# INVESTIGATING FACTORS THAT INFLUENCE THE CATCH RATES OF NORTHERN STONE CRAB (*Lithodes maja*)


by

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A thesis submitted to

The School of Graduate Studies

In Partial fulfillment of the requirements for the degree of

Master of Science, Environmental Science


Faculty of Science

Memorial University of Newfoundland


August 2016

St. John's Newfoundland Canada

## Abstract

Natural resources in marine and coastal areas are of crucial economic importance for the province of Newfoundland and Labrador. They sustain the livelihoods and natural heritage of communities, and provide stable income for current and future generations, provided they are well-managed. Not all fisheries in Newfoundland and Labrador are fully exploited, and there are ongoing efforts to establish new sustainable industries in the province. For commercial fisheries, management requires a detailed assessment of the gear used in the fishery to ensure a sustainable industry. Assessing the effectiveness of fishing gears, and understanding the extent of fishing gear impacts on marine ecosystems, can provide unique protection for aquatic habitats and help ensure sustainability of marine species.

In this study, I assessed a potential fishing gear for use in a northern stone crab (*Lithodes maja*: Linnaeus, 1758) fishery, and investigated how abiotic factors - water current direction, hourly variation in water current direction, turbidity and interspecific interractions, influence catch rates of this species, with the aid of an underwater video-camera. Results demonstrate that the Norwegian two-door pot is effective in capturing this species, and catch rates of this species is partly influenced by water current directions, hourly variation in water current direction and interspecific interactions of species. Turbidity had no effect on the catch rates of northern stone crab. In addition, there was little or no impact of the pot on the sea bed, there were no cases of escape and discard mortality, ghost fishing, lost pot, or injury to both target or non-target species in the study. Conscientious fishery management strategies remain essential in the effort towards ensuring sustainable existing and emerging commercial fisheries, as well as the benthic ecosystem.

**Keywords:** Fishery management, Sustainable, Ecosystem, Fishing gear, Species, Technology

**Acknowledgements**

I will like to express my most profound appreciation to my dear husband for his love, support, understanding and prayers throughout the duration of my program. His unequalled encouragement and support helped me achieve success on this research. Also, my sincere thanks go to my siblings, parents and friends for their prayers, support and encouragement throughout the duration of my program.

I will also like to express my thanks and sincere gratitude to my supervisor, Dr. Brett Favaro, and co-supervisor, Dr. Paul Winger, the Director of the Center for Sustainable Aquatic Resources (CSAR) at the Marine Institute of Memorial University of Newfoundland, for their constructive guidance and support throughout all stages of my research work.

I thank Philip Walsh and my fellow graduate students, as well as the crew of the *F. V. Burin Tradition* for their substantial co-operation and assistance during the course of my research.

Thanks are due to other faculty members of the Environmental Science department, particularly Dr. Norm Catto and Gail Kenny for their support.

Finally, I would like to express my thanks to the Canadian Centre for Fisheries Innovation (CCFI), the Department of Fisheries and Aquaculture (DFA), the Government of Newfoundland and Labrador (FTNOP program) and Memorial University of Newfoundland for providing the financial assistance required for conducting this research, without which this research would not have been successful.

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**List of Abbreviations and Symbols**

| | | |
|---|---|---|
| BRT | - | Bycatch Reduction Technology |
| COSEWIC | - | Committee on the Status of Endangered Wildlife in Canada |
| DFA | - | Department of Fisheries and Aquaculture |
| DFO | - | Department of Fisheries and Oceans Canada |
| GLMMs | - | Generalized Linear Mixed Models |
| HD | - | High Definition |
| LED | - | Light Emitting Diode |
| NAFO | - | Northwest Atlantic Fisheries Organization |
| NL | - | Newfoundland & Labrador |
| NTU | - | Nephelometric Turbidity Unit |
| ROVs | - | Remotely Operated Vehicles |
| SARA | - | Species at Risk Act |
| UHD | - | Ultra-high definition |
| $q$ | - | Catchability |
| $C$ | - | Number of northern stone crab or white hake that entered the pot |
| $B$ | - | Number of northern stone crab or white hake in the vicinity of the pot |
| $f$ | - | Fishing effort |

# Chapter 1 General introduction

In Newfoundland and Labrador, the fishing industry holds tremendous commercial, cultural, and historic value. Traditionally, fisheries have been the mainstay of Newfoundland and Labrador's economy (Copes, 1970). However, in 1992, the largest layoff in Canadian history occurred with the closure of the northern cod (*Gadus morhua*: Linnaeus, 1758) fishery, which was largely depleted by overfishing (Hutchings and Myers, 1994; Myers et al., 1997). As a result, fisheries diversified and targeted other traditionally unfished species. At present, in Newfoundland, fisheries that target crustaceans are more valuable than fisheries that target bony fishes (DFA, 2014). In 2012, 83.1 percent of total landed value was attributable to invertebrate fisheries (DFO, 2012). The snow crab *(Chionoecetes opilio*: O. Fabricius, 1788*)* fishery is the province's most valuable invertebrate fishery (DFO, 2013a), with at least $217 million in revenue generated from this species in 2012 (DFA, 2012). In 2013, catch increased by 0.7 percent (50,806 t) compared to the previous year (DFA, 2014). Also, 2013 lobster landings increased by four percent relative to 2012, creating a total landed value of $17 million (DFA, 2014). Therefore, if this trend is sustained through proper management, crustaceans, due to their value, can contribute immensely towards the local economy. Currently, they are extensions of the growing emphasis on the sustainability and conservation of the marine resources.

How and where we fish matters, both to marine species and habitat, and the people who depend on a healthy marine ecosystem for their livelihoods (Fuller et al., 2008). The sustainability of any fishery is partially determined by the environmental impact of the gear used in fishing (Suuronen et al., 2012). Some techniques, such as trawling and dredging, are inherently impactful on the marine environment (Fuller et al., 2008). Despite advances in bycatch reduction and gear improvement efforts, trawls and dredgers are notorious for damaging coral, sponges, and other sessile habitat-forming organisms on the seafloor (Fuller et al., 2008;

Pham et al., 2014). Trawling specifically has been found to cause adverse changes in the structure of ocean food webs (Allen and Clarke, 2007). It can also decrease diversity and abundance of commercial species that live in close association to the seabed (Muntadas et al., 2014). Finally, the bycatch rate, or the rate of capture of species not targeted by the fishery, can be high in trawl gear (EJF, 2003). Collectively, these impacts have direct economic consequences, for instance, the failure of *G. morhua* stocks to recover completely after overfishing has been partially attributed to the detrimental impacts of trawling activities, because trawling disrupted the ocean substrate and fish habitat (Mason, 2002).

Despite its impacts, bottom trawling remains a widespread fishing technique due to the gear's efficiency in terms of catch per unit effort (CPUE; Collie et al., 2000). Bottom trawls are widely used in tropical shrimp fisheries, producing approximately 1.3 million t of tropical shrimp caught annually around the world (Macfadyen et al., 2013). Furthermore, there are conditions in which their environmental impacts are less concerning. For example, a recent study conducted on plaice (*Pleuronectes platessa*: Linnaeus, 1758), a member of the flatfish family, suggests that sea bottom disturbances, such as bottom trawling, may improve the feeding conditions for target species that feed on small invertebrates (Hiddink et al., 2008). In addition, not all trawling activities are destructive – mid-water trawls do not contact the sea bottom, and they target species that often live in homogenous groups near the sea bottom and hence, does not have detrimental environmental impact on bottom habitats and structures (FAO, 2015). In another recent study conducted on the effect of trawling on the Newfoundland and Labrador's northern snow crab, no direct effect on mortality or carapace damage was recorded; however, results suggest that intense trawling activities could cause increased leg loss (Dawe et al., 2007) as non-target species caught in the net hardly ever exit from the gear unharmed. Follow-up work by Nguyen et al., 2014 found that *C. opilio* were quickly overtaken by the approaching footgear and generally unable to avoid an interaction, approximately 54% of the crabs observed experienced a direct encounter with the footgear, suggesting a damaging effect of trawling (increased mortality) to *C. opilio*.

Pots and traps are an alternative set of low-impact fishing gears that can be used at commercial scale (Suuronen et al., 2012). These gears, (the terms ‘pot’ and ‘trap’ are interchangeable, but in keeping with local terminology, we refer to them collectively as ‘pots’) are used by fishermen all over the world to catch aquatic animals (He and Inoue, 2010). They are maze-like structures of netting, or cage-like enclosures, made of metal or other rigid materials (DFO, 2007), and may be deployed baited (bait is used to increase the area within which fish and other species may react and be attracted to the pot) or unbaited *in situ* (Miller, 1978; He and Inoue, 2010). Pots are versatile in that they can be deployed in deep or shallow water, for varying periods of time (DFO, 2007). Furthermore, they cause minimal disturbance to underwater habitat, and can be built to be highly selective to target species (Miller, 1990), allowing control over the amount of bycatch species (Miller et al., 1997; DFO, 2007). They also produce minimal damage to captured aquatic organisms, often allowing for their safe release if they are under-aged, egg-bearing, or female – particularly relevant to crab fishing (Atar et al., 2002; DFO, 2007). Pots are durable fishing tools, especially because they can be left in the water for long amounts of time without degradation in the meat quality of the captured species (Atar et al., 2002). At present, there are snow crab pot-based fisheries in Newfoundland that target snow crab (DFO, 2009a).

One of the primary environmental benefits of pots is their low rates of bycatch relative to other fishing gears. Various bycatch reduction strategies, including the use of bycatch reduction technologies (BRTs) and improved fishing gear modifications, have been developed to limit the incidental capture of non-target marine species in fishing gear, especially for species at risk of extinction (Piovano et al., 2012). In addition, due to their low bycatch rates, pots can be a best-practice option (Gomes et al., 2013). For example, a study using onboard observers' quantified bycatch on several shrimp-pot boats along the central coast of Maine during the 2010 and 2011 winter fishing seasons. They found the average bycatch rate was 1.21% in 2010 and 1.11% in 2011 by weight of landed catch (Moffett et al., 2012). By contrast, the Pacific groundfish bottom trawl fleet is known to produce up to 23% bycatch rate (Driscoll et al., 2009), and is responsible for up to half of all discarded fish and marine life worldwide (Kelleher and FAO, 2005).

One species that may be targetable using baited pots is the northern stone crab (*Lithodes maja*). This deep-water crustacean was identified as a target for a potential fishery because it has been reported as frequent bycatch in other fisheries along the south coast of Newfoundland and Labrador (DFA, 2000). While *L. maja* is widely distributed across different bottom types and depths, low catch rates have precluded its establishment as a viable commercial fishery (DFA, 2000; Hiscock and Grant, 2006; Walsh et al., 2012).

To establish a new fishery for *L. maja*, several criteria must be met as outlined in Fisheries and Oceans Canada's emerging fisheries policy (DFO, 2001). First, a feasibility study must be conducted, which includes identification of a particular gear type that is suitable for targeting the species, market demand for the target species and identification of multi-species and habitat impact to ascertain conservation of the marine environment. Second, it must be determined whether the target species can sustain a commercially viable operation, and to collect biological data in order to build a preliminary database on stock abundance and distribution. Third the commercial fishery can then be implemented, with a formal integrated fisheries management plan introduced to establish a sustainable fishery.

## 1.1 Northern stone crab (*L. maja*) biology and ecology

The family Lithodidae is a diverse group of decapods on which investigative research is coming of age (Zaklan, 2002). This family of decapod crustaceans is divided into two subfamilies Hapalogastrinae and Lithodinae (Ortmann, 1901), that collectively include 16 genera (Dawson, 1989) and approximately 105 species, including *L. maja*, a species of the king crabs, that are broad-scale omnivores with seasonal reproduction (Zaklan, 2002). They have a global distribution, but reside mainly in anti-tropical waters from low intertidal (for *Cryptolithodes*; Hart, 1965) to abyssal depths of 4,152 m (for *Paralomis*; Macpherson, 1988), and mainly found in the North Pacific Ocean (Zaklan, 2002). Much remains unknown about this economically important group, most likely due to their abyssal nature (Zaklan, 2002). The genus *Lithodes* is derived from the Greek lithos, meaning stone, and eidos, meaning form. Therefore Lithodes can be taken to mean "like a stone" or "having a stony nature" (Donaldson and Byersdorfer, 2005).

*L. maja* (Figure 1) is a cold-water species, commonly found at temperatures above $0^{o}$C (DFO, 1998). This decapod crustacean can be found on both sides of the North Atlantic, East and West Greenland, and along the east coast of North America extending southward to the Baltimore Canyon (eastern US) on the outer continental shelf (Williams, 1988). In Canada, *L. maja* is found at the seabed around the southern coast of Newfoundland and Labrador (Squires, 1990; Hiscock and Grant, 2006; Walsh et al., 2012). They are identified by their pear-shaped carapace, and legs covered with many short spines, and are usually red or brownish in color (DFA, 2000). The males and females reach sexual maturity at a carapace width (CW) of approximately 98 mm and 65 mm respectively (DFA, 2000). Exploratory surveys show that these species are captured in depths between 65-790 m (DFO, 1998), inhabiting sandy and clay sea beds. At present, its population size is unknown as the multi-species bottom trawl survey does not yield adequate results on the absolute abundance of benthic crustaceans like the *L. maja* (DFO, 1998).

**Figure 1:** The northern stone crab (*L. maja*).

### 1.2 Fishery potential of Lithodid

Similar species of the Lithodes family, such as the *Lithodes santolla:* Molina, 1782, also known as the southern king crab, have constituted a mixed fishery since the 1950s in the Argentinean Beagle channel because of their abundance (Lovrich and Vinuesa, 1999). *L. santolla* is large, possessing a maximum size of 190 mm carapace length (CL) and 8 kg weight (Lovrich and Vinuesa, 1999). It has a generation time of six years with an annual reproductive cycle, and females carry between 5,000 - 60,000 eggs per female per clutch (Lovrich and Vinuesa, 1999). This species constitutes a mixed fishery in Chile and yielded 90% of the historic landings of the region - approximately 3000 tonnes/year from 2003 to 2013 (Stevens, 2014). In the United States, the red king crab (*Paralithodes camstchaticus*: Tilesius, 1815) is one of

Alaska's top shellfish fishery (ADF&G, 2006). Since statehood in 1959, about 2 billion pounds of *P. camtschaticus*, worth $1.6 billion, has been harvested from Alaskan waters, making *P. camtschaticus* the second most valuable species in the region (ADF&G, 2006). This fishery is managed by a three-month season (October 15 - January 15), minimum shell size requirement (≥ 7 inches), pot specifications, and pot limitation program (ADF&G, 2006; ADF&G, 2015). Both male and female *P. camtschaticus* are estimated to live up to 20-30 years, weighing up to 24 and 10.5 pounds, respectively (Stevens, 2014). They are hailed for their colossal size, snowy white meat, exceptional flavor, and are sold throughout the United States (Stevens, 2014).

*L. maja*, occurs in the North Atlantic and may represent a viable target for commercial fisheries in the region. This species has been found as bycatch in groundfish and *C. opilio* fisheries for several years (DFA, 2000). In 1992, a survey conducted on *L. maja* found that it could be harvested using the traditional *C. opilio* pot (Dooley and Johnson, 1994). A relatively large population of this species was observed during the survey, with some pots capturing approximately 23 kg of *L. maja* each (Dooley and Johnson, 1994). The survey was expanded in 1993 to determine if other locations may support commercial-scale fishing. *L. maja* appeared to be widespread on the south coast of the province, but results showed low catch rates, with catch per unit effort of 1.6 kg/pot/haul realized (Dooley and Johnson, 1994). In 2000, an additional survey conducted in previously surveyed areas, including adjacent areas with both mud and rock bottom types at varying depths, found that catch rates of *L. maja* were different from *C. opilio* catch rates, which was estimated at 9.1 kg per pot (DFA, 2000). Quality tests of *L. maja* showed that the meat is sweeter than *C. opilio* meat and thus, may be able to fetch a higher market value (Dooley and Johnson, 1994). Therefore, it is possible that species could be commercially viable even with low catch rates produced for *L. maja*, because the average price for *C. opilio* in Newfoundland is $5.05 per pound (Gardner, 2014).

Low catch rates of *L. maja* were also reported, by Hiscock and Grant (2006), in Newfoundland and Labrador region based on local historical catch data. According to them, low CPUE may be normal when small conical pots are used, with evidence of increased catches of *L. maja* when larger pots were used in the Gulf of St. Lawrence. They suggested that catch rates of *L. maja* may be improved upon with modified pots and altered fishing methods.

A follow up study conducted by Walsh et al (2012)., reported that baited square pots with two circular entrances outperformed other experimental pots (square pot with two large rectangular entrances, square pot with two small rectangular entrances, and conical pot with two semi-circle entrance), with an average catch of 3.67 *L. maja* per retrieval recorded, compared to the other pots which captured significantly less. Based on their findings, they recommended that further behavioural studies be conducted using subsea cameras, in order to investigate the effects of pot entrance shape, position, and size on the behaviour and subsequent catch rates of *L. maja* (Walsh et al., 2012).

### 1.3 Assessing Fishing Gears

Assessing the viability of a *L. maja* fishery first requires that a gear be identified that is suitable for targeting the species. Fisheries and Oceans Canada's (DFO) emerging fisheries policy requires that a detailed assessment be conducted in order to, among other requirements, determine the most suitable gear type for capturing a particular species (DFO, 2001). The Norwegian pot, in particular, is a good candidate for catching *L. maja*. It was successfully used in a joint Norwegian-Greenlandic trial pot fishery for *L. maja* (Woll and Burmeister, 2002).

Traditionally, new gears have been assessed almost entirely by looking at catch data collected in experimental fisheries (MacLennan, 1992; Atar et al., 2002; Woll and Burmeister, 2002). By contrast, direct observation of organisms interacting with gear *in situ* through the use of underwater cameras is not as widely used. Much of our knowledge of species that live below depths accessible to scuba divers (i.e. deeper than 40 m) comes from destructive sampling as organisms are brought to the surface in fishing or sampling gear. While these methods of collection can provide information about the animals' characteristics, distribution, physiology and diet, they are inappropriate for the study of animal behaviour. As a result, less is known about the *in situ* behaviour of deep water-dwelling organisms compared with shallow living species (Winger, 2008; Favaro et al., 2012).

As underwater video cameras become cheaper and easier to use, they are becoming more widespread in fisheries research (Favaro et al., 2012; Struthers et al., 2015). For example, an underwater HD video camera attached to an offshore groundfish trawl found that yellowtail flounder (*Limanda ferruginea*: Storer, 1839) could be identified to the species level with a high degree of certainty (72%), something not feasible with traditional standard definition camera systems (Underwood et al., 2012). This allows generation of crucial knowledge and understanding of *L. ferruginea in situ* which is challenging without the use of underwater video cameras. In another recent study, cameras were attached to bottom trawls in an effort to understand how individual *C. opilio* interact with the footgear components of a traditional inshore shrimp trawl (Nguyen et al., 2014). They found that while about 54% of the crabs observed encountered the footgear, the majority of the crabs observed appeared to be aware of the trawl and were actively responding and/or reacting to the approaching threat (Nguyen et al., 2014). As a result, Nguyen et al., in 2014, were able to propose viable gear modification designs to reduce shrimp trawl impacts. With the aid of underwater videos, Winger and Walsh, in 2011, demonstrated that installing rigid escape mechanisms of either 95 or 100 mm diameter into traditional 14.0 cm mesh crab traps resulted in a significant reduction in the capture of undersized crab (<95 mm CW) with no significant reduction in standard (95–101 mm CW) or premium crab (>101 mm CW) at two of the three sites tested. This suggested that based on the temporal and spatial prevalence of undersized crab, escape mechanisms could have the potential to reduce the incidental capture of undersized crab, reduce discard mortality, and help protect the resource (Winger and Walsh, 2011). Also, an underwater video system mounted over a commercial crab trap *in situ* was used to qualitatively describe several of the most common behaviours utilized by Dungeness crabs (*Cancer magister*: Dana, 1852) in and around traps, including the documentation of previously undescribed behaviours in this species (Barber and Cobb, 2009). They found that crabs commonly guarded trap doors without entering the trap, and prevented other inspecting crabs from entering the trap. Their observations indicated that crab behaviour merits further attention in future studies of gear saturation and the catchability of *C. magister* (Barber and Cobb, 2009). Videos from underwater cameras can inform the design of fishing gear as well. The design and improvement of fishing gear requires a thorough understanding of the behaviour, distribution and physical characteristics of both target and non-target species (Favaro et al., 2012), and videos can provide qualitative insights to understanding interactions between animals and deep-water fishing gear (Underwood et al., 2012). This understanding can enhance the ability to evaluate and improve the efficiency of fishing gear for target species, and effectively minimize bycatch ( Winger, 2008; Favaro et al., 2012; Underwood et al., 2012). Videos can also provide quantitative data such as the density of target species in a trap, saturation rates, frequency at which organisms approach the pot, number of entry and exit attempts, as well as the residence time of target species in the pot.

