Promoting conservation through the improvement of cod pots – a low impact fishing gear and alternative harvesting strategy for Atlantic cod (*Gadus morhua*) in Newfoundland and Labrador

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Abstract:

Pots are baited fishing gears that are growing in use as a tool for harvesting Atlantic cod (*Gadus morhua*) in Newfoundland and Labrador (NL).

To study how cod behaviours affect pot efficiency, I used underwater video cameras to assess two models of pot deployed in the Fogo Island fishery. Cod made few entry attempts relative to the number of approaches, and only 22% of entry attempts were successful. The majority of approaches, entry attempts, and successful entrances occurred from the down-current direction, and 25% of cod were able to escape following capture.

Following video analysis, I made modifications to existing pots, and created a new design. I then collected catch and length data, across five models of pot, over two years, to determine the optimal design for a re-emergent cod fishery in NL. All five pots caught cod effectively, but the new and modified pots caught the most per deployment, and increasing mesh size was effective at reducing the number of undersized fish caught.

This thesis demonstrates that modifications can have a substantial impact on catch rates, that potting gear is fundamentally sound, and fishermen can select a pot that is most appropriate to their needs.

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Appendix 1. Response to external examiner comments

Chapter 1: General Introduction

Atlantic cod (*Gadus morhua*) has been caught extensively along the coasts North America and Europe for centuries (Hutchings and Myers, 1995, 1994), and overexploitation leading to the subsequent decline of cod populations in Newfoundland and Labrador (NL) is perhaps the developed world's most famous example of failed fishery management (Milich, 1999). Large-scale commercial fishing for Atlantic cod in Newfoundland and Labrador ceased with the moratorium on the cod fishery in 1992, and for the first time since the closure there are signs of a slight population recovery (Rose and Rowe, 2015). If increases in the cod population are sustained, it is likely that there will be pressure to increase the fishing effort in the region, and resume widespread commercial fishing for Atlantic cod in NL. The re-opening of the cod fishery could potentially assist in the economic recovery of regions that were previously devastated by the cod collapse (Schrank, 2005), however the sustainability of this industry will depend in part on the types of gears allowed within the fishery.

The ecological impacts of fisheries are linked to the technology used to catch fish used by the industry (Chuenpagdee et al., 2003). Prior to the collapse of cod in NL, the fishery was reliant on bottom trawls, gillnets, and cod traps (Hutchings and Myers, 1994). Trawls can negatively impact benthic habitats (e.g. Freese et al., 1999; Suuronen et al., 2012) , while gillnets produce high rates of bycatch (Northridge, 1991; Suuronen et al., 2012) (the capture of non-target species), including both seabirds (Regular et al., 2013) and marine mammals (Kastelein et al., 1995). The collapse of the previous NL cod fishery was a product of multiple contributing factors, including over-fishing (Hutchings and Myers, 1994), environmental changes (Lilly et al., 2013), as well as unsustainable fishing practices (Milich, 1999). If the moratorium is lifted, and total allowable catches are allowed to increase, it is likely that gillnets in particular will return to the fishery in NL, potentially repeating the negative impacts on North Atlantic ecosystems that were observed in the past.

Pots (also known as traps), are stationary, cage-like, baited fishing gears widely used in commercial fisheries throughout the world (Cole et al., 2003; Furevik and Løkkeborg, 1994; Siddeek et al., 1999; Wolff et al., 1999) to capture fish and other aquatic species. In Canada, pots are currently used to harvest many species, including spot prawns (*Pandalus platyceros*) (Favaro et al., 2010; Fisheries and Oceans Canada, 2017a) and sablefish (*Anoplopoma fimbria*) (Fisheries and Oceans Canada, 2017b) in British Columbia, and snow crabs (*Chionoecetes opilio)* in NL (Winger and Walsh, 2011). These fisheries are widely regarded as highly sustainable, and they have been recognized by eco-certifications such as Oceanwise and Seachoice (Ocean Wise Conservation Association, 2017). In the case of spot prawns and sablefish in particular, collectively these fisheries produced a landed value of 50.6 million dollars in 2013, and both species fetch a high market value per kilogram (British Columbia Ministry of Agriculture, 2013). These fisheries demonstrate the viability of pots as a foundational fishing technology for sustainable fisheries. Pots are not yet widely used in NL to harvest Atlantic cod, with only a small group of fishers currently using this gear. However, as cod populations recover, pots are being considered as an alternative fishing gear on which to base a potential re-emergent cod fishery (Simms, 2017).

The benefits of using pots include decreased bycatch (Pol et al., 2010), minimal impacts to marine habitats, and a reduced contribution to ghost fishing (when constructed with biodegradable twine) when compared to gillnets (Suuronen et al., 2012). Pots have also been classified as a 'Low Impact and Fuel Efficient' (LIFE) fishing gear, because their stationary nature requires less fuel to harvest than mobile fishing gears (Suuronen et al., 2012). Another advantage to fishing with pots, is that fish are not subject to the various forms of pre-capture damage (such as meshing, or depredation), which can occur when a fish becomes trapped in gillnets (Walsh et al., 2006). This is because trapped fish are still alive, and able to swim freely within pots until retrieval. As a result of the fish being alive within the pots, the quality of meat retrieved from pots is superior, relative to many other fishing methods (Pol et al., 2010). This results in a greater market price for pot-caught products, when compared to seafood produced using other methods (The Shorefast Foundation, 2016). These high-quality fish are sought after by high-end restaurants, which focus on both quality and sustainability, and a great deal of media attention has been garnered towards these pot-caught fish due to their ecological importance (Sullivan and Walsh, 2010). In addition, the most recent report on Northern cod, by the Canadian federal Standing Committee on Fisheries and Oceans suggests that higher quality products fished using sustainable methods will be required for NL to be successful in a competitive global market (Simms, 2017).

Although pots can be an effective method for harvesting marine species, the design of pots is an important factor in determining whether a pot will be useful for a given target species, and for avoiding unwanted bycatch, because the feeding behaviours of fish in response to stationary gear can vary (Stoner, 2004). Mesh size, and entrance type has been found to influence the selectivity of fish pots in Australia (Moran and Jenke, 1990; Sheaves, 1995), while floating pots were able to reduce the bycatch of crustaceans in Norway (Furevik et al., 2008), and escape mechanisms have been found to reduce the catch of undersized snow crab (*Chionoecetes opilio*) in Canada (Winger and Walsh, 2011). These examples demonstrate the considerable effect that modifications to pot designs can have on their catch composition.

Pots are not widely used in NL to harvest Atlantic cod, with only a small group of commercial fishers on Fogo Island, NL, fishing their small cod quotas with pots since 2007 (Walsh and Sullivan, 2010), using the Newfoundland style cod pot (NL pot) developed at the Fisheries and Marine Institute of Memorial University of Newfoundland (Walsh et al., 2006), as part of the ongoing Atlantic cod stewardship fishery (i.e. the small commercial fishery that has permission to occur every year despite the ongoing moratorium) (Fisheries and Oceans Canada, 2016a). Potting has not yet been adopted as the primary cod fishing strategy in the region, with the majority of fishers still harvesting their quotas using gillnets or hand-lines. Experimental pots have been previously observed to yield commercially viable catches of cod along the coastline of Sweden (S. J. Königson et al., 2015), however the reluctance to switch gear types in NL may be due to inefficiencies in the design of current cod pots, such as the entrance design and retention mechanisms on the NL pot, which may act as a barrier to the entry of cod (Olsen, 2014), and that pots need to ensure at least one entrance is in-line with the downstream current direction to increase successful entries by cod (Anders et al., 2016; Meintzer et al., 2017). When developing alternative fishing gears, achieving greater, or at least comparable catches, with similar input effort is the most important factor for harvesters to abandon traditional gear methods (S. J. Königson et al., 2015). In addition to these design inefficiencies, the currently implemented NL pot is expensive to produce, large, heavy, and challenging to manipulate on board of certain vessels. Therefore, improvements to the current design of cod pots are required to encourage fishers to adopt this gear as an alternative harvesting strategy to gillnets.

Understanding the way animals behave in response to fishing gears is an important factor in assessing the gear's environmental impacts, and is a crucial factor in determining the efficiency of the gear (Underwood et al., 2012). Underwater video cameras have been successfully used in previous studies to observe the behaviours of target and non-target species within the vicinity of fishing gears including pots (Bacheler et al., 2013; Favaro et al., 2013; Jury et al., 2001), hooks (He, 2003), and trawls (Nguyen et al., 2014). These visual observations provide a greater understanding of the interactions between marine species and fishing gears, and the processes that influence the gear's catch composition (Renchen et al., 2012). In addition, studies to understand the behaviour of fishes in relation to pots are important for increasing their efficiency for commercial quantities of marine species (Furevik and Løkkeborg, 1994).

This thesis describes two field studies conducted over the course of two consecutive fishing seasons during the summers of 2015, and 2016 within the Fogo Island cod stewardship fishery. The first field study used long-duration underwater cameras of Atlantic cod behaviour near cod pots, to assess four factors that are directly related to the efficiency of pots: the number of times that cod approached deployed pots, the number and proportion that successfully enter pots, and the number that exit the pots before they get retrieved. Following the analysis of our underwater videos, I made modifications to existing cod pots, and created a novel design which were then tested during the following fishing season.

In the second study, I assessed the effectiveness of five different types of pots (including our modified and novel designs – based on the previous video observations) at catching cod, using catch, and length data collected on board of commercial cod fishing vessels. Our primary objective for this study was to analyze the effectiveness of each pot type, comparing the catch-per-unit-effort, and average body sizes for cod across all pot types, to determine the optimal pot design on which to base re-emergent cod fishery in NL.

