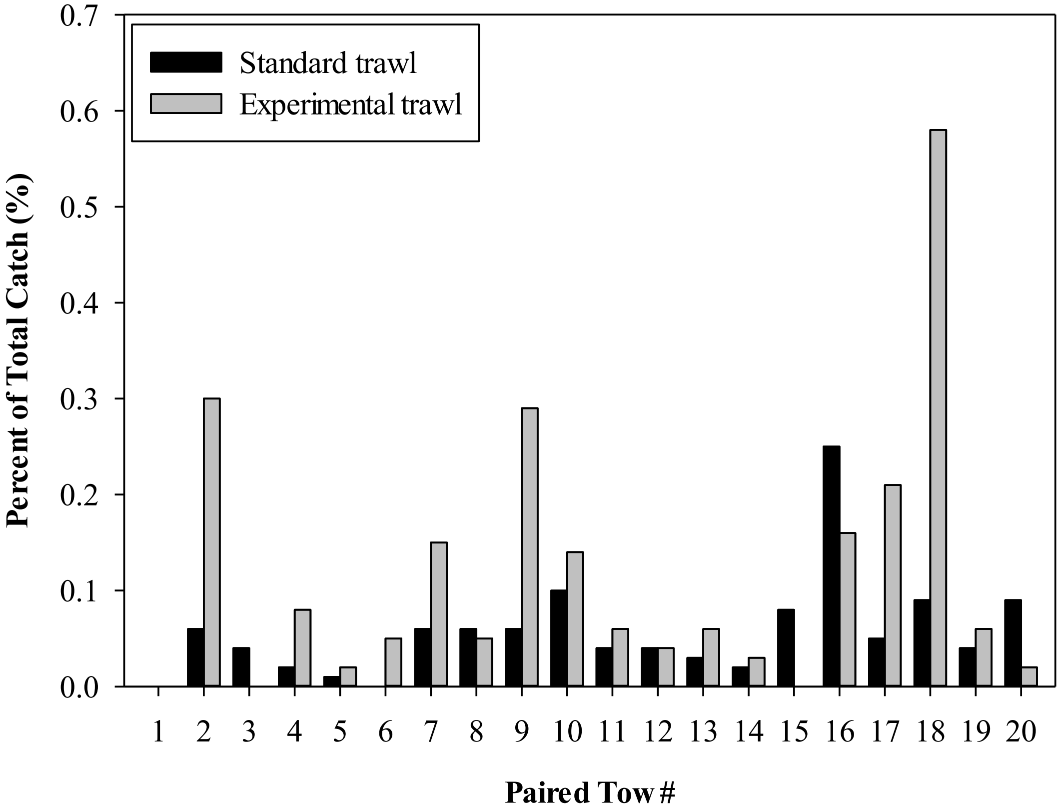


**Figure 3.12** Percent contribution of redfish to the total catch weight across 20 paired tows of the standard and experimental trawl.