In my thesis, I assessed the ability of baited pots to capture *L. maja*. I collected data from underwater videos to supplement catch data of three different pot types, collected at sea. In doing so, I assessed factors that may influence the catch rates of this species and evaluated the effectiveness of pots. I hypothesized that (1) *L. maja* catch per pot is correlated with the design of pot, and that (2) the catch rates of *L. maja* would be significantly correlated with (a) water current direction; (b) hourly variation in water current direction, and (c) turbidity of sea bottom. Findings from this thesis will be useful in assessing whether *L. maja* could form the basis for a potential commercial fishery.

# Chapter 2 What can we see when we look through the lens? Investigating factors that influence the catch rates of *L. maja*.

## 2.1 Abstract

The sustainability of any fishery is partially determined by the impact of the gear used by the industry. Choosing the right fishing gear is central to ensuring the sustainability of new and emerging fisheries. In this study, conducted off the south-western edge of Northwest Atlantic Fisheries Organization (NAFO) Division 3Ps, I compared catch rates of *L. maja*, a species of interest for targeted fishing in Newfoundland, across three pot types; Norwegian one-door pots, Norwegian two-door pots and the Newfoundland-style pots. Also, using an underwater video camera, I assessed the effectiveness of the rectangular Norwegian two-door pot at catching this species. I directly observed the behaviour of *L. maja* in and around the rectangular Norwegian two-door pot, and examined how water current direction, hourly variation in water current direction, turbidity and the presence of hagfish (*Myxine glutinosa*: Linnaeus, 1758) affected catch rates. I found that the Norwegian two-door pot was the most effective at catching *L. maja* compared to other pots; it also caught white hake (*Urophycis tenuis*: Mitchill, 1814), which co-occurred in the study area. The majority of both crab and hake tended to approach and enter pot against the direction of water current, with fewer individuals caught during higher frequencies of hourly variation in water current direction. The presence of *M. glutinosa* in the pot obstructed the ease of entry for *L. maja*, and turbidity had no evident influence on the catch rates of this species. This study demonstrates that baited pots may be a viable technique for targeting both *L. maja* and *U. tenuis*, provided the stocks can sustain commercial levels of exploitation.

**Keywords:** Behaviour, Catch rates, Newfoundland pot, Norwegian pot, Species.

## 2.2 Introduction

Fishing is an entrepreneurial activity and it plays a vital role in Canada's economy, particularly for coastal regions (DFO, 2015a). Fish and invertebrate populations are renewable but are not inexhaustible. To achieve sustainability, fisheries scientists must consider the impacts of a given industry beyond just the species targeted by the fishery.

When new fisheries are established, the selection of a type of gear for use in the industry is important. In Canada, new fisheries must follow the Emerging Fisheries Policy (DFO, 2001) that requires assessment of a gear for use in the fishery after confirming that harvestable quantities of species are present in a particular fishing area. The gears should have minimal or no detrimental impact to both target and non-target species habitat, with the ability of capturing commercial quantities successfully (DFO, 2001). Traditionally, gear assessments are limited to catch data (Atar et al., 2002; Woll and Burmeister, 2002), direct observation can greatly supplement this and teach us about the environmental impacts of gear, its effectiveness at catching target species, as well as other factors that may influence catchability which may not be evident without an *in situ* observation. Underwater video cameras aid direct observations, which can provide biological information on the distribution of fish and crustacean populations (e.g., Cooke and Schreer, 2002). It also provides the observer with a continuous picture of events that occur within the field of view of the submerged video-camera, in the marine organism’s natural habitat.

An important factor in an assessment is determining catchability of target species with a given gear type. Catchability is expressed as the proportion of individuals in a given area caught per unit effort (Jul-Larsen et al., 2003; Sainte-Marie et al., 2003). It is used in fisheries to measure the efficiency of the type of fishing gear employed, or to find the relationship between abundance of species and fishing effort (Arreguin-Sanchez, 1996). The catchability of any given species is influenced by a wide range of biological and environmental factors (Stoner, 2004), including the behaviour of the fish within its environment; migration patterns; season; gear design; catch size and mesh size; maturity; relative age (time elapsed since the moult); size of individuals (Miller, 1990; Tremblay et al., 1998; Sainte-Marie et al., 2003; Favaro et al., 2014); reactions to different fishing gear; and swimming endurance (Miller, 1990). Catchability can also be estimated using models that account for several sources of variations, such as density-dependent effects, and fishing fleets (Arreguin-Sanchez and Pitcher, 1999); or by direct observations using deep-water videos (Godo et al., 1999; Favaro et al., 2014).

In this study, I compared the effectiveness of three different pot types - Norwegian one-door pots, Norwegian two-door pots and the Newfoundland-style pots - in order to identify the most suitable pot for the capture of *L. maja*, a species of interest in Newfoundland. Also, with the aid of an underwater video camera, I assessed the effectiveness of the rectangular Norwegian two-door pot at capturing this species by observing its performance *in situ.* Using the underwater videos collected, I investigated the influence of water current direction, hourly variation in water current direction, turbidity and interspecific interactions on catch rates of *L. maja*. Findings and recommendations from this research will help fisheries managers make informed decisions on effective ways of catching *L. maja* in a responsible and sustainable manner, and also aid in identifying areas for further research.

## 2.3 Materials and Methods

### 2.3.1 Direct Observation of *L. maja*

To directly observe the behaviour of *L. maja* in and around baited pots, we first built an apparatus capable of conducting the recordings. We attached a 1Cam Alpha HD video-camera system developed by SubC Controls (St. John's, Newfoundland and Labrador, Canada) to a Norwegian-style pot mounted on a large steel observation frame (Figure 2). We built the frame out of 2.54 cm solid T-slotted aluminum, fitted together with corners and braces. The video camera had a maximum depth rating of 3000 m and continuous runtimes in water temperature range of $0^{o}$C to $25^{o}$C, *in situ*. It had a built-in recording capacity of 288 GB, capable of recording up to 50 hours of high definition video, either in interval or continuous mode. It weighed 2.2 kg and 3.3 kg in water and air respectively. Its field of view was $60^{0}$ in water, and it had a flat sapphire viewport. The system used a red Aquorea LED lighting system to illuminate the field of view, as red light is invisible to crustaceans and therefore unlikely to affect animal behaviour (Goldsmith and Fernandez 1968; Widder et al., 2005; Weiss et al., 2006). This approach has proven successful in observing other crustacean traps in deep water (Favaro et al., 2012). The lights and camera are powered by three deep-water SubC lithium ion battery packs, rated for a maximum depth of 3000 m.

The dimensions of the Norwegian-style pot were 1 m long x 1.5 m high x 0.75 m wide made with a 3/8 galvanized steel round stock in the bottom and 3/8 aluminum used in the middle and top sections (Figure 2). The pot was collapsible, and the frame of the pot was made with 50 mm nylon mesh size and 50 mm monofilament mesh size in the entrances. The pot had two funnel entrances with a bait device positioned at the center. The pot was baited with about 1.3 kg of squid, positioned in bait bags. Squid has been found to yield higher catch rates of *L. maja* than other bait types (DFA, 2000). Fresh bait bags were placed in the pots every time pots were set for deployment. Bait bags were made of net material with approximately 2 mm nylon mesh for optimal release of the bait plume to attract target species. The bait bag was suspended from the top of the pot, so that it hung in the center of the pot between the funnel openings.

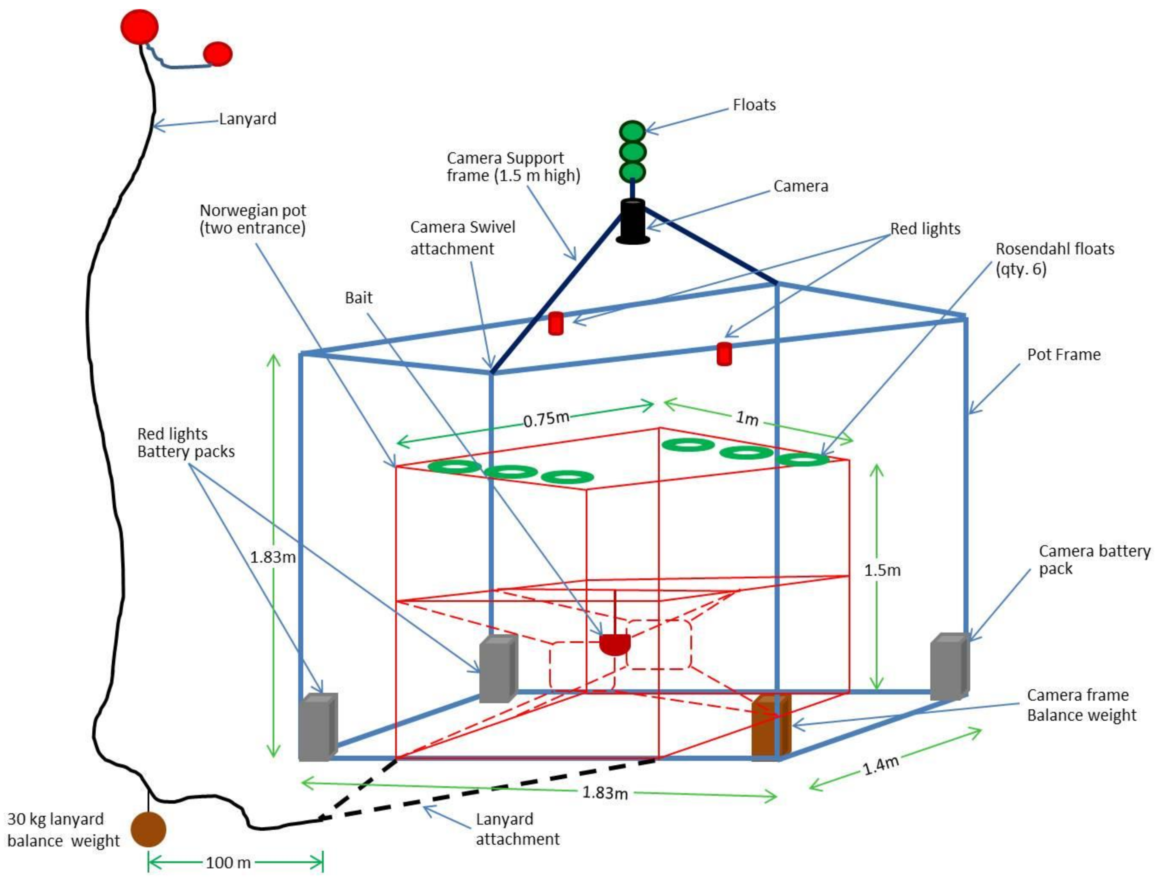


**Figure 2:** Schematic diagram of the Norwegian pot frame (red lines) and the camera frame (blue lines) showing how camera, lights, batteries, balance weights, lanyard rope lengths and attachment, and the Norwegian two-door pot were attached. Pot and camera frame dimensions (green dimension lines) are also shown. Figure not to scale**.**

We built a large metal frame for the camera that provided a top-down view of the pot (Figure 2). Six (6) Rosendahl floats were attached to the topsides of the pot to enable the unfolding of the collapsible pot in water. A twisted polyethylene leadline (lanyard attachment) was attached to the pot’s mainline (lanyard) for easier handling. This attachment also contributed to the weight required to sink the pot in water. The observation frame had a camera support frame, 1.5 m high, attached at two corners which allowed swivel movement of the attachment points to keep the camera support frame resting on the observation frame when it's not deployed in water. While in water, the camera support frame was floated by three 8" iceplast centre hole trawl floats which floated the camera upward, providing the top-down viewing angle. Lanyard attachments were fixed to the observation frames for hauling purposes, and the structure was connected to a surface buoy.

We tested the camera and the complete assembled apparatus in the flume tank at the Centre for Sustainable Aquatic Resources (CSAR), Marine Institute, in simulated underwater and near surface conditions to assess its performance before deploying in the oceans (Figure 3). The tank is an ideal testing facility that offers the opportunity to investigate efficiency and performance of fishing gears under controlled conditions (Winger et al., 2006; Moret and Legge, 2014). We found that the apparatus performed as expected and was ready for deployment at the study location.

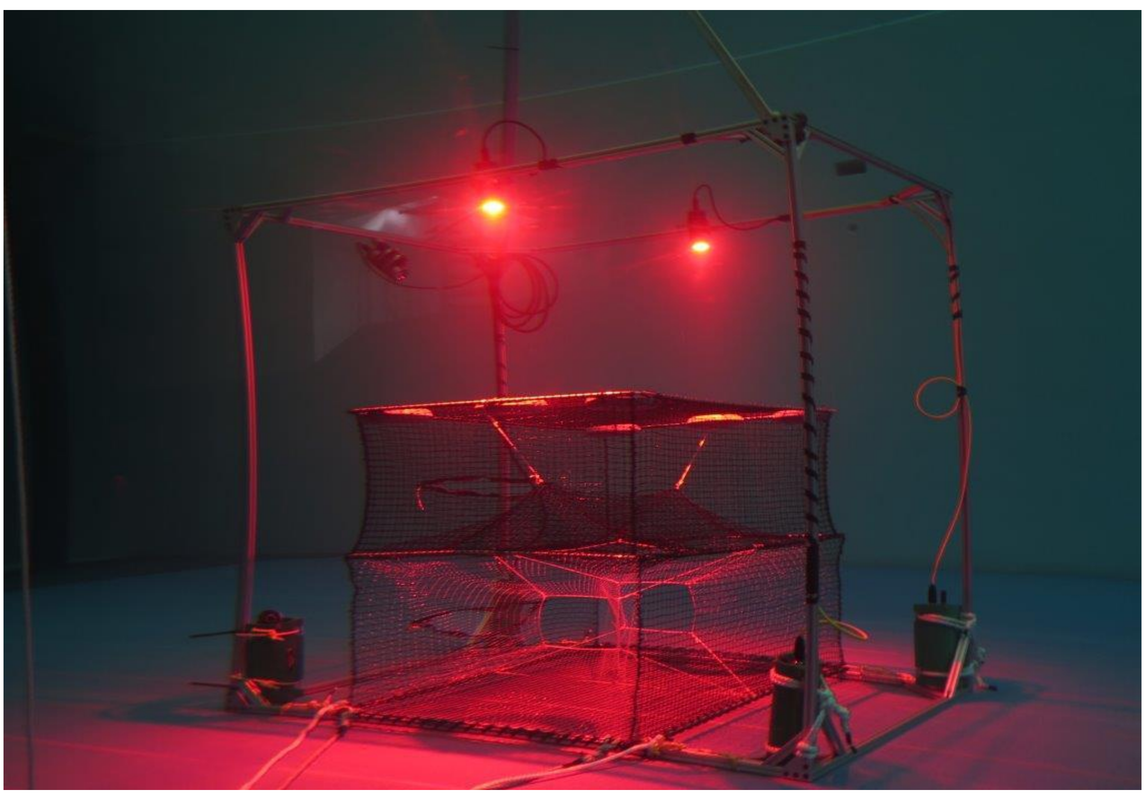

**Figure 3:** The apparatus deployed in CSAR's Flume tank during simulation.

### 2.3.2 Catch Comparison

In addition to observing the behaviour of *L. maja* using a video camera, we compared catch rates of *L. maja* across three different pot styles. We also collected catch rate data for *U. tenuis* and Jonah crab (*Cancer borealis*: Stimpson, 1859) since they co-occurred in the study area. The first pot was a Newfoundland (Nfld) style pot, which was developed by the Fisheries and Marine Institute of Memorial University for cod fishery (Walsh et al., 2006). It was collapsible with double floor and floating roof sections. The pot was rectangular with a dimension of 1.98 m by 1.98 m by 1.02 m (Figure 4). We constructed frames of 16 mm (5/8”) round stock steel and covered them with 100 mm polyethylene net. The pot had two funnel entrances, with a bait bag positioned at the center of the pot, between the two funnel entrances. We attached hauling ropes to the observation frames, made with 3/8” polyethylene, and supported the ropes with the aid of an eight inch trawl float, above the pot for roof buoyancy. The other pot styles were the one-door and two-door Norwegian pots (Figures 5 and 6), with dimensions the same as that of the pot used in the apparatus earlier described in section 2.3.1. The only difference was that the Norwegian one-door pot had only one funnel entrance.

<u>Legend (Figure 4)</u>

1. Circular entrance x 2
2. Rope frame 3/8” polyethylene
3. Entrance net 60 mm knotless nylon
4. Bait bag
5. Hauling rope
6. Main net 100 mm polyethylene
7. Eight inch trawl float for roof buoyancy

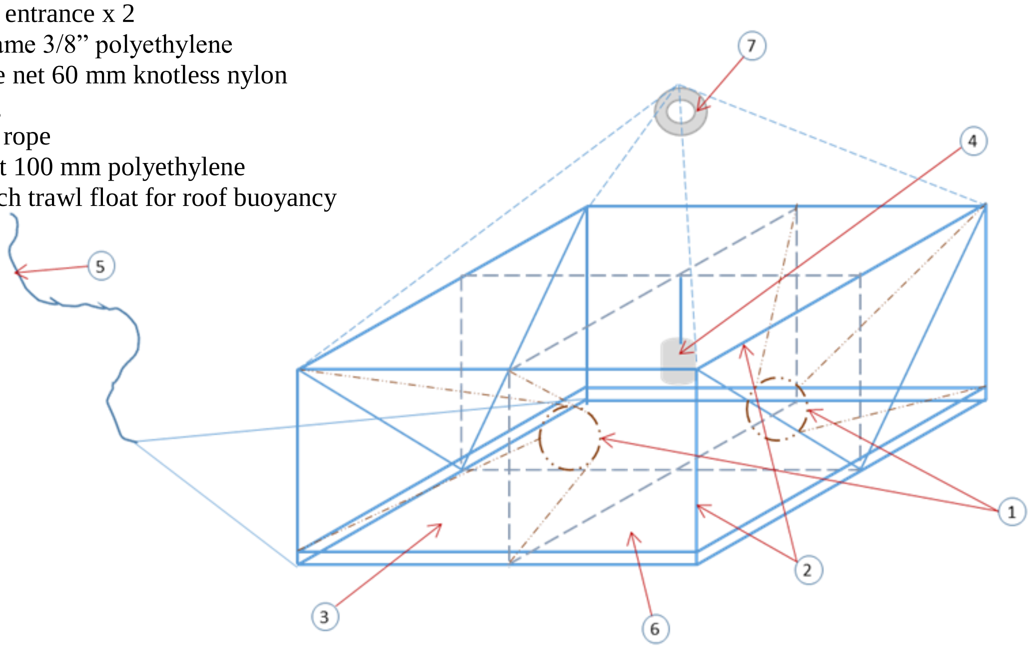


**Figure 4:** Newfoundland pot (L x W x H = 1.98 m x 1.98 m x 1.02 m)

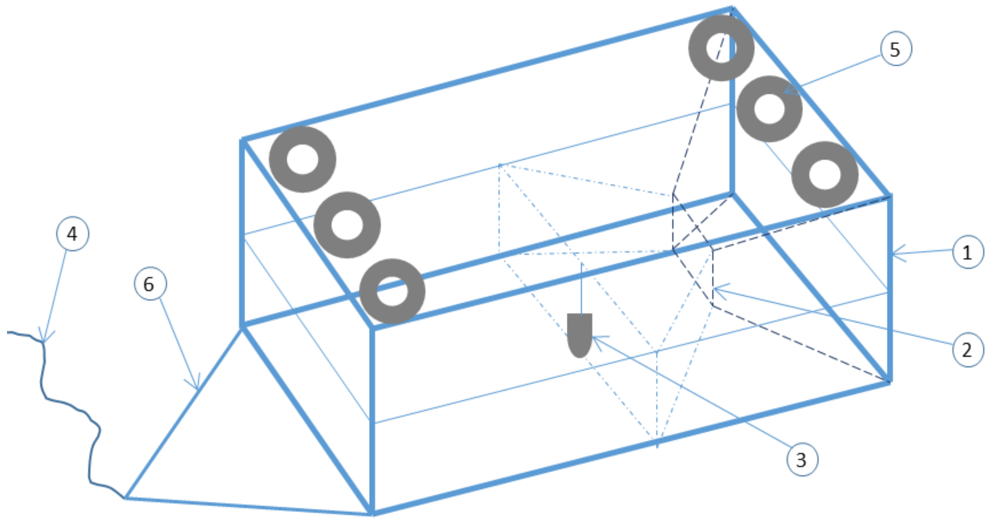


**Figure 5:** Norwegian one-door pot (L x W x H = 1 m x 0.75 m x 1.5 m)

Legend (Figures 5 and 6):

1. Pot Frame
2. Square entrance
3. Bait bag
4. Hauling rope
5. Rosendahl floats for buoyancy (qty. 6)
6. Rope attachment frame

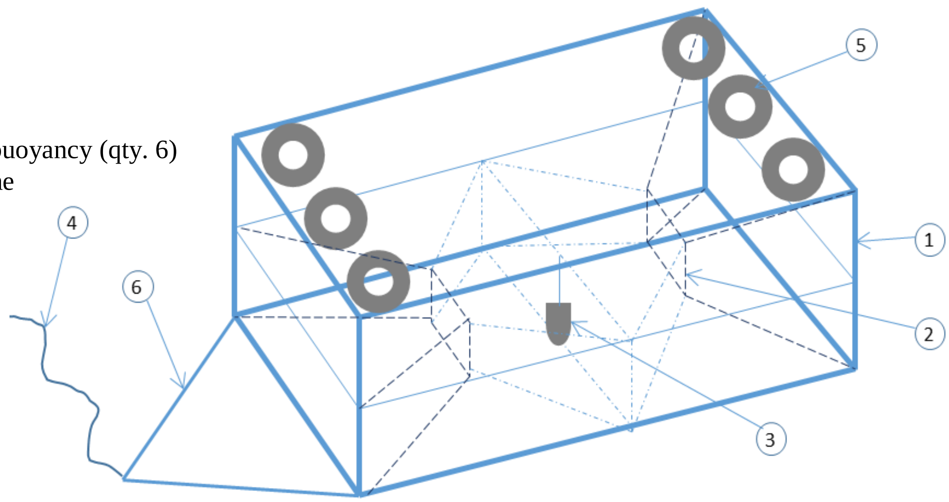


**Figure 6:** Norwegian two-door pot (L x W x H = 1 m x 0.75 m x 1.5 m)

### 2.3.3 Field study

We conducted the field study on the south-western edge of Newfoundland, in NAFO Division 3Ps, near the Laurentian channel (Figure 7), onboard the 16 m *F.V. Burin Tradition* vessel (Figure 8). We collected field data from October 21st to November 1st 2014. We deployed the apparatus at depths between 210 and 260 m (Table 1), while the other pots used for the catch comparison, were set between 176 and 318 m in the same vicinity. The pots were released from the stern of the research vessel, pulled upright when submerged, and then allowed to sink to the substratum. We ensured the ropes and floats were always streamed out to minimize the risk of entanglement and possible loss of pots. Hauling pots took less than ten minutes, while hauling the camera apparatus took approximately fifteen minutes. Care had to be taken to safely deploy and retrieve the apparatus, without damaging the attached video camera system.