The goal of the research described in this thesis is to combine visual observations of Atlantic cod behaviour in the vicinity of pots with actual landed catch data of various styles of cod pot collected at sea within a commercial fishery, in order to improve the efficiency of these typically lower impact fishing gears for cod. If an improved cod pot can be designed, with an increased catch efficiency for cod, fishers could be encouraged to adopt pots as a low-impact alternative to gillnets and other traditional fishing methods in NL and beyond.

Co-authorship Statement:

I, Phillip Meintzer, and Dr. Brett Favaro conceived and designed the experiments, performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, wrote the two manuscripts (data chapters), prepared figures and/or tables, and reviewed drafts of the manuscripts prior to submission and publication. Philip Walsh conceived and designed the experiments, performed the experiments, contributed reagents/materials/analysis tools, and reviewed drafts of the manuscripts prior to submission and publication. I, Phillip Meintzer, Dr. Brett Favaro, and Philip Walsh are listed as co-authors on both the manuscripts for both data chapters within this thesis that were submitted for publication.

Chapter 2: *In situ* observations of Atlantic cod (*Gadus morhua*) interactions with baited pots, with implications for gear design

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2.1 Abstract

Pots (also known as traps) are baited fishing gears widely used in commercial fisheries, and are growing in use as a tool for harvesting Atlantic cod (*Gadus morhua*) in Newfoundland and Labrador, Canada. Pots produce lower environmental impacts than many other fishing gears, but they will only be a viable fishing strategy if they are efficient and selective at catching their target species. To study the behaviour of cod in and around pots, and how those behaviours affect pot efficiency, we used long-duration underwater video cameras to assess two models of cod pot deployed in the nearshore waters of Fogo Island, NL. We examined the number of cod that approached the pot, the number and proportion that successfully completed entries into the pot openings, and the number that exited, and related these factors to the direction of water movement. We observed very few entry attempts relative to the number of approaches by cod, and only 22% of all entry attempts were successful. We observed that 50% of approaches, 70% of entry attempts, and 73% of successful entrances occurred from the down-current direction, and 25% of cod were able to exit the pot following capture. Based on our observations, we suggest that future cod pots should have a greater number of entrances, or a mechanism to ensure that entrances rotate in line with the current, in order to maximize their catch efficiency for cod.

2.2 Introduction

In any fishery, the type of fishing gear used influences the environmental footprint and impacts of commercial fishing operations (Chuenpagdee et al., 2003). Mobile gears, such as bottom trawls have been linked to the destruction of seafloor habitats (Freese et al., 1999) and bycatch, or the capture of non-target species (Kennelly, 1995). Bycatch has also been reported as a prominent issue with static gears such as gillnets (Northridge, 1991; Regular et al., 2013) and longlines (Anderson et al., 2011; Gallagher et al., 2014; Lewison et al., 2004).

Understanding the way animals behave in response to fishing gear is one factor in assessing the gear's impact on the environment, and understanding behaviours can be aided through the use of underwater video cameras (Underwood et al., 2012). Underwater video cameras have been used to study animal behaviours near pots (also referred to as traps; Jury et al., 2001; Bacheler et al., 2013; Favaro, Duff & Côté, 2013), hooks (He, 2003), and trawls (Nguyen et al., 2014). Despite challenges such as low light levels (Underwood et al., 2012), cameras are beneficial because they can enable direct visual observations of the behaviours of target and non-target species within the vicinity of fishing gears. This can facilitate understanding of the interactions between marine species and fishing gears and the processes that influence the gear's catch composition (Renchen et al., 2012).

Potting technology is a popular method of harvesting marine species in fisheries around the world (Cole et al., 2003; Furevik and Løkkeborg, 1994). Pots are a transportable, cage-like, stationary fishing gear, which typically use bait as an attractant for target species, along with retention devices to prevent the escape of caught individuals (Suuronen et al., 2012). Pots are generally selective, and are classified as a low impact fishing gear (Suuronen et al., 2012, Rotabakk et al., 2011) because they typically produce low rates of bycatch (Pol et al., 2010) and minimal impact to marine habitats. Furthermore, the stationary nature of pot-fishing typically reduces the fuel consumption of fishing vessels versus those using mobile gears (Suuronen et al., 2012). Another advantage to using pots is that trapped fish are alive and freely swimming within the pots, and are not subject to depredation, or other forms of pre-capture damage and mortality that can occur when a fish is trapped within gillnets (Walsh et al., 2006) and trawls (Rotabakk et al., 2011). Although there is the potential that predation between species, or cannibalism between individuals of the same species could occur while trapped together within a pot (S. J. Königson et al., 2015). Factors that can influence the catch rate of pots for target species include: fish density in the vicinity of gears, the feeding motivation and behaviour of the target species, the ability of fish to detect, and locate the bait within the trap, and environmental factors such as water temperature, visibility, current direction and velocity (Stoner, 2004). In Canada, pots are used to fish for several species, including spot prawns (*Pandalus platyceros*) in British Columbia (Favaro et al., 2010) and snow crabs (*Chionoecetes opilio) in* Newfoundland and Labrador (NL) (Winger and Walsh, 2011).

In NL, pots are not widely used to harvest Atlantic cod (*Gadus morhua*), however pots are under consideration as an alternative gear on which to base a re-emergent fishery for Atlantic cod. Despite a history of intensive over-fishing (Hutchings and Rangeley, 2011; Hutchings and Myers, 1995), subsequent collapse, and continued depletion

(COSEWIC, 2010), the cod stock has begun to show signs of recovery, with an increase in biomass for the pre-spawning and spawning components of the “northern” cod stock detected from acoustic-trawl surveys since 2007 (Rose and Rowe, 2015). If this recovery continues, cod fishing could re-emerge as a source of income for NL communities, which would assist in the economic recovery of regions devastated by cod collapse (Schrank, 2005). However, the sustainability of this industry will depend in part on the types of gears used within the fishery, as well as management measures such as total allowable catches, quotas per fisher, length of fishing season, the location of marine protected areas, and trap number limits per license. Traditionally, commercial-scale cod fishing has been conducted using gill-nets and bottom trawls (Hutchings and Myers, 1994). These are both efficient techniques, but they bear ecological costs, with the former producing high rates of bycatch (Northridge, 1991), including marine mammals (Kastelein et al., 1995) and seabirds (Regular et al., 2013), and the latter resulting in the destruction of seafloor ecosystems (Freese et al., 1999; Thrush and Dayton, 2002), including changes to benthic species diversity and habitat loss (Thrush and Dayton, 2002). In the case of the NL cod fishery, its collapse was a product of both over-exploitation (Hutchings and Myers, 1994) and unsustainable fishing practices (Milich, 1999).

A small group of commercial fishers on Fogo Island, NL, Canada, have been operating as a pilot-fishery for sustainable cod-fishing in NL, trialing cod pots since 2007 (Sullivan and Walsh, 2010). However, potting has not yet been adopted as a common fishing strategy with the majority of fishers, who mainly catch fish with gillnets. Experimental cod pots have been observed to yield commercially viable catches as an alternative to gillnets along the coastline of Sweden (S. J. Königson et al., 2015), but the reluctance to switch gears in Newfoundland may be due to inefficiencies in the design of the current cod pots, such as the entrance design, and retention mechanisms, which may act as a barrier to the entry of cod (Olsen, 2014).

In this study, we used underwater cameras to assess four factors that are directly related to the efficiency of pots: the number of times that cod approached deployed pots, the number and proportion that successfully enter pots, and the number that exit the pots before they get retrieved. These parameters, taken together, describe the catch rate of a deployed pot, and problems with any one of these steps can be addressed by improved gear design, informed by underwater video (Graham et al., 2004).

2.3 Materials & Methods

2.3.1 Specifications of NOR pots, and camera apparatus

Two styles of pots were examined: Newfoundland-style (Hereafter, NL), and Norwegian-style (NOR) pots. We tested these two models because the NL pot is currently in use by local fishers in Newfoundland (Walsh and Sullivan, 2010), and the NOR pot is used to catch Atlantic cod in Sweden (S. J. Königson et al., 2015). Our intent was to perform a full quantitative analysis on videos collected with both pot types. However, the floating cod-end of the NL pot obstructed our camera, and therefore we had to modify the pot to provide a clear field of view. This distorted the geometry of the pot, and drastically reduced catch rates and our ability to record quantitative data. Therefore, discussion of our qualitative observations of NL pots is addressed in the supplementary materials. In this manuscript, we focus on the results we obtained using NOR pots

The NOR pot is similar in structure to the pots used by Furevik et al. (2008), with dimensions of 1.5 m x 1.0 m x 1.2 m (Figure 2.1A). It is a two-chambered cod pot consisting of three rectangular frames in a collapsible structure. The bottom frame is made of 14 mm circular steel (to provide weight on the pot's bottom), and the two frames above are both made of 10 mm circular aluminum. There are six floatation rings fastened to the upper mesh of the pot, which allows the pot to open vertically underwater, with the heavier frame sinking to the seafloor while the upper frame and floats extend upwards with buoyancy. The pot is divided by a mesh false bottom that extends midway through the horizontal axis of the pot, creating two-chambers. A slit in the false bottom mesh allows cod to enter the upper chamber. Zippers are present in the mesh on the side of both the lower and upper chamber to allow for removal of fish as well as easy re-baiting of the pot. The two entrances of the NOR pot face each other from opposite directions within the lower chamber, with a single bait bag suspended between them. The entrance funnels are constructed with monofilament twine.

We constructed a large aluminum camera frame for each model of pot (Figure 2.1B). Both frames were rectangular prism-shaped, and were constructed of aluminum channels. The frame for the NOR pot had dimensions of 1.83 m x 1.83 m x 1.40 m made of 2.5 cm (1.0 inch) channel beams.