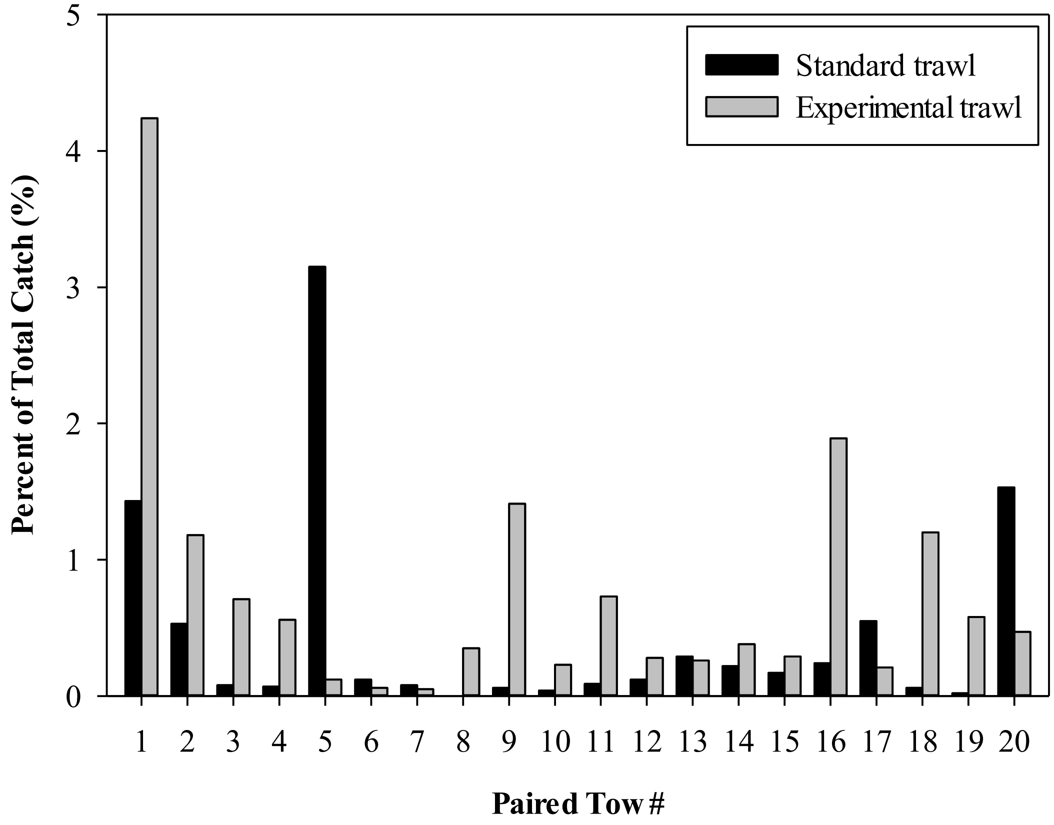


**Figure 3.13** Percent contribution of miscellaneous fish to the total catch weight across all paired tows of the standard and experimental trawl.

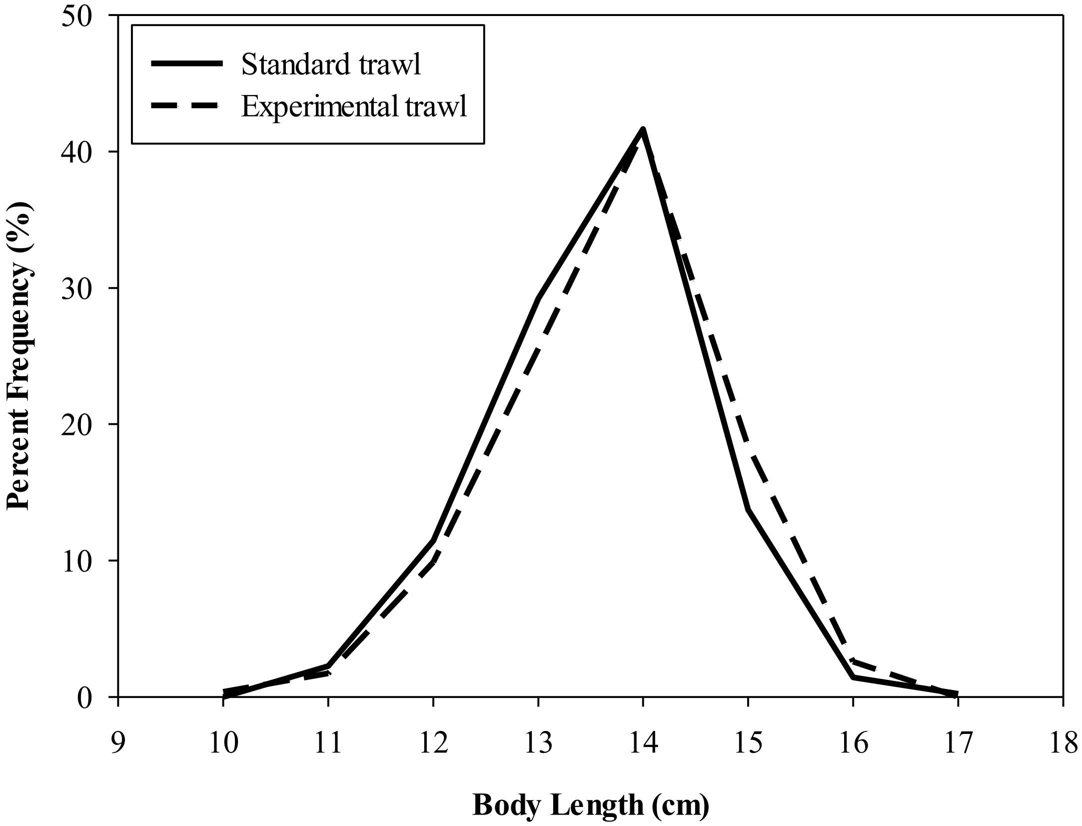


**Figure 3.14** Body length frequency distribution of capelin captured across 20 paired tows of the standard and experimental trawl.