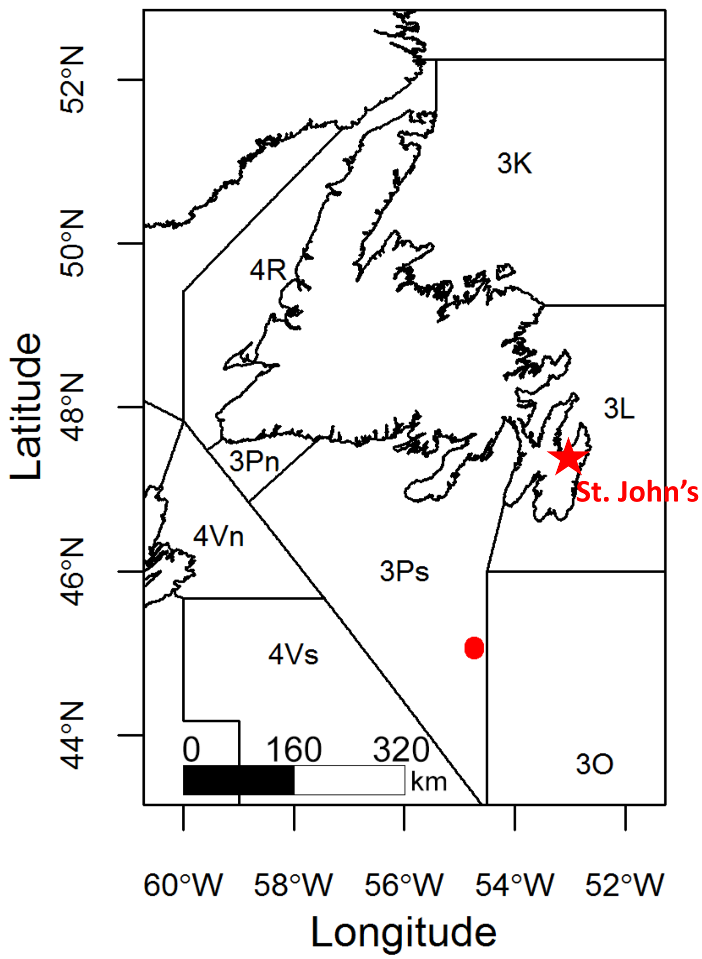


**Figure 7:** Map showing study area (red dot) on the south-western region of NAFO Division 3Ps, near the Laurentian channel. The red star indicates location of the city of St. John's for easier reference. Map also shows other NAFO management regions. Field trip was carried out from October 21st to November 1st 2014.


**Figure 8:** Picture of the *F. V. Burin Tradition*, the vessel used for the research (owned by Mr. Winston Pitcher).

The video camera recorded ten-hour videos for each daily deployment. At the conclusion of each deployment, we hauled back the camera, downloaded its videos, and recharged its batteries. Captured individuals were placed in bins of running seawater, and each individual was identified to species, counted and tagged. It took six hours to recharge battery packs before subsequent deployments. We stored videos on 2 TB Western Digital portable USB hard drives. We recorded a total of seven ten-hour videos, for a total of 70 hours. One video was not usable because ocean conditions were extremely poor during this study, and caused us to be unable to retrieve data from one video. Therefore we analyzed only 60 hours of video.

A total of four Nfld pots, seven one-door Norwegian pots and 20 two-door Norwegian pots were used in this study. We deployed the pots in two fleets of either 15 or 16 pots on a single line, with each pot type represented in each fleet. We tagged the first fleet as “Fleet A”, comprising of eight two-door Norwegian, five one-door Norwegian, and two Newfoundland pots, interspersed on the ground line. We tagged the second fleet as "Fleet B", comprising of twelve two-door Norwegian, two one-door Norwegian, and two Newfoundland pots, also interspersed on the ground line. As with the pot used in the apparatus, we baited all pots in the fleets with approximately 1.3 kg of squid positioned in the bait bags, and fresh bait bags placed in pots each time the pots were deployed. Our aim was for each deployment to soak for approximately 24 hours. In practice, weather conditions and sea state meant that our deployments ranged in length between 20.1 and 72.3 h.

**Table 1:** Summary data from each deployment of the camera-equipped two-door Norwegian pot

| Camera set | Latitude | Longitude | Depth (m) | Date Set | Time set | Soak time (h) |
|---|---|---|---|---|---|---|
| 1 | 45.05 | -54.73 | 256 | Oct 23 | 5:05 | 10.0 |
| 2 | 45.07 | -54.73 | 231 | Oct 23 | 22:20 | 10.2 |
| 3 | 45.08 | -54.72 | 218 | Oct 24 | 17:20 | 9.5 |
| 4 | 45.07 | -54.74 | 232 | Oct 25 | 10:13 | 10.0 |
| 5* | 45.08 | -54.73 | 234 | Oct 26 | 3:00 | 11.2 |
| 6 | 45.07 | -54.73 | 232 | Oct 26 | 21:15 | 10.0 |
| 7 | 45.08 | -54.72 | 218 | Oct 27 | 16:15 | 10.5 |

* Data was not collected for this set.

### 2.3.4 Video Analysis

I analyzed the videos using a Samsung U28D590 Ultra-high definition (UHD) 4K monitor. I developed a scoring system for the videos that ensured I recorded observations in a consistent manner. I recorded the following quantitative parameters for *L. maja*: the number of approaches to the pot, the direction the species approached from (i.e. the sides of the pot frame), the number of successful entries into the pot, the number of failed entry attempts, and the number that exited the pot. I collected all data with reference to the time of day, and time since start of the deployment, and binned data within periods of 30 s (as per Favaro et al., 2014). I collected the same parameters for *U. tenuis* as this species frequently appeared in videos, in and around the deployed apparatus. Also, *M. glutinosa* co-occurred in the study area, and given their small size and large numbers, I recorded their estimated densities in the pot under four groups (0 = no individuals, 1 = 1 to 10 individuals; 2 = 11 to 20 individuals; 3 = 21 to 30 individuals; and 4 = > 30 individuals).

For *L. maja* and *U. tenuis*, I focused especially on entry attempts into the pot (Figure 9). An entry attempt was considered successful if species approached the pot through either of the entrance tunnels and successfully entered the pot. However, if it exited the tunnel before getting into the pot, it was scored as a failed entry attempt. For each attempt, I also recorded the time elapsed– beginning from when an individual entered the tunnel, and ending either when it made it through the inner opening into the pot, or when it backed out of the entry tunnel. I also recorded whether the successful or failed entry attempt occurred on the left or right tunnel.

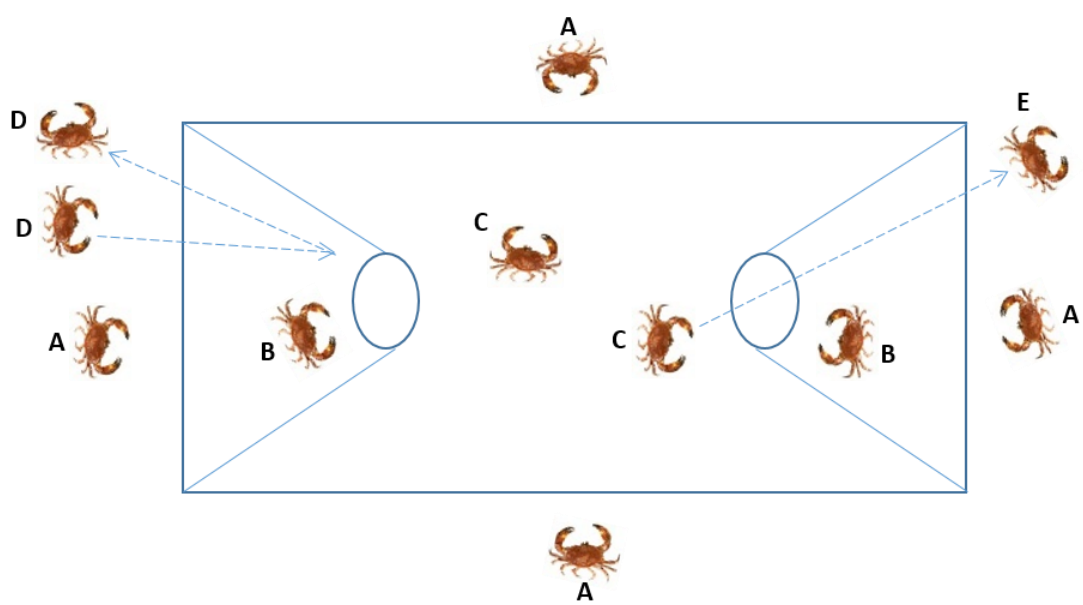


**Figure 9:** Diagram showing the approach, successful and failed entry attempts, and exits of species. (A) Approach (from top, right, bottom, or left), (B) Entry attempt, (C) Successful entry, (D) Failed entry attempt, (E) Exit.

I recorded the direction of water current, relative to the video camera frame, in each 30 s bin of videos by watching the movement of suspended sediment particles as they floated through the field of view. I recorded these directions as up, up-right, right, down-right, down, down-left, left, or up-left (Figure 10). I then classified approaches as occurring in three main directions: with, against or perpendicular to the water current direction. In addition, I recorded the water current variation within an hour to determine its effect on species approach and entry rate into the pot. I counted the number of times water current direction changed within an hour, which ranged from 1 to 7 times. I also observed the clarity of the sea bottom (turbidity levels) and classified my observations into three categories; Low, medium, and high turbidity levels at the sea bottom (grouped as Low < 30 Nephelometric Turbidity Unit (NTU); Medium 30 - 450 NTU; and High > 450 NTU) (SFIEST, 1998; Osch, 2009). I estimated approach rates (approach per bin), of both *L. maja* and *U. tenuis*, during each of the three turbidity levels observed, in order to ensure unbiased results. I graphically compared the effect of the changes in turbidity levels on *L. maja* approach, *U. tenuis* approach, and *M. glutinosa* concentration in the pot, over the duration of the six pot deployments.

In addition to quantitative data, I also recorded relevant qualitative data. I observed the in-trap behaviour of all individuals, and focused especially on their behaviour once they were in the pot. Other qualitative observations I recorded include the interspecific interactions between *U. tenuis*, *L. maja* and other species that were present within the study area.

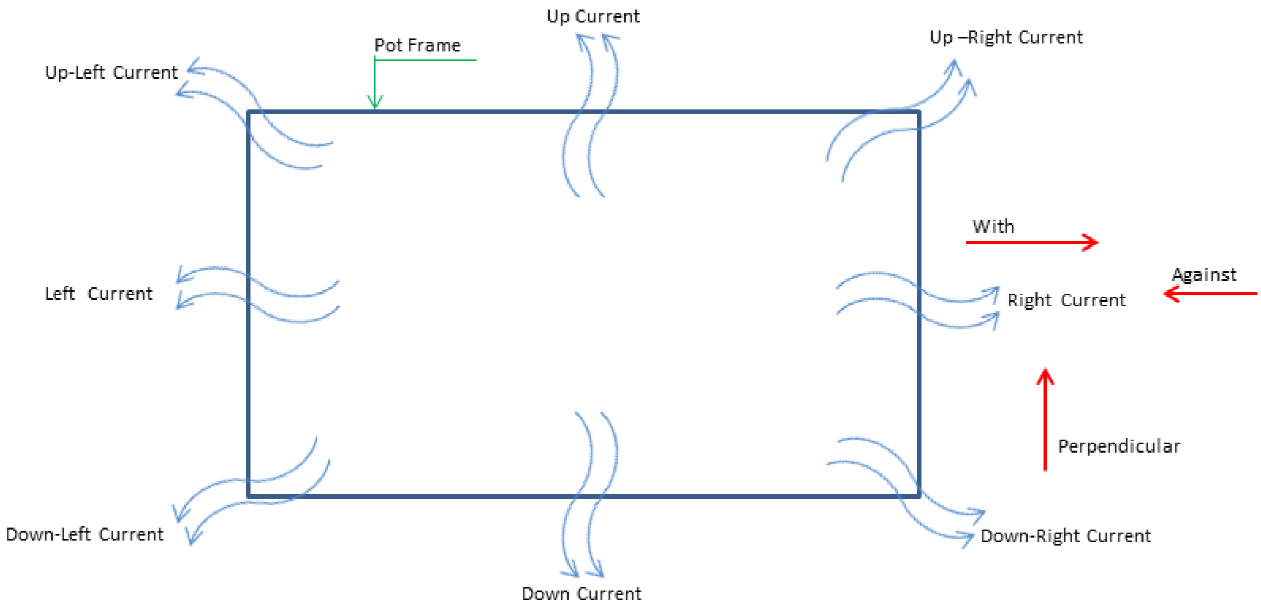


**Figure 10:** Diagram showing the direction of water current, relative to the video camera frame, recorded in each 30 s bin of videos - up, up-right, right, down-right, down, down-left, left, or up-left. The red arrows represent the direction of species approach with respect to water current direction ("with", "Against" or "Perpendicular"); the "right current" was used as a reference to define approach types.

### 2.3.5 Statistical analysis

All statistical analyses and figures were produced using R v2.15.0 statistical software (R development core team, 2011). I generated the study site map using the 'maptools' package (Bivand and Lewin-Koh, 2014), and conducted the Generalized Linear Mixed Models (GLMMs; Zuur et al., 2009) using the lme4 package (Bates et al., 2015).

I used GLMMs to compare catch rates across pots. The error structure of count data is usually not normally distributed, making traditional parametric statistics inappropriate. GLMMs are an extension of generalized linear models and a useful tool in the analysis of ecological data. GLMMs allow for the analysis of fixed effects, which are the pot types used, and the soak duration. They also allow for the inclusion of random effects, which are the fleet, accounting for the nested structure of the data. Finally, they allow analysis of non-normal data such as counts or proportions when random effects are present because they combine the properties of both linear mixed models (which incorporate random effects), and generalized linear models (which handle non-normal data).

In this study, we built three models: one for *L. maja*, one for *U. tenuis*, and one for *C. borealis*, to measure the effect of pot type (i.e. Newfoundland - Nfld, Norwegian one-door, and Norwegian two-door (hereafter referred to as one-door and two-door)) and soak duration on catch rates. In each we measured the impact of pot type and soak duration (fixed effects) on the count of organisms caught per pot, while incorporating the fleet identification (ID) number as a random effect.

While our intent was to maintain consistent soak durations, some fleets were left in the water longer than others due to our inability to haul back the pots in a timely manner given the dangerous turbulent water conditions (our study took place immediately after Hurricane Gonzalo passed through the region).

To determine the factors that influence the catch rates of *L. maja*, I used chi-squared tests to examine the relationship between several variables identified (such as water current direction, variation of water current direction per hour, and turbidity of sea bottom), and the total approach and successful entry rates for *L. maja*. I also did the same for *U. tenuis* as they co-occurred in the pot. First, I tested the null hypothesis ($H_0$) that equal number of approaches and successful entries over time, occurred with, against, or perpendicular to the flow of water current direction; the alternative ($H_1$) is that approaches and successful entries over time are unequal in each current condition. Second, I tested the null hypothesis ($H_0$) that the hourly variation in the water current direction has no effect on the number of approaches and successful entries that occurred over time; the alternative ($H_1$) is that approaches and successful entries over time are affected by the hourly variation in current condition. Third, I tested the null hypothesis ($H_0$) that there is no relationship between turbidity, at the sea bottom, and the number of approaches and successful entries of species that occurred over time; the alternative ($H_1$) is that there is a relationship between turbidity levels, at sea bottom, and species approach and successful entry over time.

Finally, I estimated the catchability ($q$) (the average proportion of stock that is taken by each unit of fishing effort) of *L. maja* and *U. tenuis* using the total number of individual approach and entry data obtained for each deployment from the videos. I developed an innovative and novel technique for estimating catchability of species based on the catchability model, Catchability ($q$) = $C / (B*f)$ (Jul-Larsen et al., 2003). Traditionally, $C$ represents catch, $B$ represents the actual population size of the target species, and $f$ represents the fishing effort. In applying this equation to my data, I treated $C$ as the number of *L. maja* or *U. tenuis* that successfully entered the pot (during each deployment), $B$ as the number of *L. maja* or *U. tenuis* in the vicinity of the pot (i.e., number of approaches within the camera field of view), and $f$ as the fishing effort (counted as one per pot deployment). Hence, I represented and calculated catchability using the equation below, based on the design of my study.

$$Catchability\ (q) = \frac{Number\ of\ individuals\ that\ entered\ the\ pot\ (C)}{Fishing\ effort\ (f) * Total\ number\ of\ individuals\ in\ the\ vicinity\ of\ the\ pot (B)}$$

## 2.4 Results

### 2.4.1 Pot Comparison

A total of seven fleets were deployed from 23 October to 27 October, 2014. The fleets deployed comprised of a total of 108 pot deployments (68 Norwegian two-door, 26 Norwegian one-door, and 14 Nfld). We had designated A fleets (8 Norwegian two-door, 5 Norwegian one-door, and 2 Nfld pots) deployed four times, and designated B fleets (12 Norwegian two-door, 2 Norwegian one-door, and 2 Nfld pots) deployed three times. The fleets were deployed for between 20.1 and 72.3 hours (hrs.; mean = 34.5 hrs.; S.D. = 17.3 hrs.), and were set at depths between 176 and 318 m (mean = 231 m, S.D. = 41 m), in the vicinity of the camera equipped pot (the apparatus). The three most abundant species we caught were *L. maja*, *U. tenuis*, and *C. borealis*. A total of 335 *L. maja*, 443 *U. tenuis*, and 105 *C. borealis* were captured across the pots.