On top of both of these camera frames, we attached a large aluminum A-frame using rope and the under-water camera was then secured, facing downward (towards the interior of the frame) to the apex of this A-frame using metal fasteners. We attached a string of round trawl floats to the apex of the A-frame, which caused the camera to float up and above the cod pot/frame apparatus during deployment (Figure 2.1B). This provided the top-down viewing angle necessary for quantitative study of potting gear (see: Favaro et al., 2012). The camera was a SubC 1-Cam Alpha+ high-definition underwater video camera, built by SubC Imaging (Clarenville, NL). The battery for the underwater camera was stored in a plastic cylindrical housing, fastened into one of the interior corners of the camera frame, with a second housing secured to the opposite corner. This second housing contained a metal weight, used to counter-balance against the weight of the battery (Figure 2.1B).

We did not use external lights, because our camera-equipped pots were set at a shallow enough depth for ambient light to illuminate the pot during the day. Artificial light has been observed to have impacts on the behaviour of fish (Dragesund, 1958; Marchesan et al., 2005; Widder et al., 2005), and previous findings suggest that cod are typically more active during the day (Løkkeborg and Fernö, 1999). Therefore, we restricted our video analysis to clips where daylight provided enough illumination for observation. As a result of this decision, the length of observable video varies for each deployment depending on time of day, water depth, and weather conditions.

2.3.2 Fieldwork

We conducted our fieldwork in the nearshore waters, within 5.00 km (2.70 nautical miles) of southern Fogo Island, NL (Figure 2.2), for a three-week period during August and September 2015. We recorded our videos during the small-scale Atlantic cod stewardship fishery operating during that same time period. Our field work was conducted on the 10.4 m (34 foot) fishing vessel *Dean & Michael*, operated by commercial fishers based in Seldom, NL. We deployed our camera-equipped pots in areas where commercial fishing experience suggested that cod density would be sufficient to support commercial fishing.

We programmed our camera to record continuously from the time of gear deployment until recovery, which was typically the following day. Soak times (i.e. the amount of time between camera deployment and retrieval) were as close to 24 hours as possible, but varied due to logistical constraints such as weather (Table 2.1). Our decision to use 24-hour soak times was consistent with the soak times used by commercial fishers, and were similar to those used in previous studies conducted with gillnets (Gearin et al., 2000). Following the retrieval of our camera, we recorded the total catch (of cod and bycatch) within the camera-equipped pot, and then re-baited the pot for its next deployment using five frozen squid (*Illex illecebrosus*). Squid were used as bait based on the commercial fishing experience of our fishery partners, as well as previous studies which demonstrated the effectiveness of this bait type (Furevik and Løkkeborg, 1994). Five frozen squid per deployment was sufficient bait for this experimental design, as previous studies have successfully captured cod using as few as three frozen squid per deployment (Furevik et al., 2008). We downloaded the videos from the camera's onboard memory after each deployment, and connected a fully charged battery for the next deployment.

To determine if the presence of our camera apparatus affected the catch rates of our pots, we compared the catch-per-deployment of camera-equipped NOR pots with the catch rates of 72 commercially fished NOR pots within the same fishing region. NOR pots with cameras were deployed one-at-a-time, while the non-camera NOR pots were fished in connected ‘fleets’ of four or five pots. We used the same type and amount of bait (5 frozen squid) in these commercially fished pots as well as our camera pots. To compare the catch rates between camera and non-camera pots, we used generalized linear mixed-effects models (GLMMs; Zuur et al., 2009). We built a model that measured the impact of the fixed effect of camera presence or absence on catch-per-deployment. We included Fleet ID as a random effect to account for the fact that non-camera NOR pots were nested within fleets. The distribution of our catch data was best explained by a negative binomial distribution. Residuals met the assumptions for homogeneity, normality, and independence.

2.3.3 Video Analysis

At the conclusion of the field study, we watched all the videos. Our camera provided a top-down viewing area of approximately 1.80 x 3.27 meters around the NOR pot. We recorded the following quantitative parameters from each video: prevailing direction of water movement (in each 1-minute segment of video), the number of each cod that approached the pot and the direction approached from, the number and direction of cod that attempted to enter the pot, and the proportion of those entries that were successful, and the number of cod that exited the pot after entering it. We defined an approach as a cod entering the visible area of the video. Note that if a fish was to swim towards the pot, swim away, and then return to the visible area of the video, we would record this as two separate approaches. The cumulative number of successful entrances over time (minus exits) gave us the total number of cod in the pot at any given time across the deployment. After the overnight soak, we manually counted the number of cod visible in the pot to give us an estimate of the number of cod in the pot in the morning. From that point, we resumed calculating the total number of cod in the pot as a sum of the number of entries minus exits over time.

We recorded the direction of cod approaches, entry attempts, and successful entrances, in relation to the direction of water movement. We scored these factors as occurring with-current, against-current, or perpendicular to the current. For instances when an approach was made while the current direction was not clearly determinable, due to visibility, camera movement, or turbulent water movement, we excluded that approach from this part of our analysis.

We defined an entry attempt as an instance where any portion of an individual cod's body crossed over the exterior limit of the funnel mesh for either entrance of the pot. We recorded the total number of attempts, and which entrance (with-current, against-current, or perpendicular-current) the attempt occurred at. The result of every entrance was scored as either a failed attempt, where the individual retreated out from the entrance funnel, or as a success, where the individual's full body crossed over the ending of the interior portion of the entrance funnel mesh, and into the body of the pot. We defined a successful entrance as an instance where the whole body of an individual cod crossed over the interior limit of the funnel mesh for either entrance of the pot. We recorded the total number of successful entrances, and which entrance (with-current, against-current, or perpendicular-to-current) the success occurred at. We assessed whether there was an association between the type of interaction (approaches, entry attempts, and successful entries) and direction of water movement (against-current, with-current, and perpendicular), using a chi-squared test.

The project was reviewed and approved by Memorial University's Institutional Animal Care Committee (Project # 15-03-BF).

2.4 Results

2.4.1 Camera impact

We found no impact of the presence of the camera on cod CPUE (GLMM: $\beta = 0.10$, S.E. = 0.21, $z = 0.48$, $p = 0.63$). The mean catch rates of cod per deployment (± 1 S.E.) for NOR pots without cameras was 25 ± 1 compared to 27 ± 6 for NOR pots with a camera.

2.4.2 Video analysis

We deployed our video apparatus six times with the NOR pot (Table 2.1). Deployment depths ranged from 28.35 to 44.99 meters (mean ± 1 S.E. = 36.21 ± 2.91). Soak times ranged between 17.52 and 68.04 hours (mean ± 1 S.E. = 29.06 ± 7.87). Soak times did not always match video length because we were not always able to retrieve and deploy the camera frame at the same times every day due to inclement weather, and in one instance our battery did not have sufficient charge to last until retrieval. From these six deployments, we collected approximately 135 hours of under-water video footage. Video recordings ranged from 18.15 to 28.12 hours for NOR pots (mean ± 1 S.E. = 23.39 ± 2.30). Of the 135 hours of video collected, 56.10 hours had sufficient ambient lighting to undergo quantitative analysis, as a result of our decision to not use supplementary illumination, and varying levels of ambient light. We analyzed all 56.10 hours of observable video collected for the NOR pot.

We observed a total of 19,940 approaches by cod across all six deployments (Table 2.2, Figure 2.3), and we observed between 389 and 9,349 total cod approaches (mean ± 1 S.E. = 3,323 ± 1,516) per deployment. It took 11.3 minutes on average for the first cod to approach a pot (N = 6, S.E. = 8.4, range = 1 – 53 min; Figure 3), and it took 51.9 minutes on average for the first cod to successfully enter the pot (N = 6, S.E. = 26.2, range = 4 – 157 min; Figure 3). We observed a total of 34 cod exit the pots across all six deployments (Table 2.2, Figure 2.3).

There were very few entry attempts relative to the number of approaches towards the pot by cod, with only 3.2% (N=635) of the number of entry attempts relative to approaches (N=19,940; Table 2.2). The proportion of entry attempts that were successful was similarly low; across six deployments, 635 cod attempted to enter, with only 137 (22%) successfully entering the pot (Table 2.2). Of those 137 cod that were able to successfully enter the pot, 25% (N=34) were able to exit prior to retrieving the gear (Table 2.2).

We were able to successfully quantify the water direction for 9,652 approaches for the NOR pot (N = 10,288 approaches occurred during sections of video where the water direction was unable to be accurately determined due to variable currents, reduced visibility, and camera movement). A total of 50.0% (N=4,821) of cod approached the pot from the down-current direction, with 27.3% (N=2,639) approaching perpendicular to the pot, and 22.7% (N=2,192) approaching from the upstream direction (Figure 2.4). For entry attempts compared to water direction, we were able to successfully quantify the water direction for 359 entry attempts. We observed 250 entry attempts (70%) at the downstream (against-current) facing entrance, with 67 entry attempts (19%) occurring at the upstream (with-current) facing entrance, and 42 attempts (11%) occurring when the current was perpendicular to the entrances (Figure 2.4). For successful entries into the pot, we were able to successfully quantify the water direction for 73 successful entries. We observed 53 successful entry attempts (73%) at the downstream (against-current) facing entrance, 14 successful entry attempts (19%) at the upstream (with-current) facing entrance, and 6 successful entrances (8%) occurring when the current was perpendicular to the entrances (Figure 2.4). Through our chi-squared test, we rejected the null hypothesis that there was no relationship between the count of approaches, entry attempts, and successful entries and water direction ($\chi^2 = 69.9$, df = 4, $p < 0.001$).