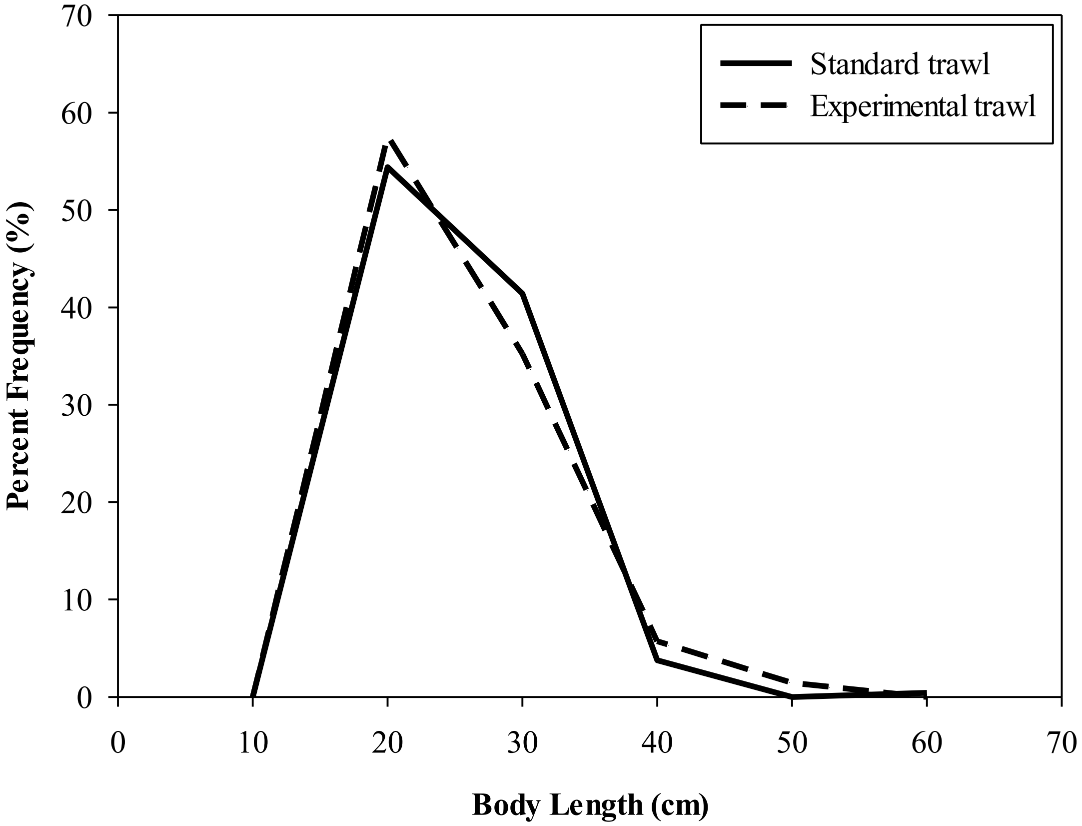


**Figure 3.15** Body length frequency distribution of Greenland halibut captured across 20 paired tows of the standard and experimental trawl.