**Table 2:** Mean catch of *L. maja*, *U. tenuis* and *C. borealis*, across the seven fleets deployed, comprising of the three different pot types

| Fleet | *L. maja* | | | *U. tenuis* | | | *C. borealis* | | |
|---|---|---|---|---|---|---|---|---|---|
| | Nfld | Norwegian one-door | Norwegian two-door | Nfld | Norwegian one-door | Norwegian two-door | Nfld | Norwegian one-door | Norwegian two-door |
| 1a | 1.0 | 1.8 | 3.9 | 3.0 | 2.4 | 3.0 | 0 | 0 | 0 |
| 2b | 2.0 | 3.0 | 5.8 | 7.5 | 2.5 | 6.2 | 0 | 0 | 0.4 |
| 3b | 1.0 | 1.5 | 3.8 | 4.5 | 2.5 | 3.9 | 0 | 1.0 | 2.1 |
| 4a | 0.5 | 3.4 | 2.6 | 7.0 | 5.6 | 5.9 | 0 | 3.0 | 5.0 |
| 5a | 0 | 0.8 | 2.5 | 4.0 | 1.2 | 3.3 | 0 | 0.2 | 0 |
| 6b | 0 | 1.0 | 2.5 | 1.5 | 1.5 | 3.2 | 0.5 | 0.5 | 0.3 |
| 7a | 0 | 5.2 | 5.3 | 2.0 | 6.2 | 4.8 | 0 | 1.0 | 0.8 |
| **Total (by pot type)** | **4.5** | **16.7** | **26.4** | **29.5** | **21.9** | **30.3** | **0.5** | **5.7** | **8.6** |
| **Total (by Species)** | **47.6** | | | **81.7** | | | **14.8** | | |

Using the dataset in Table 2, a comparison of the catch data of the three different pot types is represented using boxplots (Figure 11). On average, the Norwegian one-door pots caught about 4 times as many *L. maja* as the NL pots, while the Norwegian two-door pots caught about 5.8 times as much *L. maja* as the NL pots, with an average catch rate of 3.8 crabs per pot as shown in Table 2. Our GLMM that tested catch rate versus pot type showed that there is a significant difference in the catch rate of the Norwegian one-door pot compared to that of the NL pot ($\beta_2$ = 1.395, S.E. = 0.355, z = 3.930, p < 0.001). The results also revealed a significant difference in the catch rates of the Norwegian two-door pots when compared to the NL pots, in favor of the former ($\beta_2$ = 1.770, S.E. = 0.339, z = 5.224, p < 0.001). Comparison of the relationship between both types of the Norwegian pots (one-door and two-door) revealed that two-door pots caught more than one-door pots ($\beta_2$ = 0.374, S.E. = 0.136, z = 2.746, p = 0.006).

**Table 3:** Summary table showing average catch by pot type for *L. maja*, *U. tenuis* and *C. borealis.*

| | ***L. maja*** | | | ***U. tenuis*** | | | ***C. borealis*** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Qty. Caught** | **# of pot deployments** | **Ave. catch** | **Qty. Caught** | **# of pot deployments** | **Ave. catch** | **Qty. Caught** | **# of pot deployments** | **Ave. catch** |
| **NL** | 9 | 4 | ***2.25*** | 59 | 4 | ***14.75*** | 1 | 4 | ***0.25*** |
| **NOR 1D** | 67 | 7 | ***9.57*** | 90 | 7 | ***12.86*** | 24 | 7 | ***3.43*** |
| **NOR 2D** | 259 | 20 | ***12.95*** | 294 | 20 | ***14.7*** | 80 | 20 | ***4*** |

*U. tenuis* catch rates were generally not affected by the pot type (Table 3). Statistical analysis results revealed that there is no significant difference in the catch rates of both Norwegian pot types when compared with the NL pot (Norwegian one-door: $\beta_2$ = -0.2049, S.E. = 0.1675, z = -1.223, p = 0.2213; Norwegian two-door: $\beta_2$ = 0.101, S.E. = 0.141, z = 0.723, p = 0.470), but there is a significant difference between both Norwegian pot types ($\beta_2$ = 0.307, S.E. = 0.118, z = 2.598, p = 0.0094). The soak time (duration of deployment) had no effect on catch of *L. maja*

(Figure 9) ($\beta_1$ = 0.009, S.E. = 0.007, z = 1.311, p = 0.190) or *U. tenuis* (Figure 10) ($\beta_1$ = 0.001, S.E. = 0.007, z = 0.245, p = 0.806). *C. borealis* catch rates were generally low overall (less than one crab per pot haul on average). However, similar to the *L. maja*, the Norwegian one-door and Norwegian two-door pots caught far more than the NL pots – 11.9 and 17.1 times more, respectively (Norwegian one-door: $\beta_2$ = 2.536, S.E. = 1.021, z = 2.485, p = 0.013; Norwegian two-door: $\beta_2$ = 2.653, S.E. = 1.006, z = 2.636, p = 0.008). Results also revealed that the soak time did not affect catch rates for *C. borealis* ($\beta_1$ = 0.001, S.E. = 0.034, z = 0.025, p = 0.980).

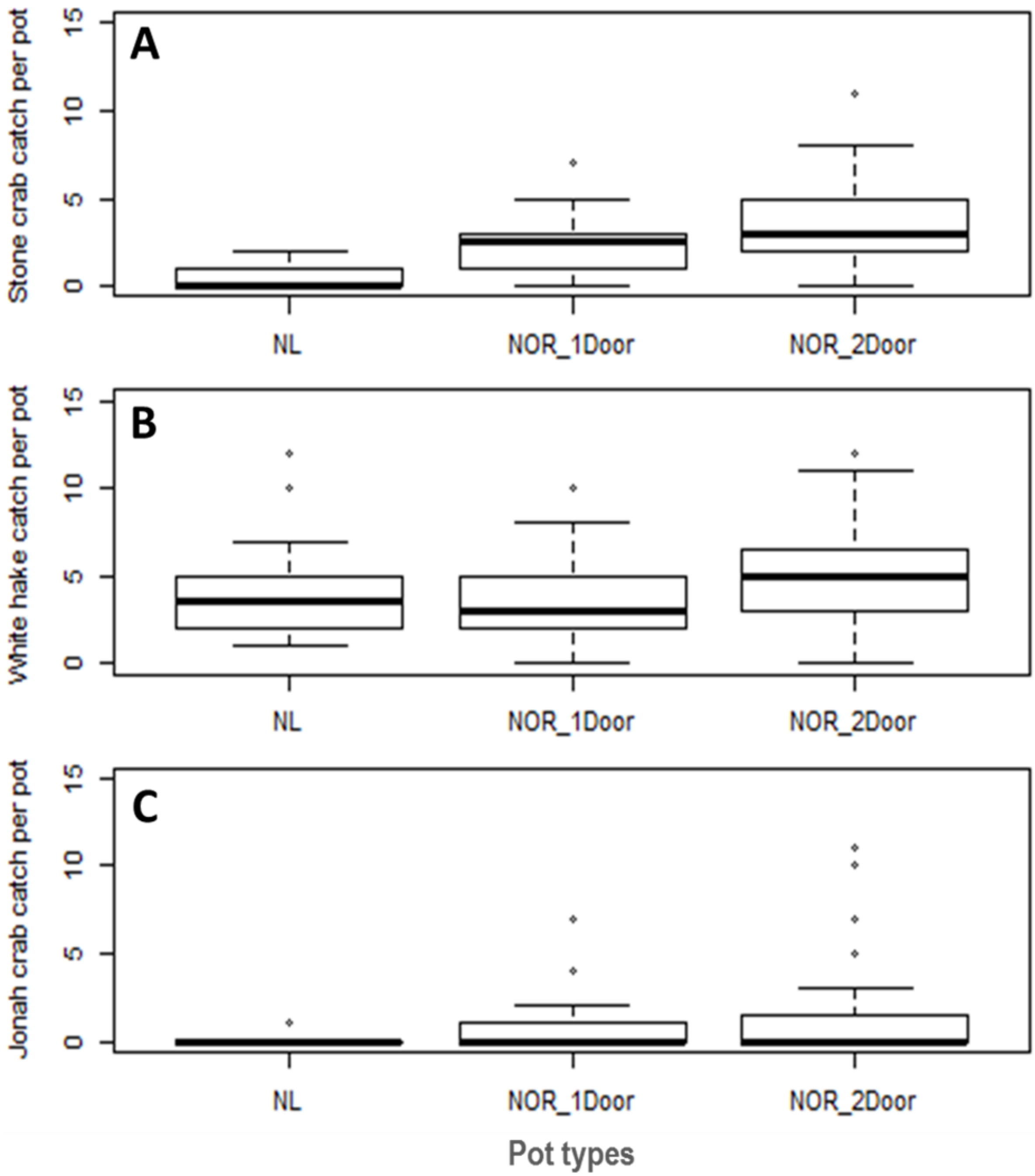


**Figure 11:** Comparison of catch rates for **A**) northern stone crab (*L. maja)*, **B**) white hake (*U. tenuis)*, and **C**) Jonah crab (*C. borealis*) across pot types (NL=Newfoundland; NOR_1Door= Norwegian one-door; NOR_2Door= Norwegian two-door). The thick black horizontal line in the boxes represents the median (a measure of the center of the distribution), the white boxes (50% of data distribution, 25-75 percentiles), the vertical dashed lines represent whiskers (95% of data distribution) and the small circles represent the outliers.

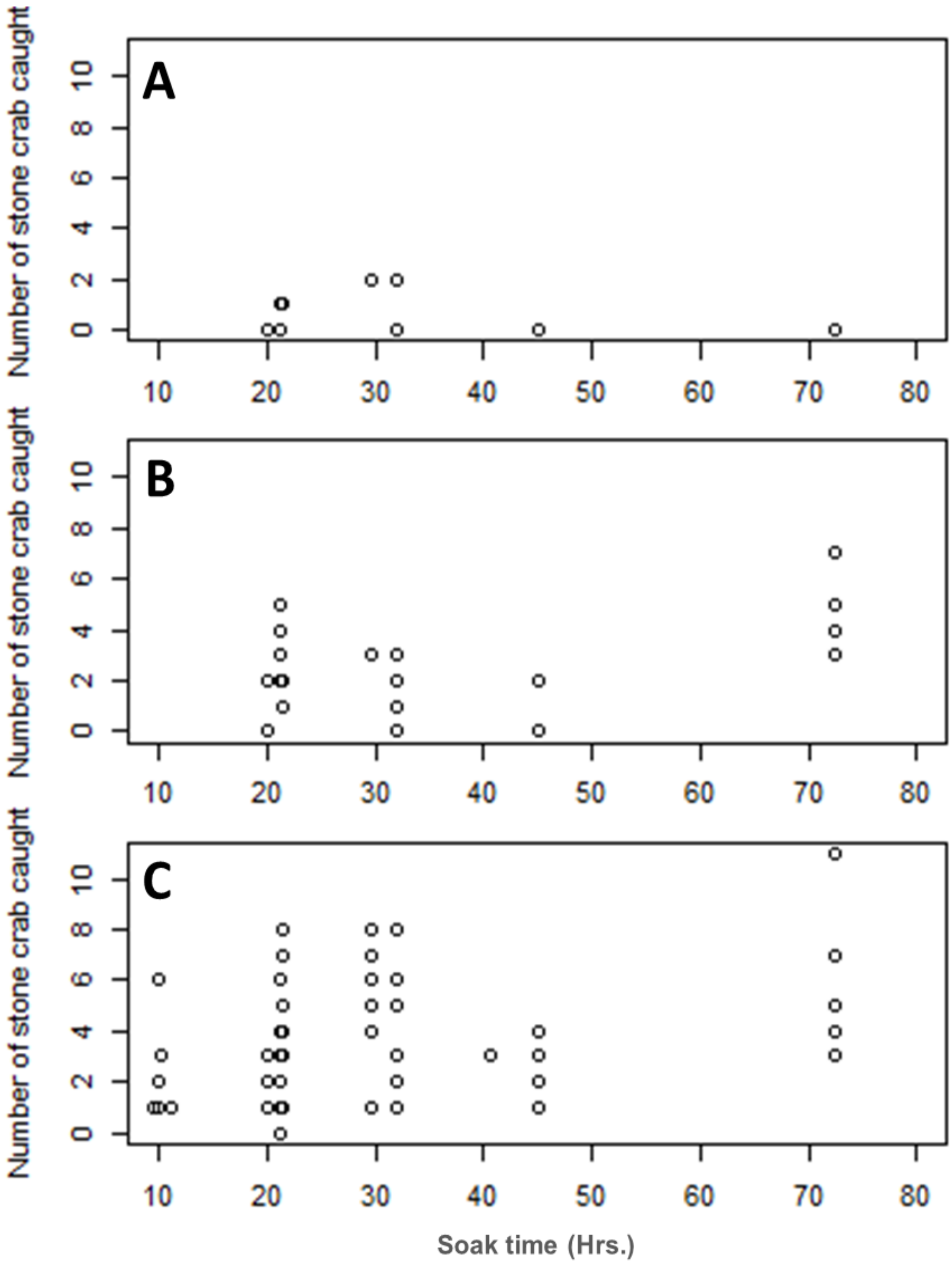


**Figure 12**: Northern stone crab (*L. maja*) catch within duration of deployment per pot types (**A**=Newfoundland pot; **B**= Norwegian one-door pot; **C**= Norwegian two-door pot).

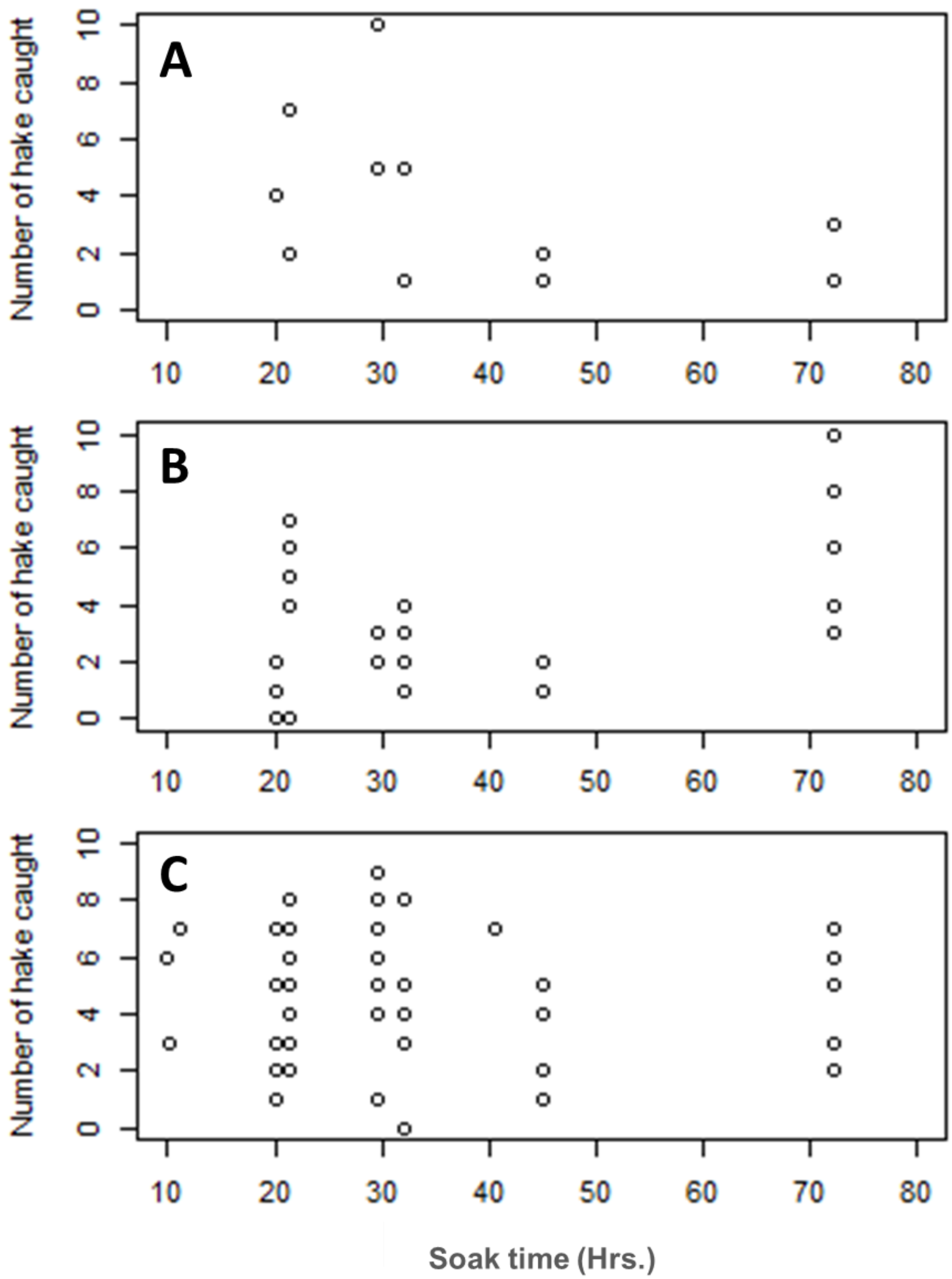


**Figure 13:** White hake (*U. tenuis*) catch within duration of deployment per pot types (**A**=Newfoundland pot; **B**= Norwegian one-door pot; **C**= Norwegian two-door pot).

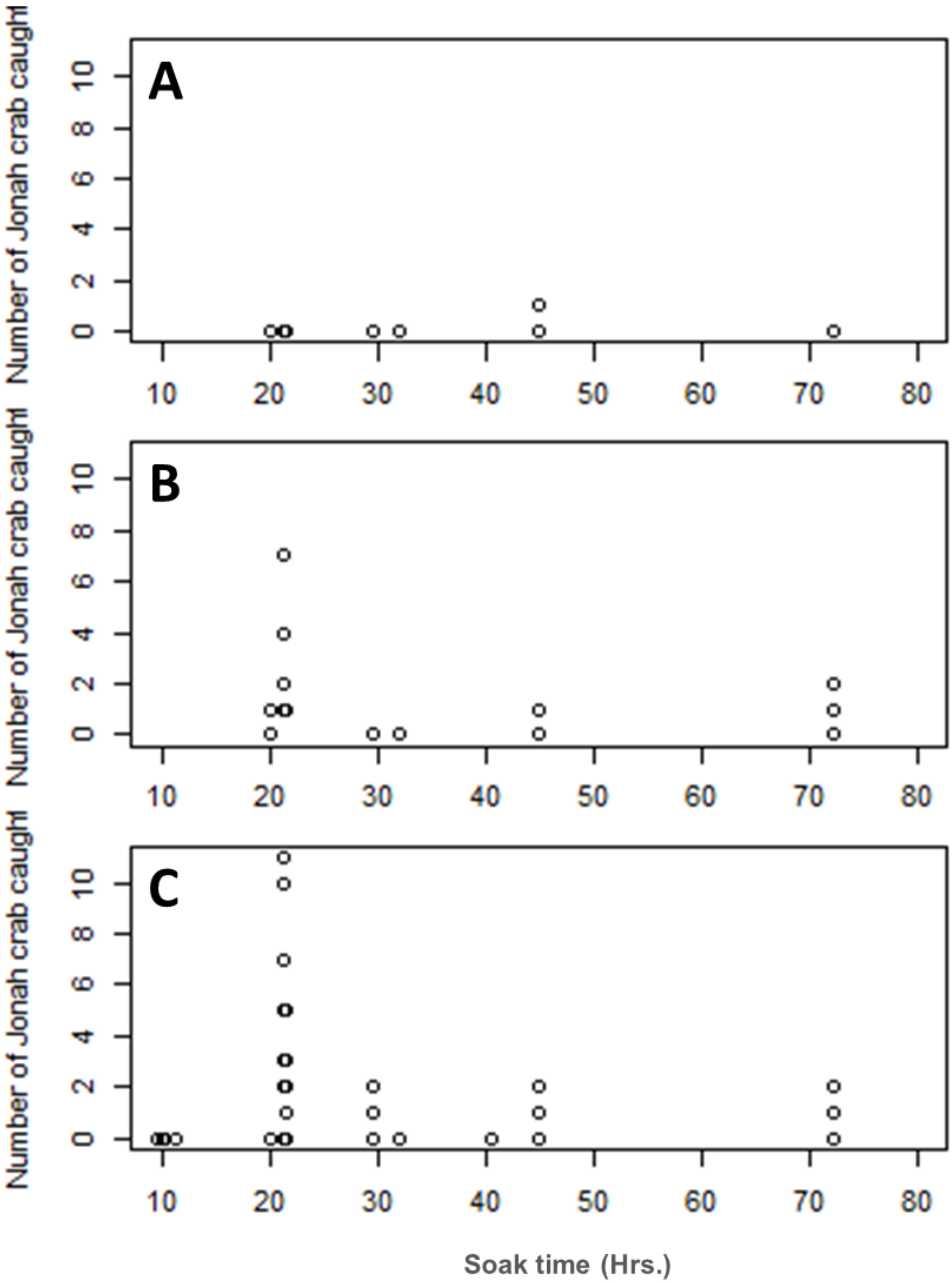


**Figure 14:** Jonah crab (*C. borealis*) catch within duration of deployment per pot types (**A**=Newfoundland pot; **B**= Norwegian one-door pot; **C**= Norwegian two-door pot).