We observed only three non-target species approach the NOR pot across all six deployments. The non-target species most observed was toad crab (*Hyas araneus*) which approached the pot 154 times total across all six deployments. We observed between 0 and 66 toad crab approach the NOR pot per deployment (mean ± 1 S.E. = 25.67 ± 11.95), with only five individual toad crab successfully entering the NOR pot across all six deployments. We saw 30 approaches by short horn sculpin (*Myoxocephalus scorpius*), and two approaches by a species of flatfish (order Pleuronectiformes). Neither of these successfully entered the pot.

2.5 Discussion

Although NOR pots were able to successfully capture cod, the majority of entry attempts were not successful. The low proportion of successful entries into the NOR pot appears to be a result of the direction of water flow relative to the pot orientation. We observed that a greater number of cod approached the NOR pot from the down-current direction. In addition, a greater number of entry attempts and successful entrances occurred at the down-current facing entrance. These observations are consistent with previous research which has described that cod will approach bait from the down-current direction (Løkkeborg et al., 1989). We also observed many instances of individual cod or groups of cod approaching the pots and attempting entry from the down current direction, regardless of the actual entrance location, resulting in cod attempting to push through the mesh at places where an entrance was not present. This indicates that in order for a pot to maximize its catch efficiency, at least one of the pot's entrances should be in line with the down-current water direction, to ensure cod are able to locate the entrance. Our finding supports the logic of Scandinavian fishers who have used floating pots that can orient in the direction of water movement (Bryhn et al., 2014; Furevik et al., 2008; S. J. Königson et al., 2015). Alternatively, future designs could feature entrances on all sides of the pot so that at least one will line up with the down-current direction, although this modification could also have the potential to increase the number of exits of cod once captured. One limitation of this study design was that the 19,940 approaches by cod did not likely represent 19,940 individual fish – since each approach by an individual fish that repeatedly re-enters the visible frame would be counted separately. This meant that we were only able to know how efficient the pots were relative to the number of approaches made by cod, in contrast to knowing how efficient the pots were relative to the actual number of cod in the vicinity of the pot.

We found that cod were able to exit pots, but that exits were uncommon. These exits were observed as early as 8 minutes following the start of a deployment, indicating that cod are able to locate the exits to the pots earlier than expected based on previous studies (S. J. Königson et al., 2015). One issue that needs to be addressed with the NOR pot to reduce exits is the distance separating the two entrance funnels. The small size of the pot in conjunction with the entrances directly opposing one another results in cases where cod successfully enter the pot through one entrance, but then swim right through and exit via the opposite opening. The majority of cod that successfully entered the NOR pot swam into the pot's upper chamber, and did not generally return to the bottom chamber. The majority of cod that escaped did so before entering the upper chamber.

For the majority of our video deployments, we also observed that there were fewer successful entry attempts made by cod following the overnight period (Figure 2.3). We propose two non-exclusive hypotheses for this observation. First, the bait may be less attractive as time goes on, either because its mass is reducing due to consumption, or because of bait plume depletion. Previous literature has shown that high release rates of attractants from bait is required to attract fish to fishing gears (Løkkeborg and Johannessen, 1992), and this may indicate why fewer successes are observed following the overnight period in our videos. Second, the pot may approach saturation in the early morning period e.g. Ovegard et al. (2011). However, we find the second hypothesis uncompelling because our six pots – which were effectively identical – appeared to 'saturate' at very different densities.

From our video observations, typically, following successfully entry into the pot, cod individuals would interact with the bait bag, and then swim upwards and enter the upper chamber of the pot. Once inside the upper chamber of the pot, the majority of fish begin exhibiting positive rheotaxis. Occasionally, an individual may exhibit escape behaviours once inside the pot, indicated by excited movements and attempting to press through the mesh walls of the pot with their snouts. This behaviour has been observed in previous research (Renchen et al., 2012), and could be motivated by cannibalistic behaviours between trapped cod individuals (Bogstad et al., 1994). However over time these individuals eventually resume rheotaxis, and for videos recorded in the morning, following an overnight soak, the majority of all fish within the pot were exhibiting rheotaxis simultaneously. For undersized or juvenile cod who become trapped in pots, larger mesh escape panels can be installed to allow for escape, reducing undesirable catches for the fishers (S. J. Königson et al., 2015; Ovegård et al., 2011).

Very few non-target species approached our deployed pots, with only 186 total approaches observed for toad crab, sculpin and flatfish combined, across all six deployments, with only five toad crab successfully entering the pot. We saw no instances of non-caught individuals becoming trapped or entwined in the mesh of the pots. This stands in contrast to traditional commercial cod fishing gears, such as gillnets, which can substantially reduce seabird populations as a result of bycatch (Regular et al., 2013), and which can ensnare substantial numbers of marine mammals as well (Kastelein et al., 1995; Read et al., 2006). Toad crab made up the largest proportion of bycatch for the NOR pots, and minimizing this bycatch could be a goal for future improvements to the design of this gear. An alternative strategy is to acknowledge this bycatch in the conditions of fishing licenses, require fishers to land it, and manage as a multispecies fishery (e.g. Gislason et al., 2000; Grafton, Nelson & Turris, 2004). The presence, and orientation of the two chambers within the NOR pot could even allow for multi-species targeting, with shellfish accumulating in the lower chamber, and cod within the upper chamber, if a multi-species fishery were established.

2.5.2 Implications for pot design

We found that NOR pots (when baited with squid) are successful at attracting a large number of cod towards the vicinity of the pot, and that the pots are able to successfully retain the vast majority of their caught cod, with only a small proportion escaping. However, the proportion of cod within the vicinity of the pot that attempted and successfully completed entry attempts could be improved. Therefore, we suggest that future cod pot designs should feature an increased number of entrances, or a mechanism allowing for the orientation of entrances in-line with the downstream current direction, in order to increase the number of entry attempts and successful entries by cod.

At present, the financial viability of cod pots as the primary harvesting tool for cod fishers in NL is uncertain. The cod pots we tested were prototypes built for research purposes. Determining the large scale viability of pots requires data on many variables, including the initial cost for purchasing a fleet of commercial cod pots, average fuel costs to harvest a commercial fleet of pots, average mass of cod collected from a fleet of pots, and the sale price of Atlantic cod paid to the fishers (which is variable depending on the quality of the caught cod).

Pots are generally considered a low-impact fishing gear, because of their reduced bycatch, live discards, and reduced fuel consumption (Suuronen et al., 2012). In addition to these benefits, pots have been observed to have higher discard survivability, with previously captured cod, becoming re-captured in pots following release, in successive deployments (Pol and Walsh, 2005). The greater survivability of pot caught individuals, could provide increased options to fisheries managers with regard to management decisions on the required landing of discards. Basing a resurgent cod fishery on pots therefore stands to produce conservation benefits relative to other gears. The information gained from this research indicates that NOR pots are generally well-designed for catching cod selectively, but there remains opportunity for improvement. Specifically, that the bottleneck in capture appears to occur at the entrances, and modifications to improve entry rates could greatly enhance the efficiency of this fishing gear.

2.6 Supplementary Methods

2.6.1 Specifications for the NL cod pot

The NL pot is large (2 x 2 x 1 m) and comprises a frame built of round reinforcing steel, covered by polyethylene mesh (100 x 3 mm; Walsh & Hiscock, 2005; Supplemental Figure 2.1). The NL pot has two offset entrance funnels, typically constructed with white nylon mesh. The interior end of these entrance funnels contains a metal retention device known as a trigger, which uses long metal finger-like projections to allow one-way movement into the pot, and to prevent escape. At the top of the pot, there is a large expandable mesh roof, known as a cod-end, which is supported by floats that extend upward during the pot's deployment.

We constructed a large aluminum camera frame for each model of pot (Figure 1B). Both frames were rectangular prism-shaped, and were constructed of aluminum channels. For the NL pot, the frame dimensions were 2.44 x 1.83 x 1.22 m, using square aluminum channel beams 3.8 cm (1.5 inches) in width.

It was our intent to perform a full quantitative analysis on videos collected with both pot types. However, the floating cod-end of the NL pot obstructed our camera, and therefore we had to modify the pot to provide a clear field of view. This distorted the geometry of the pot, and drastically reduced catch rates relative to NL pots without cameras. Therefore, we limited our analysis of NL pots to qualitative observations only, noting the behaviours of cod and other species in and around pots. For the NOR pot, we recorded both qualitative and quantitative data.

2.7 Supplementary Results:

We deployed our video apparatus four times with the NL pot (Supplementary Table 2.1). From these four deployments, we collected approximately 79 hours of underwater video footage. Video recordings ranged from 5.63 to 30.73 hours for NL pots (mean ± 1 S.E. = 19.66 ± 5.51). Of the 79 hours collected, 30.25 hours had sufficient ambient lighting to undergo quantitative analysis, as a result of our decision to not use supplementary illumination, and varying levels of ambient light. We analyzed all 30.25 hours of observable video collected for the NL pot.

Although our apparatus made quantitative analysis of the NL pots impossible, we were able to make qualitative observations of its performance. We found that cod typically attempted to enter the NL pot through the mesh at heights similar to the height of the bait bag, inappropriate for successful entry. This could indicate that the bait bag needs to be closer to the bottom of the pot, or at least level with the entrance funnel height. The inappropriate height of the bait bag might not only affect entrance attempts, but could also influence the detection of the bait bag and bait plume, which may at least partially explain why we observed fewer cod approaching the NL pots, because correct bait plume orientation with pot entrance funnels and current direction are important factors influencing a pots catchability (Pol et al., 2010). We have also observed many cod entry attempts deterred by the presence of the metal triggers, similar to the observations made by Olsen, 2014. Individual cod change direction and exit the entrance funnels following contact with the triggers, however small cod pass between the triggers' rods without contact.