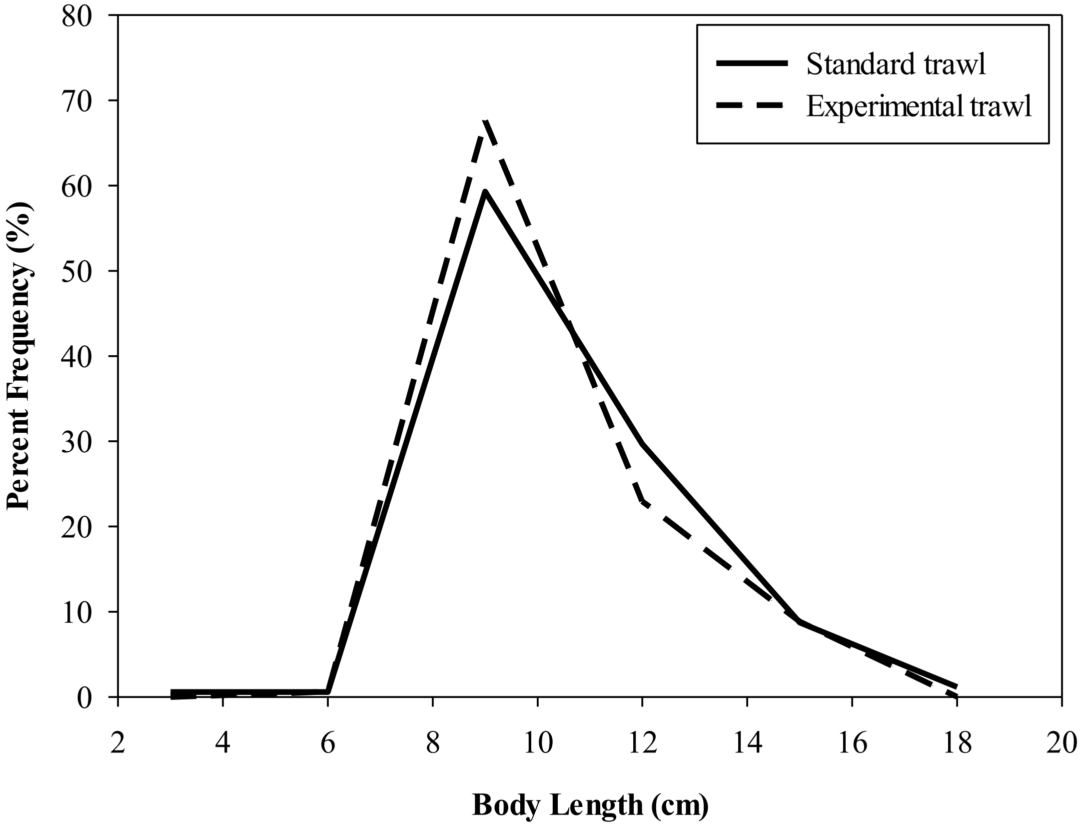


**Figure 3.16** Body length frequency distribution of redfish captured across 20 paired tows of the standard and experimental trawl.

## Chapter 4. Summary

The objective of the research performed for the two studies presented in this thesis was to evaluate the catch characteristics of newly developed, innovative fishing gears designed with the purpose of mitigating ecological concerns identified for each study's respective fishery. In developing and assessing the effectiveness of several modifications to the Newfoundland cod pot design to capture multiple species of flatfish (Chapter 2), it was found that artificial light was very important in capturing American plaice within the depths fished in the study area. Few Greenland halibut were captured in pots, possibly because they were not attracted to the artificial light source or concealed bait in bait bags. However, there was uncertainty with regard to the presence of suitable quantities of Greenland halibut in the study area. The results for Experiment I of this study illustrate the importance of artificial light as plaice were captured almost exclusively in pots that possessed artificial lights. This result prompted a second experiment (Experiment II) to determine if artificial light alone could serve as the sole attractant to entice plaice to enter the pot and reduce the catch rates of snow crab. Surprisingly, more plaice were captured in pots when bait was absent which was an unexpected outcome. This led to fewer snow crab being captured in pots and snow crab catches were significantly lower in the conical entrance pots that possessed artificial light alone. The results indicate that artificial light in unbaited pots can capture American plaice and substantially reduce the capture of snow crab. Entrance shape of the pots was also found to be significant in determining catch rates of plaice in both experiments with more plaice captured in the trapezoid entrance pots than the conical entrance pots. The results of this study demonstrate that minor modifications to the Newfoundland cod pot can allow for the selective targeting of certain fish species, and reduce bycatch. Also, the results highlight the overall importance of artificial light and entrance shape on catch rates of American plaice. It is important to note however that the catch rates of American plaice and Greenland halibut in this study were not commercially viable and additional research is necessary before flatfish pots are implemented into industry.

In Chapter 3, comparisons of the catch characteristics of a trawl designed to have reduced seabed contact area over that of a standard trawl currently used in the northern shrimp fishery were carried out. The results illustrate comparable catches by both trawls with regard to catch rates of shrimp, count per kg of shrimp, and carapace lengths of shrimp. These results were encouraging, however the percent contribution to the total catch weight of all bycatch species combined was found to be significantly higher in the experimental trawl. Further, the incidental capture of erect, sessile habitat forming soft coral species of sea pens were substantially higher in the experimental trawl. This outcome is undesirable as more bycatch can result in higher injury and mortality rates of bycatch species which is damaging to marine ecosystems. More bycatch can also negatively influence recruitment of targeted commercial species to the fishery and equates to more time spent sorting the catch for fishermen in addition to reduced profits when bycatch is landed with the catch. Evidence of mud caked on the ground gear of the experimental trawl, as well as mud in the catch, coupled with greater bycatch of groundfish species and sea pens suggests that the experimental trawl may have dug into the seabed. Further modifications to the ground gear of the experimental trawl are recommended in order to reduce potential seabed impacts and bycatch levels.