### 2.4.2 Video Data Results

#### 2.4.2.1 Effect of Water Current Direction

Over the course of six apparatus deployments (approximately 60 hours successful recording), I observed a total of 150 *L. maja* and 947 *U. tenuis* approach the pot (Table 4). I observed a total of 20 *L. maja* and 80 *U. tenuis* successful entries in the pot. There were a total of 34 and 117 failed entry attempts of *L. maja* and *U. tenuis* respectively. Once they attempted entry, it took 174.7 sec, on average (S.D. = 185 sec, range = 41 -780 min), and 9.5 sec, on average (S.D. = 5 sec, range 2 – 29 sec) for *L. maja* and *U. tenuis* to make a successful entry respectively. Also, it took 164.8 sec, on average (S.D. =136 sec, range 5 – 534 sec), and 13.3 sec, on average (S.D. = 9 sec, range = 3 – 43 sec) for *L. maja* and *U. tenuis* to make a failed entry attempt respectively. A total of six *L. maja* and 16 *U. tenuis* exited pots through the pot openings. It is also likely that additional exits occurred during the hauling of the pot, as is evident from the difference in the final number of *L. maja* and *U. tenuis* observed in some of the videos (Table 4).

Water current direction was strongly associated with different numbers of approach at different water current conditions, for both *L. maja* and *U. tenuis* (*L. maja*: $\chi^2 = 43.32$, df = 2, $p < 0.001$; *U. tenuis*: $\chi^2 = 164.13$, df = 2, $p < 0.001$). I found that 87 *L. maja* and 501 *U. tenuis* approach occurred against the current (Figure 15) (e.g. by approaching the pot from the left opening while water current is moving in the leftward direction). This pattern is consistent between both *L. maja* and *U. tenuis* as shown in Figure 15 (A and B, respectively). There was no significant difference in the proportion of successful entries with water current conditions for *L. maja* ($\chi^2 = 0.7$, df = 2, p = 0.7047), but there was a significant difference in the proportion of successful entries for *U. tenuis* ($\chi^2 = 6.175$, df = 2, p = 0.0456), Figure 15 (C and D).

**Table 4:** Summary table of observations from underwater videos. Final catch can differ from the recorded number of entries and exits because individuals can be lost from the pots during haulback.

| Set | # of *L. maja* approaches | # of *L. maja* entry attempts | # of successful *L. maja* entries | # of visible *L. maja* exits | Final # of *L. maja* caught | # of *U. tenuis* approaches | # of *U. tenuis* entry attempts | # of successful *U. tenuis* entries | # of visible *U. tenuis* exits | Final # of *U. tenuis* caught | Final # of other species caught |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 47 | 10 | 1 | 0 | 1 | 275 | 74 | 18 | 7 | 11 | 0 |
| 2 | 15 | 6 | 4 | 0 | 3 | 268 | 30 | 7 | 4 | 3 | 0 |
| 3 | 29 | 9 | 3 | 1 | 1 | 168 | 34 | 17 | 3 | 12 | 1 |
| 4 | 20 | 13 | 7 | 2 | 6 | 107 | 33 | 23 | 2 | 17 | 2 |
| 6 | 36 | 16 | 5 | 3 | 2 | 109 | 16 | 8 | 0 | 6 | 0 |
| 7 | 3 | 0 | 0 | 0 | 3 | 20 | 10 | 7 | 0 | 7 | 0 |

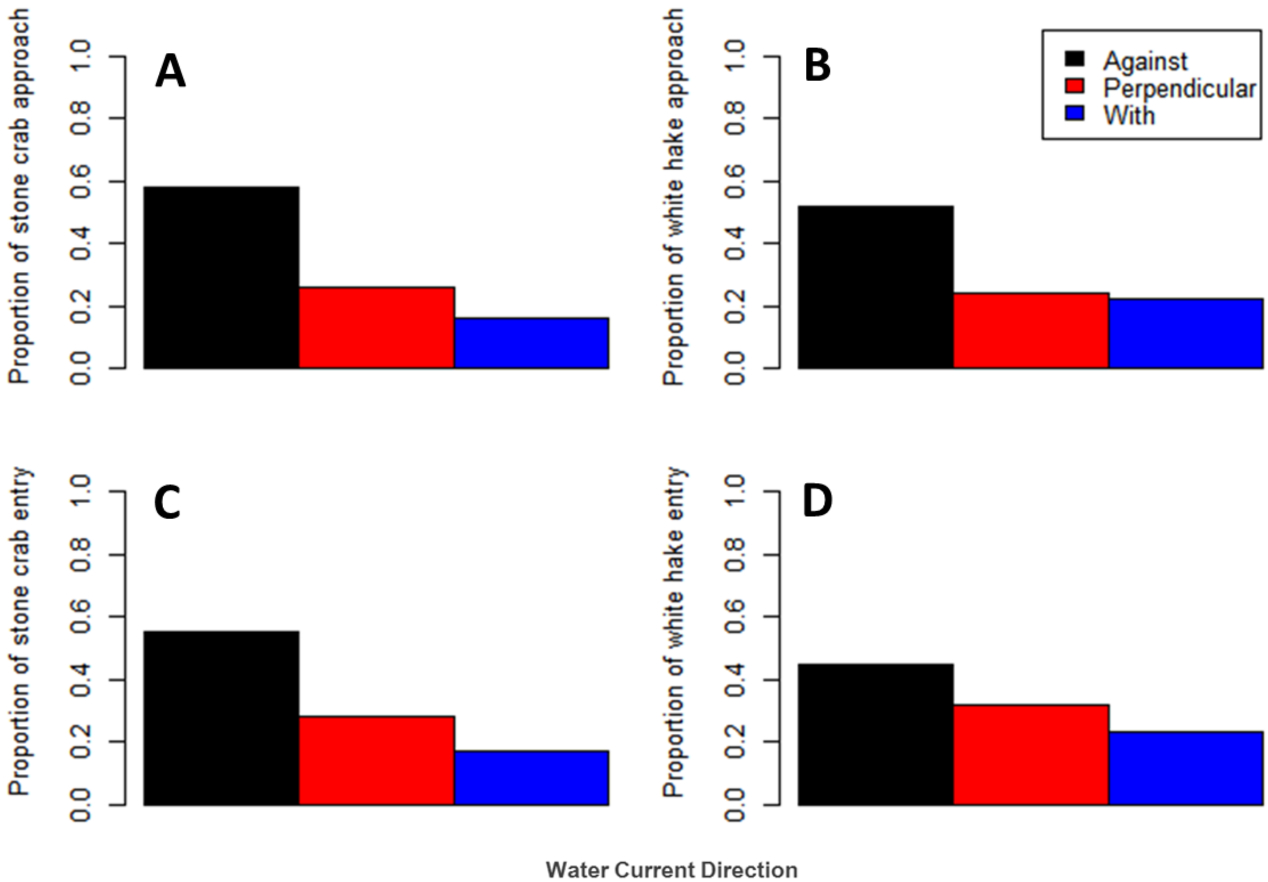


**Figure 15:** Effect of water current direction on the proportion of approach (**A** and **B**) and successful entry (**C** and **D**) of northern stone crab (*L. maja)* and white hake (*U. tenuis*). The legend represents the direction of movement (approach or entry) with respect to the direction of water current.

### 2.4.2.2 Effect of Variation in Water Current Direction

I tested the null hypothesis ($H_0$) that the hourly variation in the water current direction had no effect on the number of approaches and successful entries that occurred over time. Hourly variation in water current was strongly associated with different numbers of approach for both *L. maja* and *U. tenuis* (*L. maja*: $\chi^2 = 285.03$, df = 6, $p < 0.001$; *U. tenuis*: $\chi^2 = 2114.90$, df = 6, $p < 0.001$), with higher numbers of approach occurring during fewer water current variation times within an hour as evident from the scatter plots representation in Figure 13. As indicated by the trend line fitted into the scatter plots, the number of *L. maja* and *U. tenuis* that approached decreased with the increase in the hourly variation of water current within an hour, and this pattern is typical to both *L. maja* and *U. tenuis* as shown in Figure 16 (A and B), with a stronger relationship observed for *U. tenuis*. There is also an association between the hourly water current variation and the number of successful entries with the *L. maja* ($\chi^2 = 36.7$, df = 6, $p < 0.001$) and *U. tenuis* ($\chi^2 = 128.6$, df = 6, $p < 0.001$), Figure 16 C and D, respectively, with a stronger association observed for *U. tenuis*.

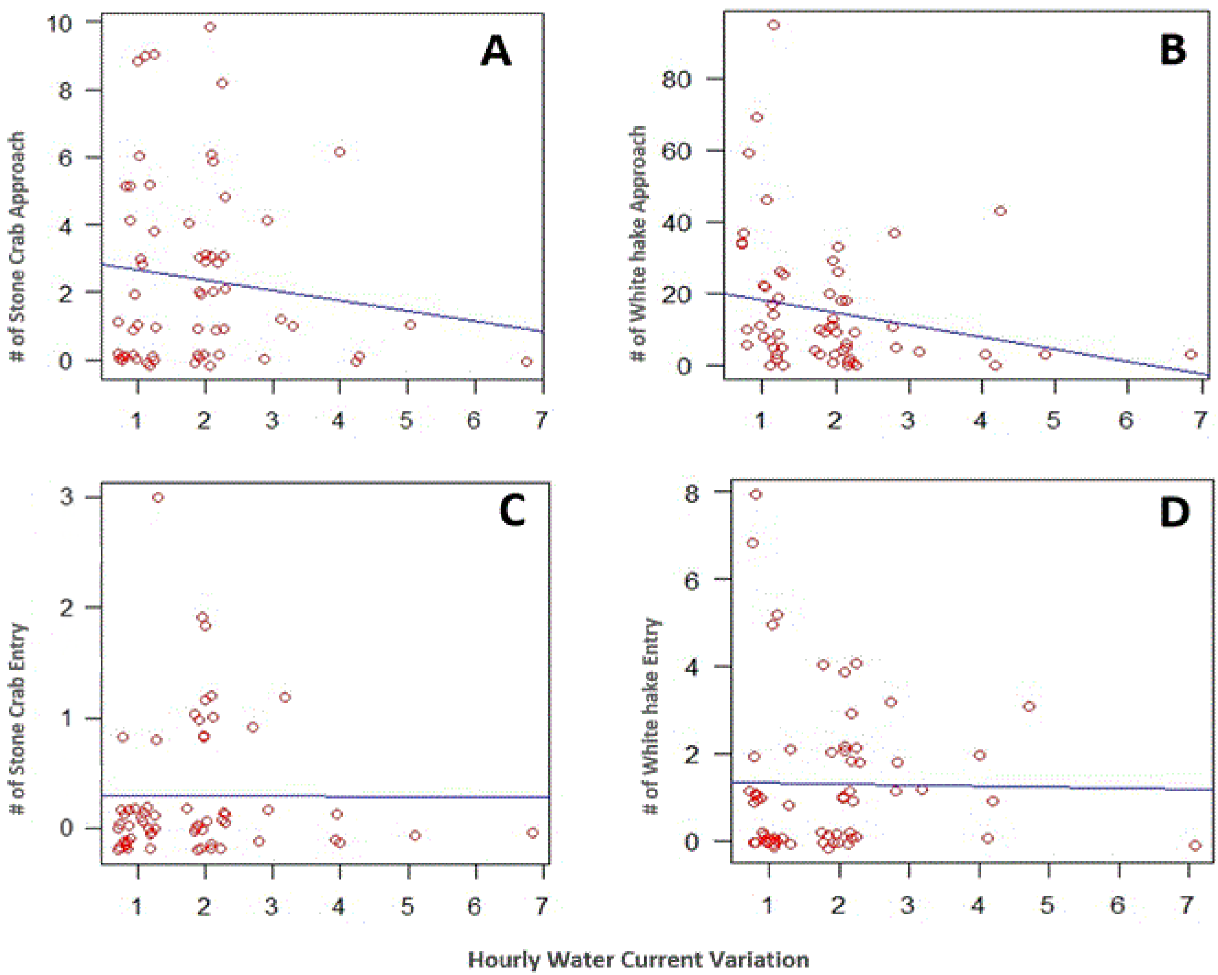


**Figure 16:** Comparison of hourly water current variation influence on approach and entry of northern stone crab (*L. maja)*, **A** and **C,** respectively, and white hake (*U. tenuis*), **B** and **D,** respectively, with each deployment. Northern stone crab and white hake approaches are shown in **A** and **B**, and northern stone crab and white hake entry are shown in **C** and **D**. The blue line represents the best fit line. This data was recorded in 1 hour bins.

### 2.4.2.3 Effect of Turbidity

Turbidity levels for my study area were found to be in either Low < 30 NTU; Medium – between 30 and 450 NTU; or High > 450 NTU turbidity levels. I tested the null hypothesis ($H_0$) that water turbidity level has no effect on approach and successful entry rates that occurred, for the six sets of deployments. Statistical tests showed no evident association of turbidity level with different rates of approach for both *L. maja* and *U. tenuis* (*L. maja*: $\chi^2 = 0.0285$, df = 2, p > 0.001; *U. tenuis*: $\chi^2 = 0.0743$, df = 2, p > 0.001). However, from the graphical representation, higher rates of approach appear to have occurred, for both *L. maja* and *U. tenuis*, during low turbidity level (< 30 NTU) as shown in Figure 17 A and B. Also, I found, from statistical tests, that there is no association between the turbidity levels and the rate of successful entries with *L. maja* ($\chi^2 = 0.0016$, df = 2, p > 0.001) and *U. tenuis* ($\chi^2 = 0.0075$, df = 2, p > 0.001). In this case, with respect to the graphical aspect, higher rates of successful entries also occurred for *U. tenuis*, during low turbidity level (Figure 17 D), while higher successful entry rates occurred during medium turbidity level, for *L. maja* (Figure 17 C).

The graph set in Figure 18 displays a comparison of the effect of changes in turbidity levels on *L. maja* approach, *U. tenuis* approach, and *M. glutinosa* concentration in the pot, over the duration of the six pot deployments. The variation of turbidity levels over the duration of each pot deployment (soak time) also had no effect on the approach of *L. maja*, *U. tenuis* and *M. glutinosa*. As evident in Figure 18 A, over the duration of the deployment, the turbidity level was predominantly in the medium turbidity level range (between 30 and 450 NTU). In general, with the fluctuating turbidity levels, for all deployments, over the duration of the deployments, the numbers of *L. maja* and *U. tenuis* approach remained on the steady increase, while *M. glutinosa* concentration rapidly accumulated within the first hour of deployment and then remained constant for the rest of the duration.

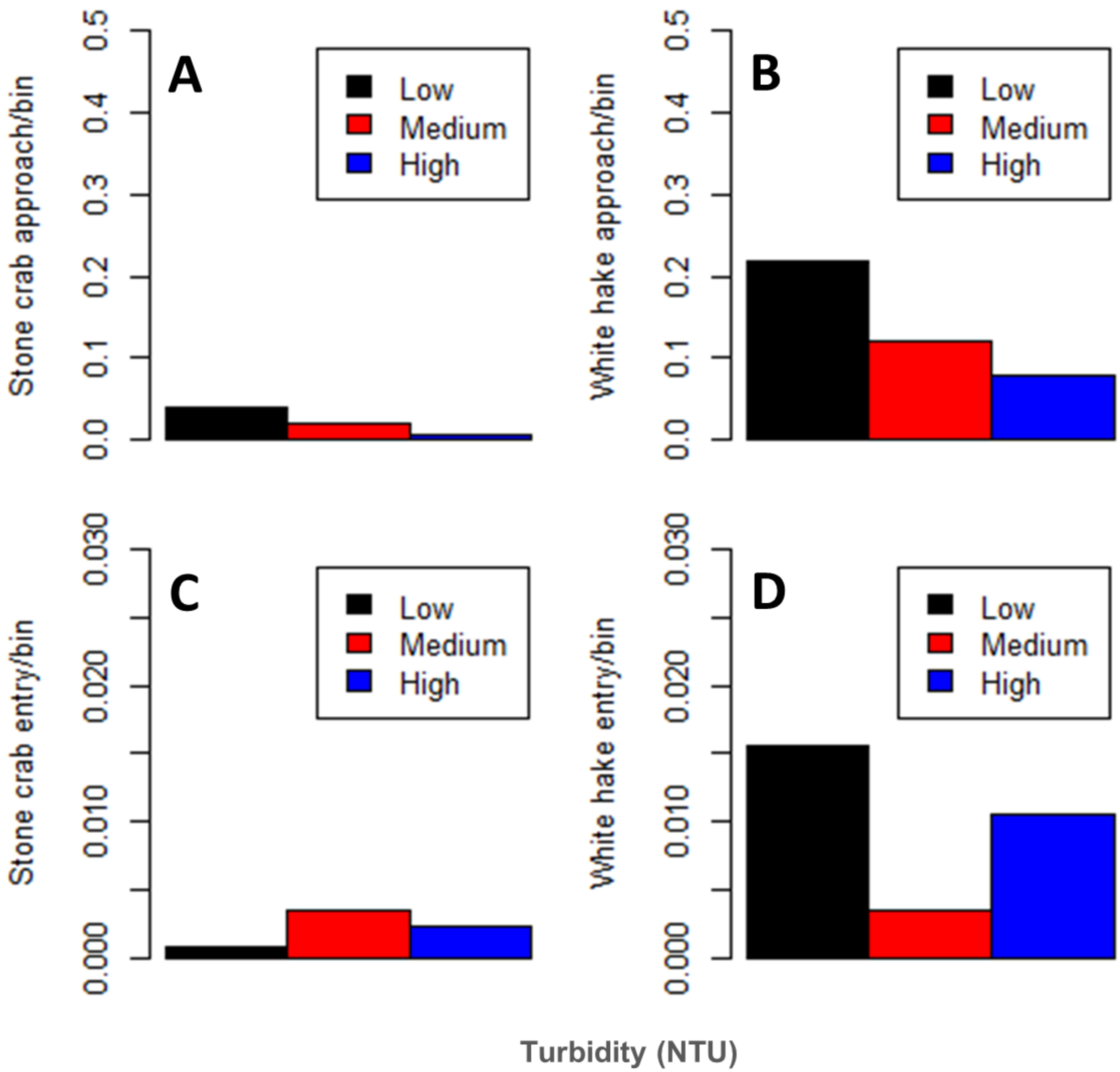


**Figure 17:** Comparison of the effect of turbidity on northern stone crab (*L. maja)* approach and entry rate (**A** and **C,** respectively), and white hake (*U. tenuis*) approach and entry rate (**B** and **D,** respectively) for the total number of pot deployments, n = 6; one bin = 30s. Each colored bar represents the different turbidity levels as indicated in the legend (Low < 30 NTU; Medium 30 **-** 450 NTU; and High > 450 NTU).