2.8 Tables

Table 2.1. Summary of camera deployments for NOR pots.

Deployment number	Pot type	Start date	Start time	End date	End time	Observed video time (mins)
1	NOR	19/08/2015	15:15:00	20/08/2015	8:46:28	281
2	NOR	20/08/2015	10:34:28	21/08/2015	12:15:13	651
3	NOR	21/08/2015	15:47:00	22/08/2015	12:51:27	555
4	NOR	22/08/2015	14:46:30	23/08/2015	12:54:10	431
5	NOR	23/08/2015	14:48:06	26/08/2015	10:50:43	950
6	NOR	26/08/2015	16:12:37	27/08/2015	12:05:35	498

Table 2.2. Summary of cod behaviour in the vicinity of NOR cod pots. Behaviours are summarized per camera-pot deployment, Deployment ID corresponds to one of our six camera-attached NOR pot deployments, approaches corresponds to the number of cod observed to enter the field of view (FOV) of the video recording, and entry attempts describes the total number of observed attempts to enter the pot. An exit describes when a cod that was already successfully caught within the pot, managed to escape the pot back into open water.

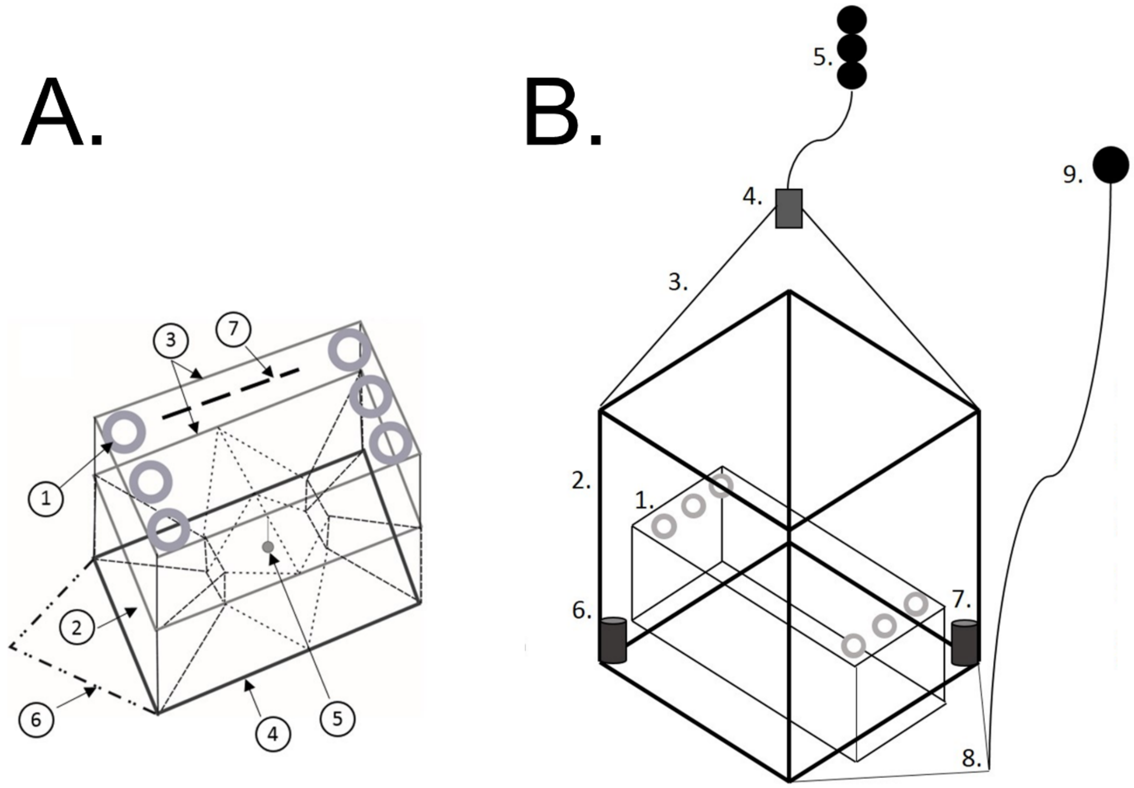
Pot type	Deployment ID	Approaches	Entry attempts	Successful attempts	Failed attempts	Exits
NOR	1	389	35	11 (31%)	24 (69%)	0
	2	988	71	21 (30%)	50 (70%)	8
	3	524	48	7 (15%)	41 (85%)	3
	4	9349	187	37 (20%)	150 (80%)	3
	5	2265	146	41 (28%)	105 (72%)	15
	6	6425	148	20 (14%)	128 (86%)	5
Total		**19940**	**635**	**137 (22%)**	**498 (78%)**	**34**

2.9 Supplementary Tables

Supplementary Table 2.1. Summary of camera deployments for NL pots.

Deployment number	Pot type	Start date	Start time	End date	End time	Observed video time (mins)
7	NL	29/08/2015	12:39:30	30/08/2015	14:17:51	795
8	NL	30/08/2015	16:32:47	31/08/2015	9:08:00	109
9	NL	31/08/2015	10:23:00	1/9/2015	8:40:32	338
10	NL	1/9/2015	10:17:38	3/9/2015	7:16:37	573

2.10 Figures



1. Float
2. Entrance
3. Aluminum frame
4. Steel frame
5. Bait bag
6. Lanyard to connect to mainline
7. Nylon zipper

1. NOR pot
2. Camera frame
3. A-frame camera mount
4. Underwater camera
5. Camera flotation
6. Battery and housing
7. Counter balance weight
8. Lanyard attachment
9. Surface float

Figure 2.1. Diagrams representing the gears used during our field research. Figure 1A is a diagram of Norwegian (NOR) pot, as it would appear deployed on the sea bottom. Figure 1B is a diagram of the camera frame apparatus created for this study, with a NOR pot attached to the frame.

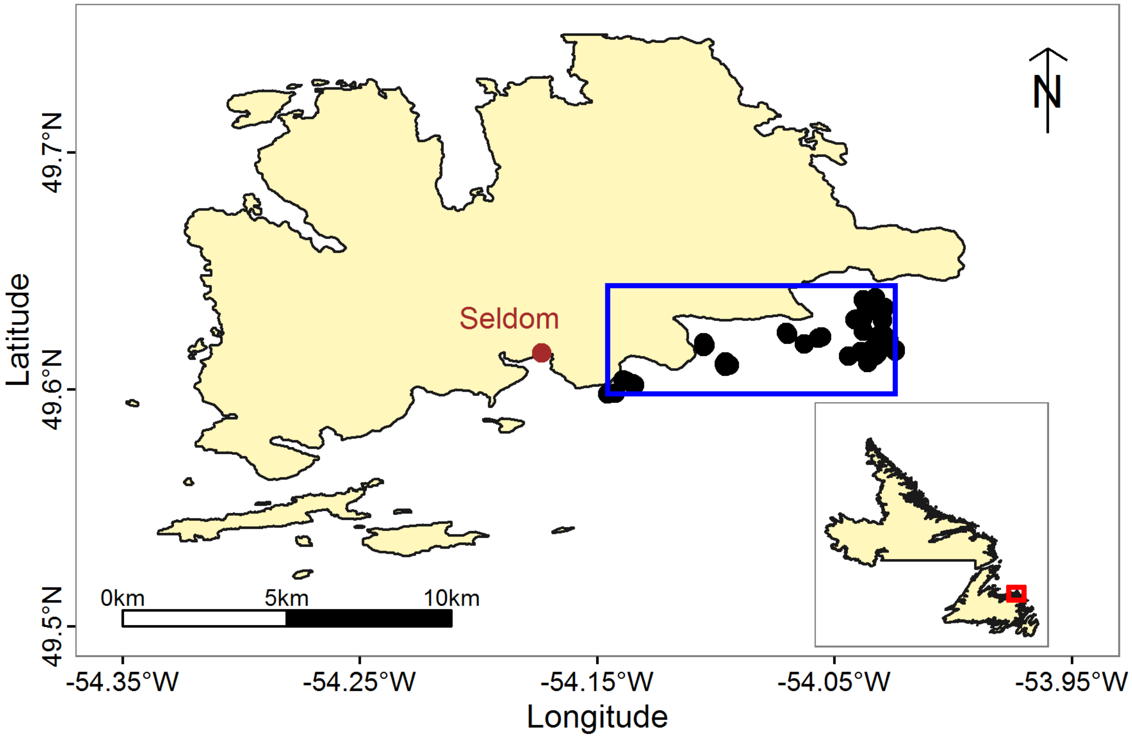


Figure 2.2. Map of our study site, off of the southern coast of Fogo Island NL. Black points indicate locations where we deployed camera-equipped pots. The blue rectangle indicates the larger fishing region of our industry partner. The red square on the inset map indicates the location of Fogo Island relative to the rest of NL.