## 4.1 Limitations of My Approach

There were limitations to the approaches taken in the two experimental studies performed in this thesis which should be considered when interpreting the results. For Chapter 2, the most apparent limitation is the number of replicates for each treatment/combination of treatments for Experiment I. Due to time and monetary constraints as well as unexpected positive results using artificial light to capture American plaice in Experiment I, it was decided that a second experiment (Experiment II) would be performed to determine the overall effectiveness of light and bait on flatfish capture instead of completing more replicates of trigger diameter and trigger spacing treatments.

Originally, Greenland halibut was the targeted flatfish species for this study. Due to the high incidence of snow crab bycatch by gillnets and the economic importance of snow crab, small boat (<35′) fishermen from the northeast coast of insular Newfoundland made a stewardship decision to voluntarily close the gillnet fishery for Greenland halibut many years ago. It was believed that Greenland halibut would be present in substantial numbers in the study area due to this resource not having been fished for some time. However, only five Greenland halibut were captured in pots throughout the entire study. It would seem that the characteristics of the artificial light stimulus and/or presence of concealed bait in a bait bag were not sufficient to facilitate Greenland halibut to enter pots. Greenland halibut have been observed in laboratory settings to attack and feed on bait that is in motion. It is recommended in future studies targeting Greenland halibut with pots to test a mobile bait (i.e., an artificial bait mounted on a pendulum) which would possibly entice Greenland halibut to enter pots while avoiding the capture of snow crab. Further, given the importance of artificial light in catching American plaice and species specific differences in responses to color and intensity of artificial light (Marchesan et al., 2005) future studies should be completed using artificial lights of varying wavelengths and intensities to determine whether the right light conditions can lure commercial quantities of Greenland halibut to enter pots. Greenland halibut were captured in gillnets to survey the study area indicating presence of Greenland halibut at the study site, regardless, Greenland halibut densities may have been low, therefore I recommend future flatfish potting studies to take place in areas of higher Greenland halibut density, in particular commercial Greenland halibut fishing grounds. Finally, given the malfunctioning of the 3 mm diameter FRD triggers in conical pots I would recommend these triggers be re-engineered to fit the entrance of conical pots more optimally, allowing the triggers to bend inward with ease.

There were also some limitations to the approach of Chapter 3. Perhaps the greatest limitation to this study was that there was no underwater video camera to document disturbance to the seabed. A video camera was used for a small portion of tows, however the video was uninformative and was abandoned for future tows. A video camera would have been helpful in determining the degree to which the trawls impacted the seabed, especially in the case of the experimental trawl. Another limitation to this study was the poor performance of the trawl geometry sensors. Only a portion of tows could be used to provide measurements of trawl headline height and wingspread while doorspread sensors had too few measurements to accurately evaluate doorspread. Accurate measurements of headline height, wingspread, and doorspread would have been useful in determining the geometry and overall performance of the trawls when fishing on the seabed. This would also explain more clearly the variability of catch rates of shrimp and bycatch species within and between tows. A full day of calibrating the trawl sensors took place before the study commenced however there still appeared to be issues with the sensors.

The gears tested in both studies were designed to capture commercial fish and crustacean species while reducing negative ecological impacts such as bycatch of non-target species and habitat degradation by fishing gears. In evaluating the effectiveness of these fishing gears it will add to the growing body of research investigating gear modifications to reduce ecological impacts and also assist in refining current gear designs to fish at optimal levels. This thesis represents the first time that the Newfoundland cod pot has been modified to capture fish species other than cod. It was a success in demonstrating that a few modifications to the pot design and the presence of an artificial light source can be used to target a different species of fish while allowing the safe release of commercially important snow crab. Also, the work completed with the shrimp trawl ground gear comparison is an important step in the direction of reducing seabed contact of bottom trawls and the design of more seabed friendly fishing gears. The information from the shrimp trawl comparison study will be used to aid in designing trawls with reduced seabed contact for Newfoundland and Labrador's offshore shrimp fishery in an upcoming study by the Centre for Sustainable Aquatic Resources (CSAR) at the Fisheries and Marine Institute of Memorial University.

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