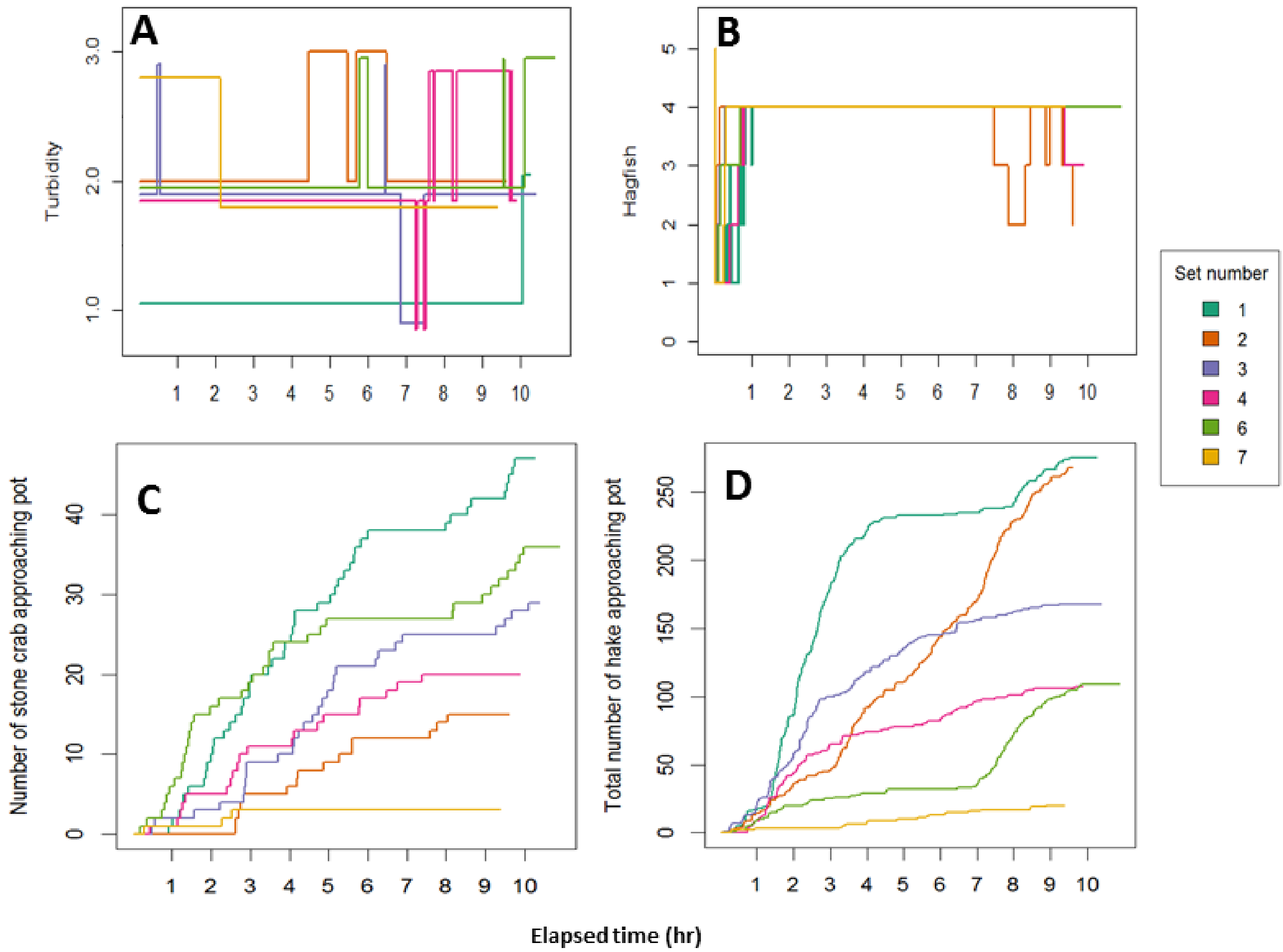


**Figure 18:** Comparison of the effect of the changes in turbidity levels (**A**), on hagfish (*M. glutinosa*) density (**B**), northern stone crab (*L. maja)* approach (**C**), and white hake (*U. tenuis*) approach (**D**), over the duration of the total pot deployments, n = 6. Each colored line represents an individual pot deployment, identified by set numbers shown in the legend. The numbers on the vertical axis of the turbidity graph, **A** (1.0, 2.0, 3.0), represent low, medium and high turbidity levels (Low: < 30 NTU; Medium: between 30 - 450 NTU; and High: > 450 NTU). The numbers on the vertical axis of the hagfish density graph, **B,** represents the number of hagfish present (hagfish counts were estimated in groups).

### 2.4.2.4 Behavioural Observations

It appeared that high concentrations of *M. glutinosa* in the pots prevented *L. maja* from accessing the pot entry openings in some cases, particularly when the water current direction caused *M. glutinosa* to move towards an opening, inside the pot, from where *L. maja* may attempt to enter the pot. As a result, this potential entry funnel for *L. maja* will often correspond to an entry opening where most of *M. glutinosa* in the pot will be concentrated, due to the pressure from the water current flow. On the other hand, when the water current direction is perpendicular to the funnel entrance, *L. maja* found it easier to get into the pot with less obstruction from *M. glutinosa,* which was positioned away from the funnel entrance with the effect of the water current direction. Also, there appeared to be little or no effect of the camera light on *L. maja*, because *L. maja* was observed making its way successfully to the top of the pot, directly below the camera (Figure 23). In some instances, it remained in the position, below the camera for long periods of time, before it crawled down the pot. Once *L. maja* made it into the pot successfully, they immediately reached for the bait bag, which showed that they were attracted to the bait. They were eventually forced to leave this position with the emergence of the pool of *M. glutinosa* around the bait. *L. maja* was observed to move around the pots in groups of two or three when they encounter each other and interact in the pot, changing positions regularly within the pot.

I also observed that when *U. tenuis* bumped into battery packs as they approached the pot, they swiftly swam off the field of view of the video camera. *U. tenuis* were more active when they first entered the pot successfully, and frequently butted the net. They become less active over time inside the pot. Once they were trapped, they tend to immediately reach for the bait bag, also showing they were attracted to the bait just like *L. maja*. In most cases, *U. tenuis* was observed to show interest in the bait for a short period of time, and would remain calm inside the pot over a longer period without attempting to exit the pot. They typically orient to face into an oncoming current to hold a position in the water stream (positive rheotaxis), and took up the spaces close to the bait bag positions before they spread out to other areas in the pot, usually at the top compartment of the pot (Figure 19). The entry rate of other species reduced when *U. tenuis* inside the pot reached a certain number, typically ≥10 individuals, an evidence of pot saturation. No evident association was observed for interspecific interactions between individuals as they approached. There was a weak correlation between *L. maja* approach and *U. tenuis* approach ($r = 0.395$, $n = 60$, $p < 0.05$). Little or no correlation was found between *L. maja* entry and *U. tenuis* entry ($r = 0.115$, $n = 60$, $p > 0.05$), (Figure 20 and 21).

**Figure 19:** *U. tenuis* in the upper compartment, two hours after deployment.

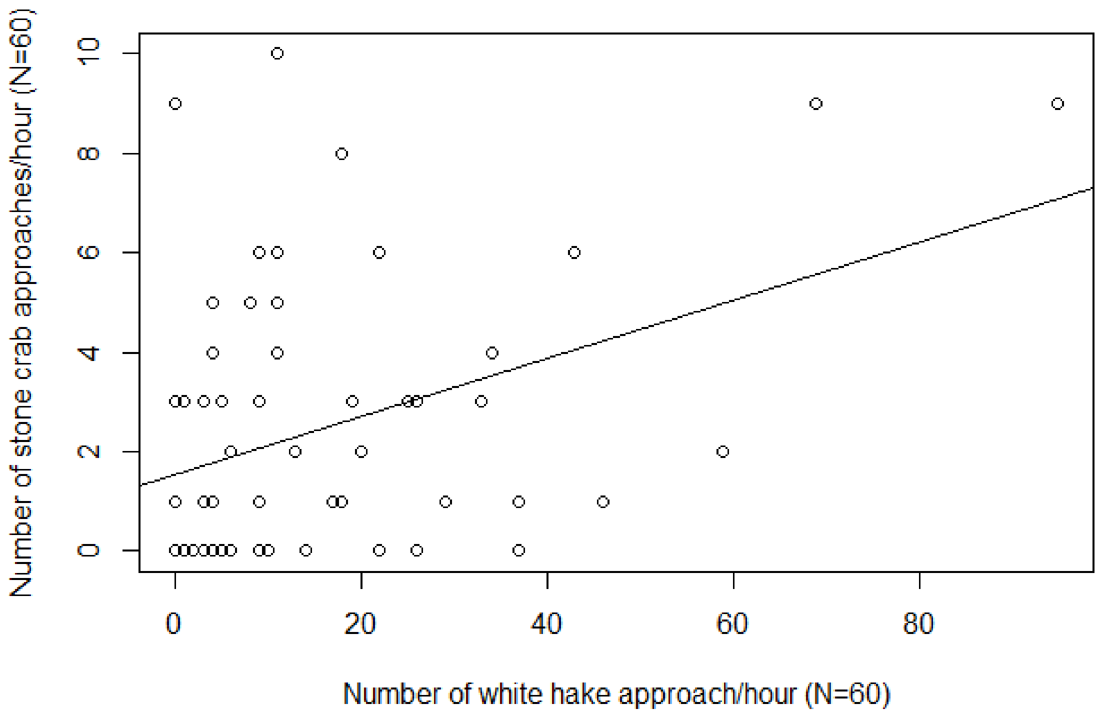


**Figure 20:** Relationship between northern stone crab (*L. maja*) approach and white hake (*U. tenuis*) approach over a 60 h period. Pearson's r = 0.395.

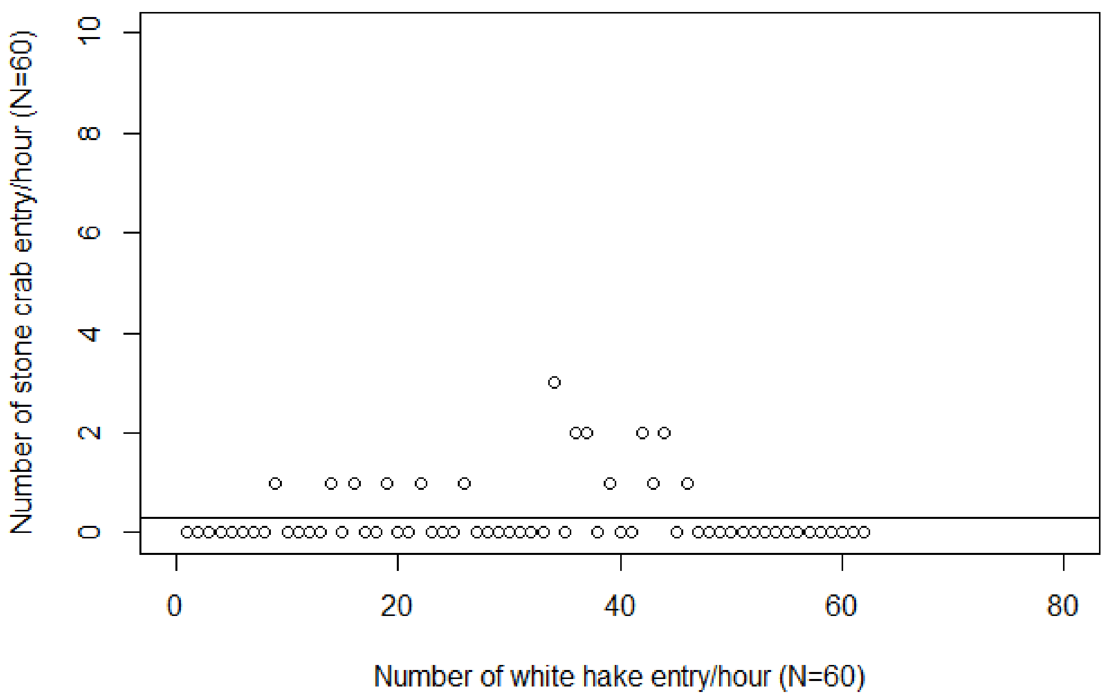


**Figure 21:** Relationship between northern stone crab (*L. maja*) entry and white hake (*U. tenuis*) entry over a 60 h period. Pearson's r = 0.115.

#### 2.4.2.5 Estimation of Catchability

The catchability of *L. maja* and *U. tenuis* were generally low (< 0.5). On average, catchability of *L. maja* and *U. tenuis* were approximately 0.3 and 0.1, respectively (Table 5).

**Table 5:** Catchability estimates of *L. maja* and *U. tenuis* for each deployment.

| Set | Catchability of *L. maja* | Catchability of *U. tenuis* |
|---|---|---|
| 1 | 0.02 | 0.04 |
| 2 | 0.20 | 0.01 |
| 3 | 0.03 | 0.07 |
| 4 | 0.30 | 0.16 |
| 6 | 0.06 | 0.06 |
| 7 | 1.00 | 0.35 |
| **Average (appx.)** | **0.3** | **0.1** |

## 2.5 Discussion

In this study, I evaluated the performance of three pot types deployed at the seabed, and investigated the factors that influence the catch rates of *L. maja* in and around pots with the aid of an underwater video camera.

My study demonstrated that the two-door Norwegian pots were most efficient in maximizing catch rates of *L. maja* over the Newfoundland pot. I also found that the Norwegian pots are suitable for effectively targeting and harvesting *U. tenuis* as well, providing a potential path in future for the target of both species at once. However, a plan based on a multi-species fishery that targets *L. maja* and *U. tenuis* is contingent on the recovery of *U. tenuis*, which has been assessed as “threatened” by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2013). This assessment occurred because surveys have demonstrated a 70% decline in *U. tenuis* abundance since the mid 1980’s (COSEWIC, 2013). If the federal government listed

*U. tenuis* under the Species at Risk Act (SARA), there will be no permission granted for targeted fishing for this species until acceptable abundance is re-established.

Throughout the analysis of the underwater videos, based on my observations, I assumed that my apparatus had little or no impact on the animals' behaviour. This is one advantage of stationary digital video cameras over remotely operated underwater vehicles (ROVs). ROVs are noisy, bright and are known to impact fish behaviour underwater (Stoner et al., 2008). Red light is suitable for filming crustaceans, since they are insensitive to that end of the visual spectrum (Weiss et al., 2006), but fish behaviour is influenced by the presence of any visible light (Marchesan et al., 2005; Widder et al., 2005). This was evident with *L. maja*, observed to successfully crawl to the top of the pot, directly below the camera light *in situ*, remaining at this position for extended periods before leaving the position (Figure 23). This indicated that there was little or no effect of light on *L. maja*, or they may have been attracted to the light. This leaves an opportunity for further research to determine the effect of red light on *L. maja in situ*.

Water current direction was an important factor that influenced the capture of both *L. maja* and *U. tenuis*. The vast majority of approaches to the pot occurred against the direction of current, this observation is reasonable because many aquatic organisms generally tend to orient to face into an oncoming current to hold a position in the water stream (a phenomenon known as positive rheotaxis), rather than being swept downstream by the current. I attribute this phenomenon to the fact that the bait plume will naturally be dispersed downstream in the prevailing water current direction and hence, would progressively facilitate the attraction of organisms to the pot (e.g., Miller, 1978), causing individuals to swim against the direction of current. This finding is consistent with the "attraction strip phenomenon" previously observed for *C. opilio* (Chiasson et al., 1993; Vienneau et al., 1993; Winger and Walsh, 2011). Further research effort is required to develop a clearer understanding of the dispersion of bait plume and how this impacts on other aquatic organism assemblages. However, once trapped inside the pot, individuals were always oriented in the direction of the current, and subsequently changed their orientation with the change in water current direction. My study also showed that most entry attempts occurred against the current (e.g. *L. maja* attempting entry through the right entrance when the current was moving left-to-right). This explains why the Norwegian one-door pots were less effective than the Norwegian two-door pots; with a one-door pot, it is less likely that the organism will be able to easily enter through the available door, when the approach is against the water current from the side of the pot not equipped with a door. The opposite will, however, be the case when the water current direction reverses.

The frequency of variation in water current direction within an hour indicated a relationship between the number of approach for both *L. maja* and *U. tenuis*, with higher number of individuals approaching, and entering pots during fewer water current hourly variation frequencies. This suggests that stable water (i.e. less turbulent), over time, may enhance the capture of these species. This finding is also in concert with previous studies on the disturbing effects of coastal ecosystems by ocean current variations, conducted in other coastal regions (Scarnecchia, 1984; McGowan et al., 1998; Lunt and Smee, 2014).

Although turbidity has been found to affect abundance of certain species (Speas et al., 2004; Lunt and Smee, 2014), my study indicates that turbidity had no significant effect on the approach and entry rates of both *L. maja* and *U. tenuis* and hence, there is not enough evidence to reject the null hypothesis. This finding is similar to the reports on the effect of turbidity on abundance of certain species. For example, the abundance of species such as the small mud crabs (*Panopeus obesus*: Smith, 1869) (< 8 mm carapace width) and oysters (*Crassostrea virginica*:

(Gmelin, 1791) were found to be unaffected by turbidity (Lunt and Smee, 2014). Also, past studies have revealed that chemosensory species, such as the blue crab (*Callinectes sapidus*: Rathbun, 1896), is unaffected by turbidity (Weissburg et al., 2003). Hence, the effect of turbidity may be species dependent (Minello et al., 1987; Liljendahl-Nurminen et al., 2008; Lunt and Smee, 2014). On the other hand, although statistical tests showed no significant relationship between turbidity levels and the approach and entry rates of both *L. maja* and *U. tenuis*, the graphical representation in Figure 17 B and D shows that *U. tenuis* were more likely to approach and enter the pot when the turbidity was low. This is supported by the findings reported by Berg and Northcote (1985) that turbidity limits fish vision, which can interfere with their social behaviour, and that foraging rates of juvenile Chinook salmon (*Oncorhynchus tshawytscha*: Walbaum, 1792) were reduced at higher turbidity levels (Gregory and Northcote, 1993). Also, recent studies have shown that abundance of red drum (*Sciaenops ocellatus*: Linnaeus, 1766), black drum (*Pogonias cromis*: Linnaeus, 1766), and southern sheeps head (*Archosargus probatocephalus*: Walbaum, 1792) were highest in low turbidity levels (Lunt and Smee, 2014). This explains that most fish species depend on vision for much of their sensory input, and turbid waters may influence the catch rates of certain species. Majority of *L. maja* appeared to have approached during low turbidity, while higher entry rates occurred during medium turbidity levels. It is possible that there were insufficient observations for the test to detect a significant relationship between the turbidity levels and species approach and entry rates. It is also worthy of note that the dangerous turbulent conditions caused by the Hurricane Gonzalo, which passed through the region right before my field study, may have resulted in substantial variability within the dataset. Further investigation, with focused effort on collecting relevant data on abiotic factors such as water current speed, water temperature, hydrodynamic forces (Martinez et al., 1998), etc., and considering human induced effects and eutrophication, using long term dataset, is recommended in order to accurately determine the effect of turbidity.

*L. maja* were slow approaching the pot. From the time they attempt entry, it took an average of approximately 175 seconds to successfully enter the pot. Unlike *L. maja*, *U. tenuis* took approximately 10 seconds to enter the pot from the moment they first attempted entry. It was unclear, through direct video observations, the reason for species (*L. maja* and *U. tenuis*) failed entry attempt after encountering the pot entrance. The entry rate of other species reduced when *U. tenuis* inside the pot reached a certain number, typically ≥10 individuals, an evidence of pot saturation. It was also unclear if the presence of a large number of these individuals inside the pot scared off other species. I observed high densities of *M. glutinosa*, inside the pot, within the first hour of pot deployment and this high density was consistent across videos – likely due to their small size which allowed them to enter the pot through the mesh holes. This species was always clustered at the bottom (Figure 22 and 23), and their position in the pot was dependent on the water current direction – typically downstream of water current inside the pot. For instance, if the water current direction was moving right-to-left, *M. glutinosa* will be positioned at the bottom left side inside the pot and vice versa. The impact of *M. glutinosa* on catch rates of other species was not entirely clear. However, on several occasions, *M. glutinosa* relative position in the pot, with respect to water current direction, seemed to have prevented the successful entry of *L. maja*, and thus may have had some impact on catch rates. This observation is logical as *L. maja* were observed to travel predominantly against water current direction, as is the case for *C. opilio* (Winger and Walsh, 2011). *M. glutinosa* can be predatory, and their emission of slime acts as a defensive mechanism against predators (Zintzen et al., 2011). Therefore, the lack of substantial proof of the effect of *M. glutinosa* on the catch rate of other species presently makes it difficult to justify efforts in separating *M. glutinosa* from other species to maximize catch. Also, given the high densities of *M. glutinosa* in the regions in which *L. maja* can be targeted (Dooley and Johnson, 1994; Hiscock and Grant, 2006), it is unlikely that shifting fishing effort will be sufficient to avoid interactions between baited pots that target *L. maja*, and *M. glutinosa*. *M. glutinosa* is typically captured using 220 litre baited barrel type pots (Grant et al., 2009; Grant and Sullivan, 2013), and will be unsuitable for the capture of commercial quantities of *L. maja* considering the size of the crab. A multi-species fishery for *L. maja* and *M. glutinosa* may be possible if a suitable pot is developed for the successful capture of both species. *M. glutinosa* have been utilized in different ways including as a source of food for human consumption, production of leather, and as a cleanser (derived from the slime of *M. glutinosa*) (Honma, 1998). In order to avoid bias in the assessment of interspecific interactions, more specific and detailed study is required in this area to ensure an accurate assessment of fish association and additional interpretation of their behaviours.

Scaling up context-dependent interactions to explain broad spatial and temporal patterns in natural communities require a thorough understanding of how biotic and abiotic factors influence interacting organisms (Lunt and Smee, 2014). This can be particularly challenging when biotic factors are strongly affected by abiotic conditions that may enhance or attenuate biotic effects (Smee et al., 2010), such as catchability. I estimated catchability of species using the catchability model, Catchability (q) = $C / (B*f)$ (Jul-Larsen et al., 2003). I represented $B$ (actual population size) as the number of *L. maja* or *U. tenuis* in the vicinity of the pot. This method was possible because I observed *L. maja* and *U. tenuis* that approached the pot with the aid of the underwater video camera. This allowed the successful account of the number of species in the vicinity of the pot, which I treated as the actual population size to ensure an accurate estimation of catchability using this model. My study demonstrates that the catchability of *L. maja* and *U. tenuis* were low at 0.3 and 0.1, respectively. This low catchability rates are likely due to the influence of the identified abiotic factors on approach and successful catch of species. Approximately 86.7% of *L. maja*, and 91.6% of *U. tenuis* that approached the pot, never made it into the pot successfully. It is also worth mentioning that the total number of approach recorded for individuals may not represent actual number in the population because (1) not all individuals in the vicinity of the pot may have been attracted to the pot, and (2) individuals were not tagged and could have been counted multiple times as they exited and entered the field of view of the camera. This calls for further research to determine the extent to which these identified factors influence catch of individuals, as the Norwegian two-door pot proved efficient in catching and retaining the *L. maja* and *U. tenuis* in the pot (exits by *L. maja* and *U. tenuis* were particularly low - 30% and 20% respectively).