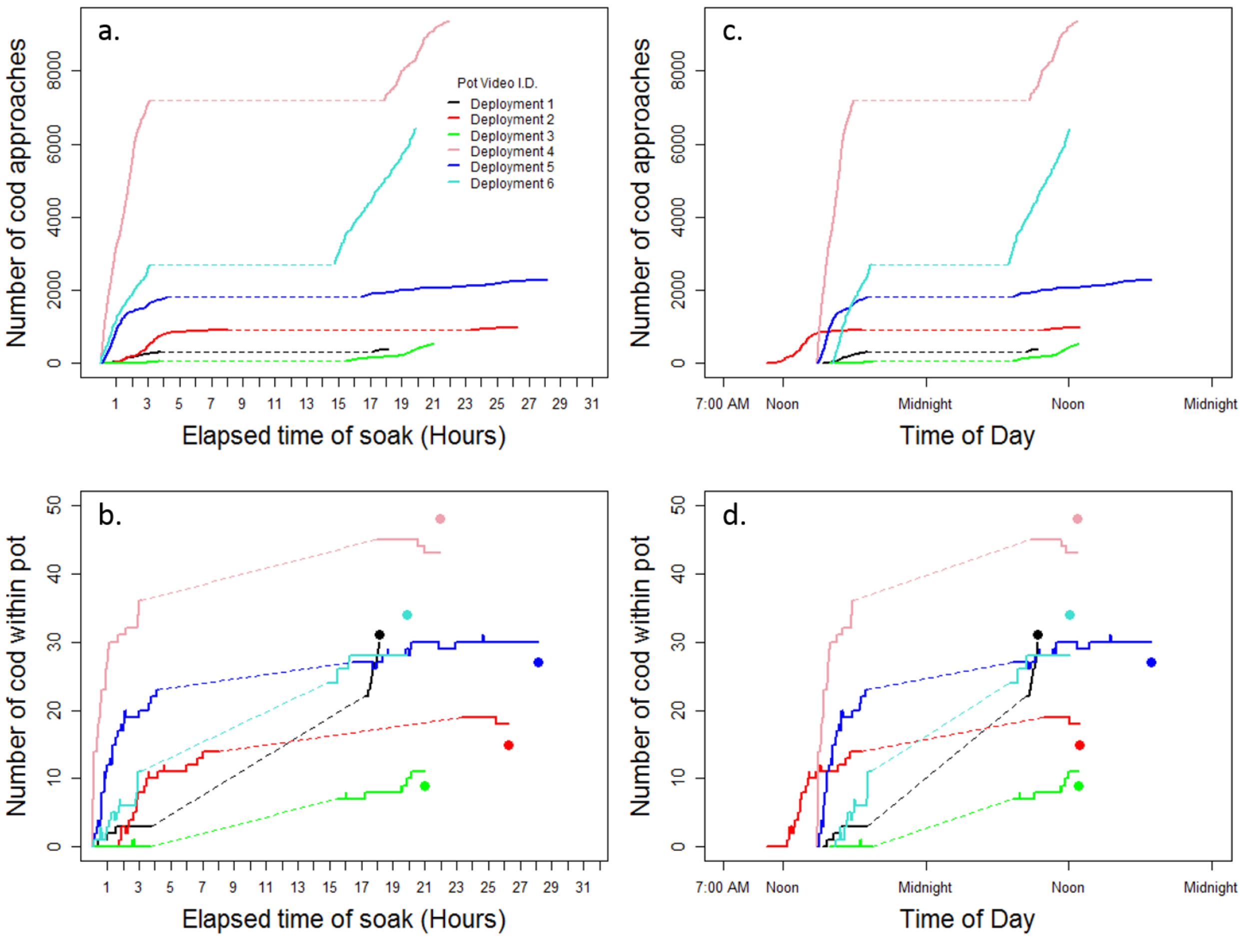


Figure 2.3. Comparison of Atlantic cod accumulation for NOR pots, over the course of both elapsed time and real time for each deployment (N = 6). Plots A and B display the accumulation over the elapsed soak time, whereas plots C and D display the accumulation over real time. Approaches by cod are shown in both A and C, and the accumulation of cod successfully within the pot are shown in B and D. Each colored line represents and individual deployment. Dashed lines represent time periods where camera footage was absent (due to low-light conditions). Coloured circles in plots C and D represent the final catch of each pot deployment. Lines represent observed catches, and dots represent the actual landed catch, recorded at sea, when the pot was hauled.

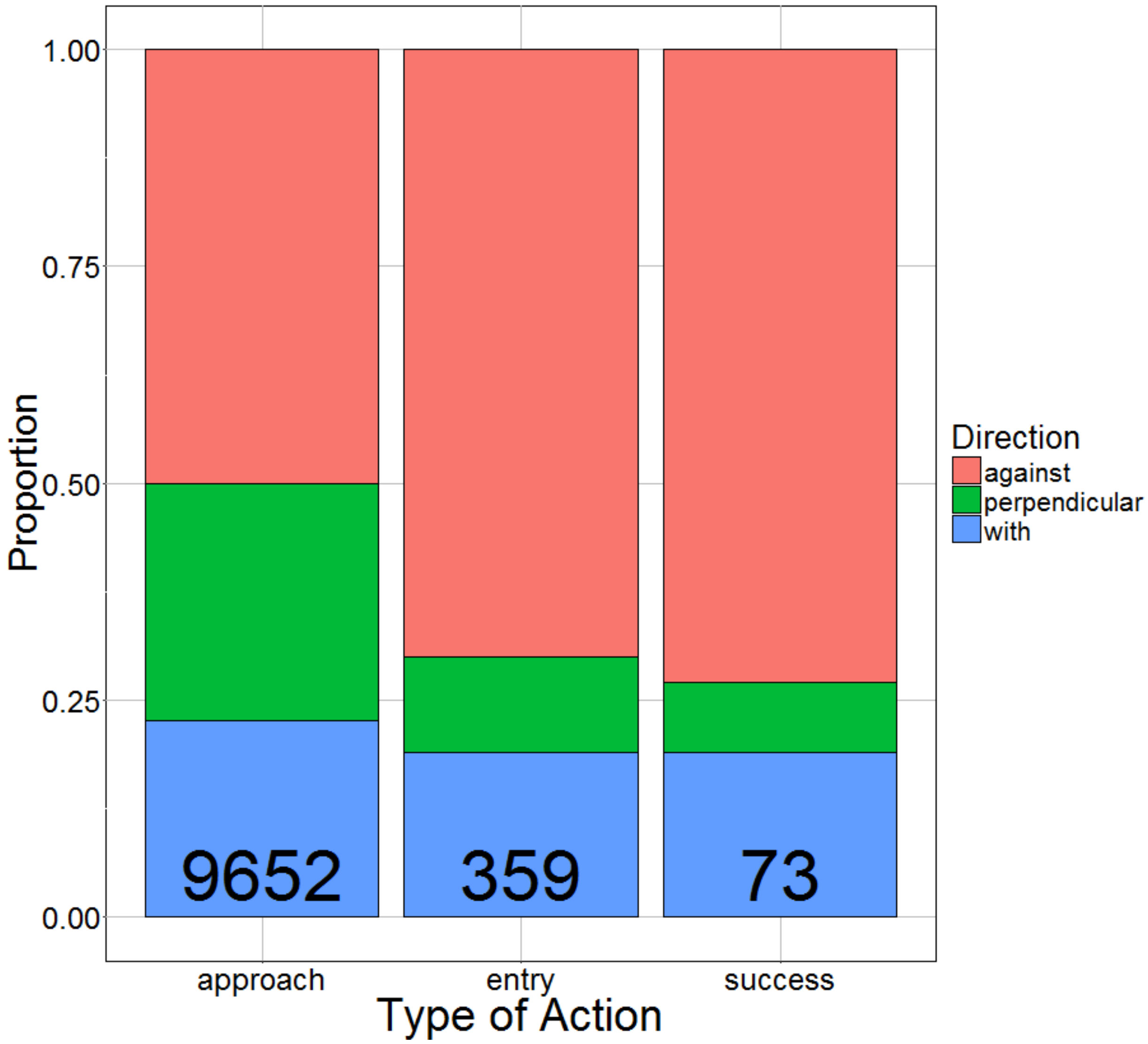
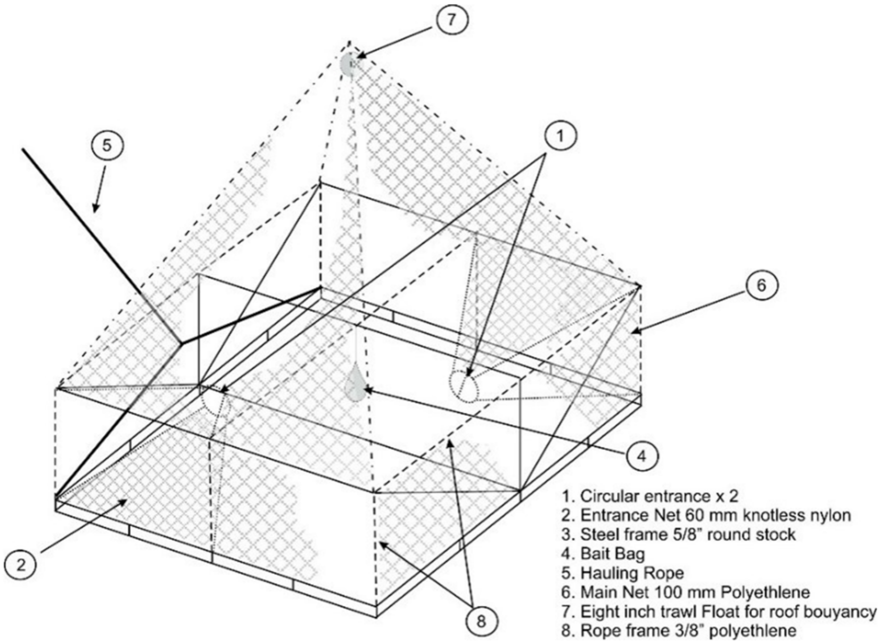


Figure 2.4. The proportions of approaches, entry attempts, and successes, occurring from the with-current, against-current, and perpendicular-current direction for the NOR pot. Numerical values represent the total number of actions (approach, entry attempt, or success) observed.

2.11 Supplementary Figures



Supplementary Figure 2.1. Diagram representing the Newfoundland (NL) cod pot used during our field research.

2.12 Acknowledgements

We acknowledge our fisher partners Aubrey Payne, Marie Payne, and Rodney Budden for the use of their fishing vessels and assistance with fieldwork. We thank Gordon Slade and the Shorefast Foundation for logistical support of this project. We also acknowledge Rennie Sullivan for assistance in constructing the camera apparatus. We thank one anonymous reviewer, Sara Königson, and Chris Barrett for their constructive reviews of the manuscript, which greatly enhanced the final paper.