I found that the overall approach and catch rates of *L. maja* were similarly low. This finding agrees with results of previous studies that suggest low catch rates of *L. maja* (Walsh et al., 2012). There are two non-exclusive explanations for this observation. First, it is possible that the ambient density of this species could be low in the study area. Second, the crabs may simply not have been attracted to the pot. Clearly, this should be investigated further by using a different pot type, mesh size, bait type, bait device, and quantity of bait to attract species *in situ.* Assessing the former requires that a fishery-independent survey be conducted to ascertain abundance.

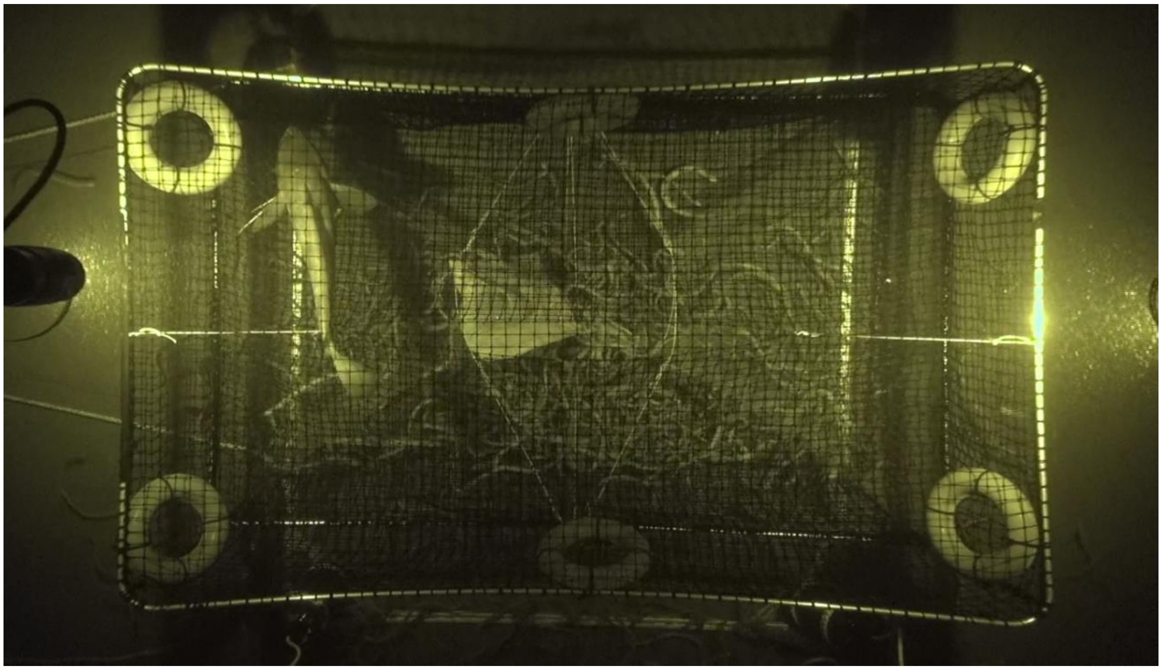

**Figure 22:** *M. glutinosa* clustered at the bottom of the pot within an hour of deployment.

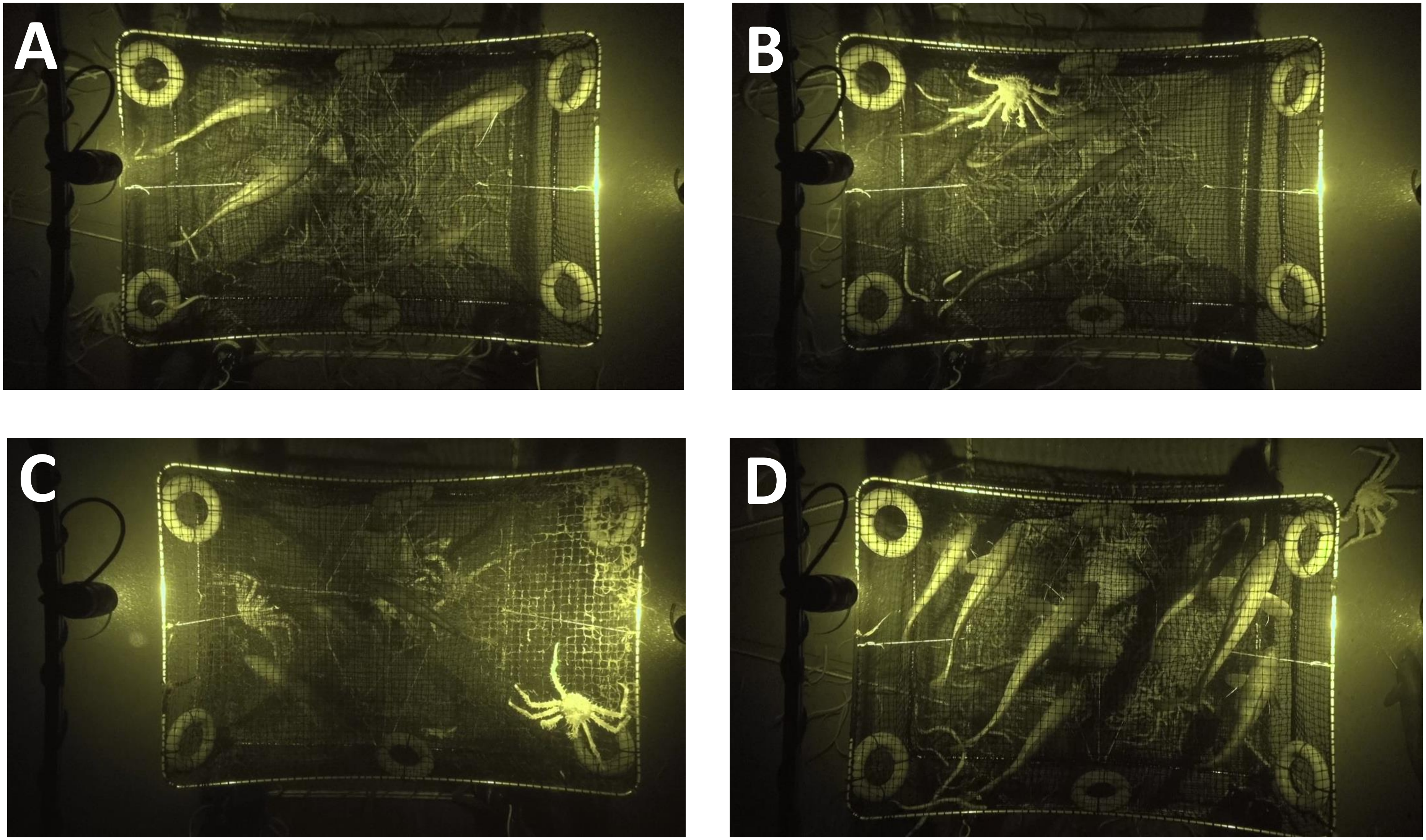


**Figure 23:** Picture snapshots from the video clips showing the behaviour of *L. maja* in and around the pot. (**A**) shows crab approaching the pot from the left bottom corner of the picture; (**B**) shows crab climbing to the top of the pot; (**C**) shows crabs inside the pot; (**D**) shows crab exited the pot and leaving the field of view.

# Chapter 3 Feasibility study of northern stone crab (*L. maja*) fishery in Newfoundland and Labrador

## 3.1 Pot fishery: Gear style, catch rates, and conservation challenges

Pots are used all over the world's marine and freshwater environment. They are fuel-efficient compared to many other fishing gears and are one of the oldest commercial fishing gears in the world (Miller, 1990). They are available in different shapes, typically conical, square or rectangular shapes (He and Inoue, 2010). In order to achieve a successful pot fishery, an in-depth understanding of animal behaviour is required (Miller, 1990). Failure to understand animal behaviour in and around pots, especially their movement patterns, can result to catch failure for a particular season (Miller, 1990). The catch success rate of pots depend on the ability to attract targeted species to the pot, lure them inside the pot, and keep them in captivity until the pot is retrieved (Thomsen et al., 2010). In most pot fisheries, bait is used in the capture processes to increase the area within which targeted animals may react and be attracted to the pot (Thomsen et al., 2010). The type of bait used can influence catch rates and proportions of different species attracted to the pot (Thomsen et al., 2010). For instance, the use of squid, instead of herring, increased catch rates of *G. morhua,* whereas only a minor difference was observed for tusk (*Brosme brosme*: Ascanius, 1772) (Furevik, 1994). Pots are generally regarded as an environmentally friendly fishing gear, with minimal undesirable side effects when catching targeted species (Miller, 1990; Thomsen et al., 2010). However, conservation challenges are also associated with pot fisheries. Conservation issues associated with pot fisheries include ghost fishing, escape and discard mortality, incidental megafauna interactions, and specific issues related to habitat alteration in vulnerable habitats (Thomsen et al., 2010). However, with the inclusion of conservation characteristics in the development and modifications of fishing gear, and appropriate management of fisheries in sensitive areas, these issues can be addressed. By using pots, fishery resources can be conserved and the protection of benthic species, and habitats, remain possible. The following sections, 3.1.1 to 3.1.3, present some background of notable pot fisheries, such as the Newfoundland snow crab (*Chionoecetes opilio*) pot fishery, the Alaskan red king crab (*Paralithodes camtschaticus*) pot fishery, and the British Columbia spot prawn (*Pandalus platyceros*: Brandt, 1851) pot fishery. These notable pot fisheries are used as precedents to help put the feasibility of a *L. maja* commercial pot fishery in Newfoundland and Labrador into proper perspective.

### 3.1.1 Newfoundland snow crab fishery

*C. opilio* is a crustacean with a flat, almost circular, body and five pairs of spider- like legs. *C. opilio* lives on muddy bottoms in cold waters (DFO, 2011). They prefer a narrow temperature range of cold water ranging from -1 to 4°C and depths ranging from 50 to 280 m (DFO, 2011). The effect of temperature on *C. opilio* depends on the stage of its lifecycle and if the oceans warm, *C. opilio* may lose their primary habitat (DFO, 2009b). Large males are most common on mud or mud/sand substrates, while smaller crabs are common on harder substrates (DFO, 2011).

Commercial fishing of *C. opilio* began in the mid-1960s in Canada (DFO, 2011). The main fishing grounds range from Quebec to western Newfoundland-along the northern shore of the St. Lawrence River, around the Gaspé Peninsula to the Magdalen Islands, around Cape Breton Island toward southwestern Nova Scotia, and from southeastern Newfoundland midway up to Labrador (DFO, 2009b). In Newfoundland and Labrador, *C. opilio* is a male-only commercial fishery, with the minimum size limit set at 9.5 cm CW (DFO, 2009b). The male is much larger with a CW of up to 16.5 cm wide, a leg span of 90 cm, and a weight of about 1.35 kg (DFO, 2009b). By comparison, the female's CW often does not grow beyond 9.5 cm, with leg span of about 38 cm and weight just under half a kilogram (DFO, 2009b). With the closure of most major commercial groundfish, it became the backbone of the fishing industry in this region. The management of the fishery is based on annual total allowable catch (TAC), quotas, effort controls, minimum legal size, minimum mesh size of pots, seasons, areas, and soft- shelled (also known as white crab) protocols (DFO, 2015b). *C. opilio* are harvested with conical baited pots, constructed of wire or tubular steel with a minimum legal mesh size of 65 mm, set in fleets (DFO, 2009b). The pot has a maximum volume of 2.1 $m^3$ when measured on the exterior, and a bottom ring with a maximum diameter of 133 cm (DFO, 2009b). The pots are baited, most often with herring, mackerel or squid (DFO, 2009b). Once captured, the crabs are kept alive on ice in the hold of the fishing boat (DFO, 2009b). The fishing season is variable, but generally takes place in the spring and summer months, and typically lasts between 8-10 weeks, opening in late April or early May and effectively closing by late June or early July (DFO, 2006; DFO, 2015b).

Harvesting licenses for *C. opilio* increased from 50 in the early 80's to approximately 3300 by late 90's (DFO, 1999a), and in 2010, 4326 *C. opilio* fishery licenses were issued (DFO, 2015b). Landings were approximately less than 5,500 tonnes annually in 1970’s, and increased to over 11,000 tonnes by the end of that decade. In 2008, landings were approximately 58,000 tonnes and by 2013, total landings increased to 98,065 tonnes (DFO, 2011; DFO, 2015b). A recent study using a vessel monitoring system showed that CPUE for *C. opilio* was 9.96 and 11.02 in 2004 and 2007, respectively (Mollowney and Dawe, 2009). Price per pound was $0.54 CAD and $0.88 in 1990 and 1998, respectively (DFO, 2011). In 2008, the price per pound for *C. opilio* increased to $1.54, and $5.82 per pound in 2014 (DFO, 2011; DFA, 2015). *C. opilio* is the second most valuable Canadian fishery export product with approximately $429 million exports valued in 2012, and approximately $434 million exports valued in 2013 (DFO, 2015b). In 2015, the landed value for *C. opilio* remained constant at approximately $258 million due to an increase in its raw material price (DFA, 2015). The importance of *C. opilio* fishery to Newfoundland and Labrador economy has increased dramatically over the years. With the closure of the groundfish fishery in the 90's, the province diversified to other species, such as the crustaceans. It went from a groundfish dominated industry to a shellfish dominated industry, and at present, in Newfoundland, fisheries that target crustaceans are more valuable than fisheries that target bony fishes (DFA, 2014). In 2012, 83.1 percent of total landed value was attributable to invertebrate fisheries (DFO, 2012).

Major concerns with the *C. opilio* fishery are ghost fishing with pots and mortality rates of discarded illegal-size species (Vienneau and Moriyasu, 1994). Although the actual number of pots lost or abandoned each year are unknown, the phenomenon of ghost fishing is well documented for this species (Vienneau and Moriyasu, 1994; Hébert et al., 2001), with an estimated annual mortality of over 600 tonnes in Newfoundland and Labrador (Bishop, 2010). Management strategies have been implemented to allow development of several technological advancements, such as disabling baited pots if they are lost or abandoned at sea. Such strategies include the installation of biodegradable or corrodible material into a pot such that when it is successfully degraded, it allows animals that have accidentally entered the pot to escape without harm (Winger et al., 2015). The uncertainty of survival of undersized or illegal sized male crab that are routinely caught and discarded have been raised by scientists over the years (Grant, 2003). Given the importance of *C. opilio* to the economy of Atlantic Canada, several studies have focused on effective pot designs to capture target and legal-sized species. For example, recent study by Winger and Walsh in 2011 demonstrated that either 95 or 100 mm diameter escape mechanisms installed into traditional 14.0 cm mesh traps resulted in 38–47% fewer undersized pre-recruit (<95mm CW) crab being captured. Also, an experiment on conical pots modified by attaching an 18 or 24 cm plastic panel around the top, caught significantly less soft-shelled crabs while maintaining the same catch rate of commercial crabs when compared to the conventional conical pot (Hébert et al., 2001). *C. opilio* fishery in Newfoundland and Labrador is, however, known to be properly managed and have been certified by the Marine Stewardship Council as sustainable in April 2013 (MSC, 2016).

Newfoundland and Labrador's seafood products are exported to more than 40 countries around the globe (ERAD, 2015). The U.S. remains the largest export market for Newfoundland and Labrador seafood products, representing 39.6% of export value in 2015, while China was the second largest export destination, representing 19.6% of export value (ERAD, 2015). Other key markets, in terms of export value, included the United Kingdom at 9.2%, Denmark at 6.0% and Vietnam at 4.1%. Combined, these markets represented 78.5% of the province's total value of seafood exports (ERAD, 2015). In 2015, the province's seafood industry exported products valued at over $1 billion, up 15.0% from the same period in 2014 (ERAD, 2015). Snow crab was the most valuable seafood export for the province in 2015, valued at over $376 million (ERAD, 2015). The U.S. remained the largest export destination for snow crab, accounting for 74.0% of export value, followed by China with approximately 17.0% of export value (ERAD, 2015). A favourable exchange rate has increasingly become an advantage for snow crab producers in the province, and was especially evident in 2014 (ERAD, 2015).

### 3.1.2 Alaskan red king crab fishery

*P. camtschaticus* are large decapod crustaceans inhabiting intertidal waters of the North Pacific Ocean from British Columbia, Canada, north to the Bering Sea, and south to Hokkaido, Japan (Stevens, 2014). They were introduced as a non- native species into the Barents Sea (Northeast Atlantic) in the 1960s and 1970s (Orlov and Ivanov, 1978). Surveys show that *P. camtschaticus* were captured in depths ranging from 9 to 460 m, and they mature between 5 and 12 years old, depending on stock and temperature (Stevens, 1990; Stevens, 2014). They are known to live up to 20 years (Matsuura and Takeshita, 1990), with males and females attaining a maximum size of 227 and 195 mm CL, respectively (Powell and Nickerson, 1965).

*P. camtschaticus* have been exploited as commercial fisheries in Alaska since the 1920s (Gray et al., 1965). As with most crab fisheries in the region, *P. camtschaticus* have experienced both high and low harvests. Some stocks in the Gulf of Alaska, such as *P. camtschaticus* off Kodiak Island, have failed to recover after more than 25 years of fishery closures (Bechtol and Kruse, 2009). The Bristol Bay *P. camtschaticus* fishery collapsed after peaking at a harvest of 58, 968 tonnes in 1980 (Briand et al., 2001). The fishery was closed for one year in 1983, with two additional closures occurring in 1994 and 1995, and since the first closure, Bristol Bay harvests have remained relatively low compared to the 80's (Briand et al., 2001). The fishery experienced a boom cycle and have exceeded the rebuilding target levels since 2003 (Vining and Zheng, 2004).

The Bristol Bay *P. camtschaticus* fishery in Alaska, is a license-limited open-access fishery managed by the Alaska Department of Fish and Game (Briand et al., 2001). The fishing season is usually from 15 October to 15 January (ADF&G, 2015). The fishery is regulated by gear restrictions, harvest rate and size, sex, and season (3-S management system) (Kruse, 1993; AFSC, 2010). The gear restrictions include pot limits, degradable escape mechanisms, and web specifications (AFSC, 2010). For this fishery, pot limits were increased from 250 to 450 pots per vessel in 2005 (ADF&G, 2015). Standard commercial *P. camtschaticus* pots are square with sides dimension ranging from 150 to 240 cm (High and Worlund, 1979). The pot has two funnels at opposite ends, two side panels, one top panel and one bottom panel, and the entrance frames at the end of the funnel vary from 89 by 19 cm to 102 by 20 cm (High and Worlund, 1979). Mesh sizes between 9 and 20 cm are used on various pots (High and Worlund, 1979). Approximately 2 kg of frozen herring in perforated plastic jars of 2 litre volume, hung at the center of the pot, are typically used as bait in the commercial king crab fishery (High and Worlund, 1979). A standard king crab pot used in the commercial fishery retains more than 60% of the bycatch of female and sublegal-sized male crabs which must be returned immediately to the sea (Zhou and Shirley, 1996). Current minimum legal size of the *P. camtschaticus* is ≥ 165 mm CW, equivalent to 135 mm CL. The season opening dates are typically set to maximize meat yield and minimize handling of soft shell crabs (AFSC, 2010).

Fishing effort in this fishery has remained high with an average number of permits at 258 during 2000–2004 (ADF&G, 2015). The average ex-vessel price per pound was $3.88 USD in 1993, $5.14 in 2003, and $6.81 in 2013 (ADF&G, 2015). In 2013/2014 fishing season, the TAC was set at 8.6 million pounds, with an estimated fishery CPUE of 25.7 crab per pot, a reduction from the 2012/2013 value of 31.0 crab per pot (ADF&G, 2015). Although abundance of target species fluctuates no matter how carefully a fishery is managed, the Alaska *P. camtschaticus* fishery remains a valuable commercial fishery which has been sustainably managed for decades (Rice, 2012). In 2012, the management system of the U.S. Alaska *P. camtschaticus* commercial fishery was certified to FAO-based responsible fisheries management standard (Rice, 2012).