We would like to respectfully acknowledge that the lands on which we conducted our fieldwork are situated in the traditional territories of the Beothuk indigenous group, and we acknowledge the diverse histories and cultures of the Beothuk of this province. We strive for respectful relationships with all the peoples of this province as we search for true reconciliation and honour this beautiful land together.

Chapter 3: Comparing catch efficiency of five models of pot for use in a Newfoundland and Labrador cod fishery

3.1 Abstract

Sustainability of commercial fisheries is best achieved when fishing gears are selective and have low impacts on bottom habitat. Pots (baited traps) are a fishing technology that typically has lower impacts than many other industrial gears. In this study we compared the efficiency of five models of pots (baited traps) designed to catch Atlantic cod (*Gadus morhua*) for use in Newfoundland and Labrador (NL)'s expanding cod fishery. We compared catch per unit effort (CPUE) and total lengths of cod across each pot type, as well as bycatch rates of each model.

All pot types were effective at catching cod, but that two models (the modified Newfoundland pot, and a four-entrance pot of our design) had highest CPUE. Specifically, we found that modifying Newfoundland pots increased their CPUE by 145% without a corresponding increase in bycatch. None of the pot types produced substantial amounts of bycatch. This study demonstrated that potting gear is an effective way to catch cod in NL, and that there is flexibility in which pot fishers can use, depending on the layout of their fishing vessel.

3.2 Introduction

Pots (also commonly referred to as traps), are cage-like, stationary fishing gears widely used in commercial fisheries throughout the world (Anders et al., 2016; Cole et al., 2003; Furevik and Løkkeborg, 1994; Moran and Jenke, 1990). Pots are transportable, and typically use bait to attract target species, with retention devices to prevent their escape (Suuronen et al., 2012). The benefits of using pots include decreased rates of bycatch (Pol et al., 2010), minimal impacts to marine habitats, and a reduced contribution to ghost fishing (when constructed with biodegradable twine) when compared to gillnets (Suuronen et al., 2012). Pots have also been classified as a 'Low Impact and Fuel Efficient' (LIFE) fishing gear, because they require less fuel to harvest than towed fishing gears such as trawls and dredges (Suuronen et al., 2012). In addition, fish trapped in pots remain alive and unensnared until the gear is retrieved (Meintzer et al., 2017; Walsh et al., 2006). As a result, meat quality of pot-caught fish often exceeds that of other gears where the act of capture imposes immediate damage to the fish (Pol et al., 2010). In addition, trapped species not intentionally targeted by fishing (i.e. bycatch) can generally be returned to the water with a high chance of survival (Suuronen et al., 2012).

In Canada, pots are currently used to capture many species, including spot prawns (*Pandalus platyceros*) (Favaro et al., 2010; Fisheries and Oceans Canada, 2017a) and sablefish (*Anoplopoma fimbria*) (Fisheries and Oceans Canada, 2017b) in British Columbia, and snow crabs (*Chionoecetes opilio)* in Newfoundland and Labrador (NL) (Winger and Walsh, 2011). These fisheries are widely regarded as highly sustainable, and they have been recognized by eco-certifications such as Oceanwise and Seachoice (Ocean

Wise Conservation Association, 2017). In the case of spot prawns and sablefish in particular, collectively these fisheries produced a landed value of 50.6 million dollars in 2013, and both species fetch a high market value per kilogram (British Columbia Ministry of Agriculture, 2013). These fisheries demonstrate the viability of pots as a foundational fishing technology for sustainable fisheries.

In NL, there have been calls to establish a re-emerging fishery for Atlantic cod around the concept of value-maximization – using gears and fishing techniques that maximize quality and enable fishers to achieve higher landed value for their catch (Simms, 2017). Large-scale commercial fishing for Atlantic cod in NL ceased with the moratorium on the cod fishery in 1992, but recent increases in the population (Rose and Rowe, 2015) have resulted in fishers and some members of the general public to call for increases in quota and corresponding increases in fishing effort (Fisheries and Oceans Canada, 2017c; Roberts, 2017). If an expanding fishery is to be built on high-value catch, the industry will need fishing gears capable of ensuring high quality of captured fish with sufficient efficiency to be economically viable.

Pots represent a reduced-impact gear that could play an increased role in an expanded NL cod fishery. While pots are not widely used in NL to catch cod, where only a small group of commercial fishers on Fogo Island, NL, have been using experimental pots since 2007 (Walsh and Sullivan, 2010) as part of the annual stewardship fishery for cod (i.e. the small commercial fishery that has permission to occur every year despite the ongoing moratorium) (Fisheries and Oceans Canada, 2016a, 2016b). However, potting has not yet been widely adopted as the primary fishing gear in the region, with the majority of fishers still using gillnets or hand-lines.

For pots to be a viable fishing gear, they must be designed around efficiency, selectivity, usability and safety, and ease of procurement. Each of these factors ultimately affect profitability and environmental impact of the gear, and therefore, the likelihood that fishers will adopt it. Modifications to any part of a pot can drastically alter its catch composition (Ljungberg et al., 2016). For example, pots with smaller mesh size were found to have greater catch rates than pots with larger mesh in an Australian fishery (Sheaves, 1995). In Norway, adding floats to pots for Atlantic cod reduced the bycatch of crustaceans when compared to bottom set pots (Furevik et al., 2008). Modifying the ability of organisms to exit the pot is important too – for example, escape mechanisms have been found to reduce the catch of undersized snow crab (*Chionoecetes opilio*) in Canada (Winger and Walsh, 2011), and the use of funnel shaped entrances resulted in an increased catch of Atlantic cod compared to entrances lacking funnels, by preventing escapes from pots fished in the Baltic Sea (Ljungberg et al., 2016). Even pot orientation matters – in a previous study, we found that existing pots needed to ensure at least one entrance is in-line with the downstream current direction to increase successful entries by Atlantic cod (Meintzer et al., 2017). These examples demonstrate the considerable effect that pot designs can have on their catch efficiency and composition.

In this study we assessed the effectiveness of five different types of pots at catching Atlantic cod, using catch and length data collected during field trials of experimental pots aboard commercial fishing vessels, over the course of two consecutive fishing seasons during the summers of 2015 and 2016. We tested these gears in real-world field conditions – aboard industry vessels fishing during the annual stewardship fishery (Fisheries and Oceans Canada, 2016a). We compared catch-per-unit-effort

(CPUE) and body sizes of captured cod across pot types. In addition, we compared bycatch rates across pot types, and qualitatively assessed their ease of use at sea. Finally, we obtained and reported summary statistics of opportunistically-acquired data comparing landed fish quality across pots, gillnets, and hook-and-line gears.

3.3 Materials & Methods

3.3.1 Field studies

We conducted two separate field experiments comparing the CPUE of Atlantic cod across several pot designs. Both studies took place within 5 km of southern Fogo Island, NL (Figure 3.1). The first experiment occurred between Aug 20 and Sept 1, 2015, and the second between Aug 22 and Sept 2, 2016. We selected these dates so our experiment would take place during the annual stewardship fishery ("Fisheries and Oceans Canada: 2016 Northern Cod Stewardship / By-catch Fishery 2J3KL management approach," 2016; Fisheries and Oceans Canada, 2016b). This enabled us to conduct our experiment aboard industry vessels conducting actual commercial fishing operations, meaning our CPUEs are likely to reflect realistic in-season fishing performance. Our experiments took place aboard the 10.4 m (34 foot) fishing vessels *Dean & Michael*, and the *Beverly Crystal*, operated by commercial cod fishers based in Seldom, NL.

3.3.2 Pot selection and development

In the first experiment we tested two pot models: Newfoundland-style pots (hereafter NL), and Norwegian-style pots (hereafter NOR). We selected these pot types for comparison because both are currently in use in fisheries targeting cod; the former, by a small group of fishers on Fogo Island NL (Sullivan and Walsh, 2010), and the latter by fishers in Norway and Sweden (S. Königson et al., 2015; S. J. Königson et al., 2015; Olsen, 2014; Ovegård et al., 2011). In our second experiment, we assessed five pot types: NL, NOR, modified NL (NL-mod), modified NOR (NOR-mod), and a four-entrance pot of our design (4-ent). All models of pot are described below.

3.3.3 Specifications of NOR, NL, NOR-mod, NL-mod, and 4-ent pots

The NL pot was a large pot (2 x 2 x 1 m), with a heavy frame constructed of round reinforcing steel (Figure 3.2 A). The frame of the NL pot was composed of a square bottom, connected to four collapsible steel beams which extend from a central pivot point to form the sides of the pot. The collapsibility allowed easy transportation and storage of the pot when not in use. The NL pot had two offset entrance funnels, typically constructed with 58 mm white diamond knotless nylon mesh. These funnels contained a metal retention device known as a trigger, which used long metal finger-like projections to allow one-way movement into the pot, and to prevent escape. The NL pots had a single bait bag suspended at the center of the pot, and contained a large expandable mesh roof, known as a cod-end, which extended upward during deployment using a flotation device. This netting panel (100 mm diamond polyethylene) covered the entire exterior of the pot and the netting was hung on the frame of the pot at approximately 65% of stretched mesh opening.

The NL-mod pot shared the same basic design as the NL pot, but with several modifications. We replaced the standard white 58 mm nylon mesh entrance funnels with 58 mm diamond monofilament netting entrance funnels, and removed the metal retention triggers. A mesh separator panel was added at the midway point up the vertical length of the pot using 58 mm mesh size black polyester netting, to divide the pot into upper and lower chambers. Finally, instead of a single bait bag suspended in the center of the pot, we used two smaller bait bags, each positioned in front of an entrance funnel.