### 3.1.3 British Columbia spot prawn fishery

*P. platyceros* belong to the family Pandalidae, and generally lives for four years (DFO, 1999b). They are protandric hermaphrodites, maturing first as males and then entering a transition phase to become functional females, sometime between the third and fourth years, near 40 mm CL (Butler, 1964). *P. platyceros* live in rocky habitats from the intertidal zone to depths of approximately 480 m, but adults tend to inhabit depths between 70 and 90 m (DFO, 1999b). This fishery is one of the most valuable fisheries in the Pacific region (DFO, 1999b). It is distributed throughout the northeastern Pacific from San Diego, California, to Unalaska Island, Alaska, and in the northwestern Pacific from the Sea of Japan to Korea Strait (DFO, 1999b).

The commercial prawn fishery began around 1914 in Howe Sound, British Columbia and reached prominence in 1970s (DFO, 2013b). The majority of commercial landings have historically come from the fishing grounds inside of Vancouver Island (> 60%), with the remainder from the west coast of Vancouver Island (< 10%) and north and central coasts (25%) (DFO, 2013b). In these areas, *P. platyceros* are captured commercially in pots (DFO, 1999b). The fishery experienced a boom period between 1979 and 1989, following a series of exploratory prawn surveys (1976-1979) to assist development of the fishery in the north and central coasts of BC, with the number of vessels reporting landings increasing from approximately 50 to 305 vessels out of eligible 900 licenses issued in 1989 (DFO, 1999b). In an effort to manage this fishery, license limitation was implemented in 1990; currently, there are only about 250 commercial license eligibilities, and vessel sizes in the commercial fishery range from 3.9 m to 20.68 m (DFO, 1999b; DFO, 2013b). In addition to the license limitation program, a pot limitation program was introduced in 1995, allocating 300 pots per license (DFO, 1999b). The British Columbia *P. platyceros* fishery is managed using an escapement-based strategy

(Boutillier and Bond, 2001). This strategy attempts to make a minimum number of spawning stock size available all year round, and this is accomplished by removing all biomass over the escapement target level (Boutillier and Bond, 2001). Other management strategies implemented for this fishery include size limits, gear limits, gear marking requirements, seasonal closures, in-season area closures, pot mesh size requirements, daily fishing time restrictions, daily single haul limit, and specification of fishery opening date (Boutillier and Bond, 2001). The size limit was initially set at 30 mm CL in 1998 and increased to 33 mm CL in 1999 (DFO, 1999b). The gear type used in this fishery is a conical pot, with a bottom ring, a middle ring, and a top ring which measures 77 cm, 72 cm, and 66 cm in diameter, respectively (Rutherford et al., 2004). The overall height of the pot is 31 cm, covered in 3.8 cm stretched web with three tunnels, and special formulated fish pellets are used as bait type in this fishery (Rutherford et al., 2004). The fishing season is short and intensive (~8 weeks in May and June), and spans the entire BC coast (Favaro et al., 2010). The total landed value of the prawn fishery exceeded $26 CAD million in 1996 and 1997, but dropped to $18 million in 1998 (DFO, 1999b). Landed value peaked at $50.3 million in 2005, and was approximately $40 million in 2011 (DFO, 2013b). The price per pound in 2004 was between $13.20 and $17. 60 (DFO, 2013b). In 2010 it was $10.78 on average, but increased to $16.04 in 2012 (DFO, 2013b).

For many years, this fishery relied mainly on the Japanese market (Nelson, 2010). However, the prawn sector has diversified its market channels and now maintains a good profile in local, domestic, and other export markets, such as China, Hong Kong, and Taiwan (Nelson, 2010). The British Columbia *P. platyceros* commercial fishery is faced with bycatch concerns and continued shrinking of season length (Mormorunni, 2001). These bycatch issues has been effectively managed through sustainable strategies such as improved pots designs (to maximize catch of target species and minimize bycatch), better fishing technology and electronics, vessel upgrades, re-powering of vessels, improved haulers, development of on-board freezing capabilities, and widespread adoption of multiple-hauling practices (Mormorunni, 2001; Roberts, 2005). A summary comparison of the Newfoundland *C. opilio*, Alaskan *P. camtschaticus,* and British Columbia *P. platyceros* fishery is presented in Table 6.

**Table 6**: Comparison of Newfoundland *C. opilio*, Alaskan *P. camtschaticus*, and British Columbia *P. platyceros* fishery. Values are CAD.

| s/n | Species | Fishing season | Price/pound | Pot shape | Bait Type |
|---|---|---|---|---|---|
| 1 | Newfoundland snow crab (*C. opilio*) | April or early May to late June or early July (approximately 8- 10 weeks) | \$5.05 (2014) | Conical | Herring, mackerel, and squid. |
| 2 | Alaskan red king crab (*P. camtschaticus*) | 15 October to 15 January (approximately 3 months) | \$9.06 (2013) | Square | Herring |
| 3 | British Columbia spot prawn (*P. platyceros*) | May to June (approximately 8 weeks) | \$16.04 (2012) | Conical | Formulated fish pellets |

## 3.2 Economics of a hypothetical *L. maja* commercial pot fishery

*L. maja* has been identified as bycatch species for decades in shellfish and groundfish fisheries along the south coast of Newfoundland and Labrador (DFA, 2000). To establish a commercial fishery for *L. maja,* stocks would have to sustain commercial levels of exploitation and must be economically profitable to explore. This section provides a hypothetical break-even analysis of a *L. maja* commercial pot fishery using the coast guard fishing cost estimation model, presented in the equation below (Brian Johnson 2016, Industrial Liaison Officer, Canadian Centre for Fisheries Innovation, *Personal Communication*).

$$Cost\ (\$\ CAD/\ day) = 11.36\ \times duration\ of\ service\ (hrs)\ \times\ length\ of\ vessel\ (m) \times 1.13\ (HST)$$

Therefore, with a vessel length of 16 m (vessel used in this research - *F. V Burin Tradition*) and assuming it operates 24 hours per day during offshore fishing, the total cost for fishing per day is;

$$Cost\ (\$\ CAD/day) = 11.36\ \times 24\ hrs\ \times 16\ m\ \times 1.13 = \$4,929.33\ CAD/day$$

This calculated value above represents the minimum landed value that must be caught per day, from the exploration of a *L. maja* fishery using the specified vessel – the break-even value. I estimated the minimum catch rate (catch per day) of *L. maja* that must be caught in order to reach this break-even point using the average price per pound of *L. maja*, based on an average individual crab weight of 0.5 kg (~ 1 pound). However, given that there is currently no established market price for *L. maja*, the market prices of *C. opilio* and Alaska *P. camtschaticus* are used to estimate the required minimum catch rate and are presented in scenarios 1 and 2, respectively;

***Scenario 1***

Using the average price of *C. opilio* in Newfoundland and Labrador, $5.05 per pound (Gardner, 2014), approximately 976 crabs must be captured per vessel, per day, to reach the break-even point for a *L. maja* commercial fishery. Based on the catch rate data from my video study - an average of 3 crabs per pot per day (where, one day = 10 fishing hours), approximately 136 pots, set in fleets, would be required per day (based on 24 hour-days) to fish, in order to break-even, provided catch rates of *L. maja* remain constant. However, given that the quality of *L. maja* meat is better, in terms of taste and size, than those of *C. opilio, L. maja* will likely fetch a higher market value than *C. opilio* and hence, may be priced higher (Dooley and Johnson, 1994).

Furthermore, a multi-species fishery targeting *L. maja* and *U. tenuis* may be possible if *U. tenuis* recovers. In that case, this will mean more business and revenue to the province- the average price of *U. tenuis* is $1 per kg (Fowler, 1998). Therefore, based on the catch rate data for *U. tenuis* from my video study, which was an average of 9.3 hake per pot per day (where one day = 10 hours, and an average weight of *U. tenuis* was 2.3 kg), approximately 3,033 *U. tenuis* per day (based on 24 hours-days) will also be captured, in addition to *L. maja*, in the estimated 136 pots required to break-even, provided catch rate of *U. tenuis* remains constant. In addition, assuming 75 pots, set in fleets, are used for a multi-species fishery that targets both *L. maja* and *U. tenuis*, a minimum of approximately 214 *L. maja* and 1,673 *U. tenuis* must be captured per vessel, per day (24 hour-days) to reach the break-even point, provided the catch rates of *L. maja* and *U. tenuis* recorded from my study remain constant.

***Scenario 2***

Applying the current market price of the Alaska *P. camtschaticus* $9.06 CAD per pound (ADF&G, 2015), approximately 544 crabs must be captured per vessel, per day, to reach the break-even point for a *L. maja* commercial fishery. Also, based on the catch rate data from my video study, as in scenario 1 above, approximately 76 pots, set in fleets, will be required per day (based on 24 hour-days) to fish, in order to break-even, provided catch rates of *L. maja* remain constant.

Also, similar to scenario 1, if *U. tenuis* recovers, considering a multi-species fishery, approximately 1,695 *U. tenuis* per day (based on 24 hour-days) will also be captured, in addition to *L. maja*, in the estimated 76 pots required to break-even, provided catch rate of *U. tenuis* remains constant. Furthermore, assuming 75 pots, set in fleets, are used for a multi-species fishery that targets *L. maja* and *U. tenuis*, a minimum of approximately 119 *L. maja* and 1,674 *U. tenuis* must be captured per vessel, per day (24 hour-days) to reach the break-even point, provided the catch rates of *L. maja* and *U. tenuis* recorded from my study remains constant.

### 3.3 Discussion

The establishment of any fishery is dependent upon the confirmation that harvestable quantities of target species are present in a particular fishing area (DFO, 2001). Therefore, before a commercial *L. maja* fishery can be established, more exploratory studies, using long term data, are required in order to estimate the density of *L. maja* in Newfoundland and Labrador. Upon confirmation of harvestable quantities, assessment of a gear for use in the fishery must be carried out to ascertain that the choice of gear has minimal or no detrimental impact to both target and non-target species habitat, while successfully capturing the target species in commercial quantities (DFO, 2001).

In my study, direct observation using underwater video camera partly assessed the impact of the Norwegian two-door pot at the sea bed. I did not observe any substantial negative impact on benthic habitat in these videos. Although the capture of bycatch species in the pot was recorded, there were no cases of escape and discard mortality, or ghost fishing associated with this study. There were also no cases or records of lost pot, injury to both target or non- target species, or damage to the fishing gear/apparatus associated with my study. In addition, no habitat alteration or disturbance was observed from the videos, probably because pots are not mobile fishing gears and upon hauling, care was taken to safely retrieve apparatus without damaging the attached video system, or dragging the pot along the bottom. Drag forces were avoided by allowing the pot to sit in its deployed position on the bottom until it was carefully lifted vertically off the sea bed. It is worth mentioning that although the Norwegian two-door pot captured bycatch species, the advantage of using pot as a fishing gear is that undersized and non-target species which could not be avoided or were unable to escape, are safely returned to the water after being brought on board (Thomsen et al., 2010). Also, due to the benign nature of the fish capture process, it is expected that the mortality of unwanted fish discarded from pots may be low as these species are usually captured alive, with low injury rates (Nøstvik and Pedersen, 1999).

Improvements in the modification of pots for the successful capture of *L. maja* should include the orientation of pot entrance downstream for maximum catch efficiency. An effective bait is a major contributor to fishing success (Miller, 1990). The release rate of odor from the bait decreases rapidly over time, and a system that prolongs the release of bait odor would produce substantial advantage in improving catch (Thomsen et al., 2010). To that end, improvements in bait and bait bag physical properties, such as increasing the quantity of bait to a range between 2 and 4 kg, using a combination of two or more fish species as bait, and a smaller bait bag mesh size, are recommended to improve catch efficiency. Pot may be designed to also have an additional entrance funnel located at the top of the pot as I observed *L. maja* crawl to the top in some occasions.

I observed low catch rates of *L. maja* in my study. An average of 3 crabs were captured in each pot within 10 hours, and if catch rates per hour remained constant, approximately 7.2 crabs per pot would be captured within 24 hours. This is somewhat comparable to CPUE of 9.96 recorded for *C. opilio* in 2004 (Mollowney and Dawe, 2009). Assuming an annual fishing season is set for 8 weeks, as in the case of *C. opilio*, and 150 pots, set in fleets, are used per day, for every deployment per vessel, each vessel can expect to harvest approximately 60,480 *L. maja* in a year, provided catch rate remains constant. This will amount to approximately $305,000 based on the average cost of *C. opilio* ($5.05). My study shows that it may be difficult to prevent *U. tenuis* from a pot that targets *L. maja*, therefore, a sustainable multi-species fishery plan targeting *L. maja* and *U. tenuis* may be viable depending on the recovery of *U. tenuis.* This will mean more revenue to the province's economy as the recovery of *U. tenuis* may open the door to other unfished species. Estimating the landed value of *U. tenuis,* based on catch data obtained from my study, will require a current established price for *U. tenuis.* The price of *U. tenuis* is typically dependent on size, and the established price recorded in the past averages $1 per kg (Fowler, 1998). Therefore, with an average of 9.3 *U. tenuis* captured in each pot within 10 hours, approximately 22.3 *U. tenuis* per pot would be captured within 24 hours, assuming current catch rates remain constant. With the same 150 pots set in fleets to capture *L. maja* for an annual fishing season of 8 weeks as described above, each vessel can expect to harvest approximately 187,320 *U. tenuis* in a year. This will amount to approximately $430,000 in addition to the estimated landed value of *L. maja* ($305,000), making a total landed value of $735,000 from a hypothetical *L. maja* and *U. tenuis* multi-species fishery.

Similarly, based on the current market price of the Alaskan *P. camtschaticus* ($9.06 CAD), if the annual fishing season for *L. maja* is set for 3 months (90 days) as in the case of the

Alaskan *P. camtschaticus,* and 150 pots are set in fleets for each deployment per vessel, per day, a total of 97,200 *L. maja* will be harvested in a year, assuming current catch rates remain constant. This is equivalent to approximately $880,000 per year in value of *L. maja*. Also, considering a multi-species fishery that targets *L. maja* and *U. tenuis*, depending on the recovery of *U. tenuis,* a total of 301,050 *U. tenuis* will be harvested in a year with the same 150 pots, set for 3 months (90 days) annual fishing season, assuming catch rates remain constant. This is equivalent to approximately $692,000 per year in value of *U. tenuis*, and a total landed value of approximately $1,572, 000 will be expected from a hypothetical *L. maja* and *U. tenuis* multi-species fishery. These estimated landed values are comparable to the average landed values of other groundfish and shellfish in Newfoundland and Labrador (DFA, 2015), which are valuable to the economy of the province. Findings from my study provide invaluable reference for future work on this species. A detailed stock assessment, performed with long term dataset, is required to ascertain the density and status of *L. maja* in Newfoundland and Labrador, before its establishment as a commercial fishery. If a detailed stock assessment of *L. maja* is conducted, and the abundance of this species is found to be higher than the number observed from my study, this could mean increased diversity of commercial shellfish species, and a potential healthy source of food and employment for Newfoundlanders and Labradorians, as well as a valuable source of revenue for the province. On the other hand, if a detailed stock assessment reveals lower densities of *L. maja*, than the number recorded in my study, then there may be no need for the establishment of a *L. maja* commercial fishery in Newfoundland and Labrador at this time. In that case, more efforts should be focused on conservation measures to nurture and protect this species for potential future exploitation.

# Chapter 4 General Discussion

This study demonstrates the importance of environmental variables in determining the catch rates of *L. maja*, as well as the behaviour of individual organisms under certain environmental conditions, which ultimately alters their perceived abundance. The effects of these identified variables on *L. maja* should be considered in the management and sustainability of this species.

I found that the Norwegian two-door pot represents the best path forward for a pot-based fishery targeting *L. maja* (this species was successfully captured in the pot, with *U. tenuis* co-occurring in the pots) and caused no detrimental impact on benthic ecosystem. This pot type proved effective for a multi-species fishery based gear in future targeting *L. maja* and *U. tenuis*, provided the stocks can sustain commercial levels of exploitation. There were no observed species entry limitations with the pot design, except for the presence of high density of *M. glutinosa*, the effect of which should be further explored. In assessing new fisheries for *L. maja*, a fishing strategy that seeks to exclude *M. glutinosa*, while considering the identified abiotic factors, in order to maximize *L. maja* catch rates would be prudent. Although previous studies have reported low fish capture rate and catch efficiency using pots, however, in comparison with other gear types, pots possess several superior characteristics compared to the other fishing gears. These include low labor and energy consumption, minimal habitat impact, and live fish delivery, amongst other characteristics (Miller, 1990; Thomsen et al., 2010). In a recent study, the catch rates of *C. magister* were observed to be low, with consistent occurrence of pot guarding by half- entry crabs, suggesting that behaviours of species play an important role in catch rates (Barber and Cobb, 2009). In another study, less than 20% of *P. platyceros* that approached the pot successfully entered the pot, although low catch rates may be attributed to counting species that approached the pot multiple times since it was a study conducted using an underwater video camera, and observed species were not tagged (Favaro et al., 2014). The low catch rates of *P. platyceros* observed were, however, attributed to the deployment of pots after the conclusion of the commercial prawn fishery in the area, when stocks were depleted (Favaro et al., 2014). Also, a recent study that examined the relationship between American lobster (*Homarus americanus*: H. Milne Edwards, 1837) catch, entry rate into traps and density, showed that when pots were pre-stocked with a single adult lobster there was a reduced rate of entry by pre-recruit lobsters (Watson and Jury, 2013). This suggested that one of the mechanisms leading to pot saturation is competition between lobsters trapped in the pot and those outside the pot and hence, they recommended that the behavioural mechanisms that influence catch be well understood (Watson and Jury, 2013). Therefore, to successfully restore, effectively manage abundance, and improve catchability of new and existing fisheries using pots, the behaviour of both target and non-target species, and the effects of abiotic factors on their ecosystem functioning must be well understood. A good understanding of these factors can also help inform future advancements in pot design.

The use of underwater video camera technology is a non-lethal technique to sample fish abundance, family richness, and community composition and is a proven tool that will aid this understanding (Dearden et al., 2010; Wilson et al., 2014). My study has also demonstrated the benefits of the underwater video camera technology. Without this technology, it would have been impossible to identify some species that co-occurred in pot (particularly *M. glutinosa* - as none of this species was captured upon hauling of apparatus), and assess the impact of their presence on the target species. Underwater video cameras can also reveal, in real-time, critical scientific information, which will otherwise be unavailable or difficult to obtain. Seeing what is going on beneath the water surface offers new information to researchers and the public. This study has demonstrated that the effects of environmental variables can mimic the effects of overfishing and can potentially lead to misinterpretation of results and misconceptions of species abundance and composition of the coastal ecosystem. However, with the aid of the underwater camera, such errors can be effectively and completely eliminated. In broader context, the practice of using underwater video camera technology can improve the overall economics of the fishery industry by minimizing the need for divers' intervention and improve efficiency. Also, the non-destructive nature of pot gears can help enhance marine conservation by minimizing disturbances to fish abundance, family richness, and species composition.

In order to determine the feasibility and promote a commercial *L. maja* fishery, it is important that the abundance of this species be establish through a detailed stock assessment using long term dataset. If the species abundance is determined to reach commercial quantity, there are three potential scenarios that can lead to a viable commercial *L. maja* fishery, and these include; (i) the price per pound of *L. maja* is fixed within the same price range of the Newfoundland *C. opilio and* Alaskan *P. camtschaticus* prices as earlier discussed, or higher (this will also be influenced by the market forces); (ii) an improved fishing gear which targets and increases the catch rates of *L. maja,* while effectively excluding *U. tenuis,* is developed; (iii) *L. maja* are landed as part of a multi-species fishery that includes *U. tenuis*, provided *U. tenuis* recovers. Based on findings from my study, scenario (iii) presents the greatest potential and may provide the best path forward, given that *U. tenuis* catch rates were high. The already established key markets for the province's seafood products, including USA, China, United Kingdom, Denmark and Vietnam, can be leveraged if a *L. maja* commercial fishery or a multi-species commercial fishery that targets *L. maja* and *U. tenuis* (provided *U. tenuis* recovers), is established. Most recently, the Canada-Korea Free Trade Agreement (CKFTA) came into effect January 1, 2015 (ERAD, 2015). Nearly 70% of South Korean fish and seafood product tariff lines will be duty free within five years and all remaining duties on seafood will be eliminated within 12 years (ERAD, 2015). This agreement provides more opportunities for provincial seafood producers and will mean more revenue and economic growth for the province and the country in general.

My study has advanced the practice of assessing new fishery for the *L. maja* by validating the suitability of the Norwegian two-door pot in targeting this species, and outlined factors that should be considered in order to ensure a sustainable *L. maja* fishery, while maximizing catch rate, in an environmentally responsible manner. This study builds on the previous research on *L. maja* in Newfoundland and Labrador. Clearly, a detailed stock assessment on *L. maja*, and extended research on the effect of *M. glutinosa* and other environmental factors, not considered in this study, will provide more useful insight.

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