The NOR pot was a two-chambered pot consisting of three rectangular frames in a collapsible structure (Figure 3.2 B, see also Meintzer et al. 2017). The bottom frame was made of steel (to provide weight on the pot's bottom), and the two frames above were both made of aluminum. Floatation attached to the top of the frame caused the pot to expand vertically underwater when deployed. The exterior netting on the pot was constructed of 58 mm black square nylon mesh. The pot was divided into upper and lower chambers by a mesh panel that extended midway through the horizontal axis of the pots. A slit in the dividing mesh allowed cod to enter the upper chamber. Zippers were present on the side of both the lower and upper chamber to allow for easy removal of fish and re-baiting of the pot. The two entrances of the NOR pot faced each other from opposite directions within the lower chamber, with a single bait bag suspended between them. The modified Norwegian cod pot (NOR-mod pot) was identical in structure to the NOR cod pot described previously (Figure 3.2 B), however we replaced the standard 58 mm mesh surrounding the exterior of the pot, with 100 mm black nylon mesh, which corresponded with the minimum mesh size for commercial cod pots as specified by Fisheries and Oceans Canada (DFO) (Fisheries and Oceans Canada, 2017d).

The 4-ent pot was a new pot we designed and constructed (Figure 3.2 C). The 4-ent pot was an intermediate size between the NOR pot and the NL pot (1.5 x 1.5 x 1.2 m), and featured a similar two-chambered, three-ring collapsible structure to the NOR pot. The bottom frame featured two cross beams and was made of 14 mm circular steel (to provide weight on the pot's bottom), while the two frames above were both made of 14 mm circular aluminum. To provide flotation to the upper rings, we used three 20.3 cm (8 inch) spherical trawl floats with a lifting force of 3.2 kg; two attached to the midway point on opposite sides of the upper aluminum ring and one in the cod-end that floated above the pot similar to the NL and NL mod pot. This allowed the pot to open vertically underwater, with the heavier frame sinking, while the upper frame and floats extended upwards. The pot was divided into two chambers by a mesh separator panel extending at the vertical midway through the horizontal axis of the pot, using 58 mm black nylon netting. A slit in the false bottom mesh allowed cod to enter the upper chamber. The 4-ent pot featured four entrance funnels in the lower chamber made of 58 mm monofilament twine, similar to the NOR pot, and all four entrances face towards the bait bag suspended in the center of the lower chamber. The exterior of the pot was constructed using two different netting materials, on the bottom and from the lower steel frame to the top aluminum frame we used 100 mm square mesh black polyethylene netting (1.2 to 1.5 mm twine diameter). From the top of the pot to the end of the cod-end which floated above the pot we used 100 mm green polyethylene netting (3 mm twine diameter) hung 50% of stretched mesh opening. We built the 4-ent pot with four entrances based on previous observations that cod primarily enter pot openings that are aligned with current direction (Anders et al., 2016; Meintzer et al., 2017), and therefore by having additional entrances, we would increase the likelihood of an entrance being in-line with the current. We embedded zippers on either in the mesh to facilitate removal of any fish snagged in the netting materials, and to allow access to the bait bags. The 4-ent pots used a single bait bag suspended at the center of the pot, and contained a large expandable mesh roof (a cod-end), which extended upward during deployment using a single round trawl float.

3.3.4 Catch comparison (Year 1 – 2015)

During our first study, to compare the difference in landed catch rates between the NL and NOR cod pots, we conducted daily deployments of 15 NL pots and 14 NOR pots along the southern coast of Fogo Island (Figure 3.1). Our intent was to deploy each pot every day, so that each pot would be fished for approximately 24 hours per deployment. In practice, due to constraints associated with weather, the needs of our industry partner, and other operational factors, the length of each deployment varied and not all pots could be retrieved each day. We selected deployment sites based on the expertise of our industry partners, selecting sites that they considered to have high densities of cod. We deployed NL and NOR pots in close proximity in the same fished area so that catch rates were comparable across gear types. However, over the course of our study, there were 14 deployments of NL pots that occurred in areas where no NOR pots were simultaneously deployed. Therefore, catch data from these 14 NL pots were excluded from our analysis.

At every pot deployment and recovery, we recorded the date, time, latitude, longitude and depth. Differences between latitude, longitude, and depth at deployment and recovery were negligible – i.e. our pots did not move during deployments.

Initially, we fished the NOR pots as one large ‘fleet’ comprised of 14 pots connected by a groundline (Figure 3.3). This is a viable fishing method for the smaller and lighter Norwegian pots because nesting pots within long strings reduces fuel consumption and handling time (N deployed in 14-pot strings = 28). However, we found that 14 pots was too many to handle on one string, especially when catch numbers were high. Therefore, we switched to fishing three fleets consisting of five, five, and four NOR pots respectively (N deployed in 5-pot strings = 35, and 4-pot strings = 12).

Upon the retrieval of pots following a deployment, we recorded the total length (TL) of each captured Atlantic cod, and the lengths and species identity of all individuals of non-target fish species caught as bycatch. Fisheries and Oceans Canada (DFO) stipulates that the proportion of landed catch of Atlantic cod below 45 cm in total length (TL) should not exceed 10% in a given fishing area (otherwise the fishing area should be subject to closure; Dave Coffin, Groundfish Resource Manager, DFO, personal communication), therefore we also recorded the number of cod ≤ 45 cm TL in each pot type. We also recorded the number and common name, but not the sizes, of non-target invertebrates caught in each pot. All bycatch species and undersized cod were returned to the water, while the rest of the cod were retained by our industry partner under their commercial fishing license.

Prior to re-deploying pots, we re-baited each pot with a single bait bag containing five frozen squid (*Illex illecebrosus*) – a standard approximate volume used by our industry partners. Squid were used as bait based on the commercial fishing experience of our fishermen partners who have used squid in previous experiments with cod pots (Walsh et al., 2006), as well as previous studies which demonstrated the effectiveness of this bait type (Furevik and Løkkeborg, 1994). Five frozen squid per deployment was sufficient bait for this experimental design, as previous studies have successfully captured cod using as few as three frozen squid per pot (Furevik et al., 2008).

3.3.5 Catch Comparison (Year 2 – 2016)

In our second study we compared differences in CPUE across NL, NOR, NL-mod, NOR-mod, and 4-ent pots. In this study (conducted in the same region as our first study), we nested pot deployments within "groups" – i.e. batches of five pots that contained one of each pot type (Figure 3). Our target deployment length was 24 hours, which in some cases was modified by the needs of our industry partner or due to weather. Once again, we selected deployment sites – based on the advice of our industry partner – that were likely to produce sufficient catch rates of cod to facilitate comparisons of catch efficiency across gears.

Because we always had all five pots within a group, fishing sites for all five pots always overlapped, therefore eliminating differences in catch among pots that could occur due to geographical location. In addition, we always retrieved groups in their entirety, ensuring that all pots within a group had nearly identical deployment durations. For every pot deployment and recovery, we recorded the date, time, latitude, longitude, and depth.

Deployment depths ranged from 33.5 to 59.1 m (mean ± 1 SE = 46.0 ± 0.6), and pots rarely moved between deployment and retrieval. Upon the retrieval of pots following a soak, we identified all organisms in the pot, counted and measured cod, and counted non-target invertebrate species (following identical procedures as the year 1 study).

3.3.6 Statistical analysis of catch comparison data

To measure the effect of both pot type and soak duration on CPUE, we used generalized linear mixed-effects models (GLMMs) [Equation (1), Equation (2)]. Our catch data violated many of the assumptions needed for parametric tests due to our catch data not being normally distributed, as well as the fact that NOR pots were nested within fleets during the 2015 field study, and that all five pot types were nested within groups during the 2016 study, and therefore could not be treated as fully independent observations. GLMMs allowed us to measure the effect of pot type on catch rate, while accounting for the non-normal distribution and nested structure of the data (Zuur et al., 2009). We used mixed effects modeling because our pot deployments were nested within fleets (for the first experiment) and groups (for the second). The distribution of our catch data for both years was best explained by a negative binomial distribution. Residuals met the assumptions for homogeneity, normality, and independence. For our analysis, we treated the standard NL pot as our control treatment, as it was the most used pot by Fogo Island fishers at the time of our study.

For the data collected in 2015, in our initial model, we tested the fixed effects of *pot type* (categorical factor, two levels) and *soak duration* (continuous variable), and tested for an interaction between the two variables, with fleet number as a random effect variable (Eqn 1). We then conducted stepwise model simplification, dropping non-significant terms one at a time until all terms in the model were statistically significant (Crawley, 2012). This procedure was repeated for data collected in both 2015 and 2016 field studies. (Equations are presented below as outlined in Zuur *et al.*, 2016). For data collected in 2016, in our initial model we tested the fixed effects of *pot type* (categorical factor, five levels) and *soak duration* (continuous variable), and tested for an interaction between the two variables, with group number as a random effect variable (Eqn 2).

$$\begin{aligned}
&\text{CatchPerDeployment} \sim NB(\mu_{ij}) \\
&E(\text{CatchPerDeployment}) = \mu_{ij} \\
&\text{CatchPerDeployment} = \beta_1 + \beta_2 \text{ x PotType}_{ij} + \beta_3 \text{ x SoakDuration}_{ij} + \beta_4 \text{ x PotType}_{ij} \\
&\text{x SoakDuration}_{ij} + \text{FleetID}_i \\
&\text{FleetID}_i \sim N(0,\sigma^2)
\end{aligned} \tag{Eqn 1}$$

$$\begin{aligned}
&\text{CatchPerDeployment} \sim NB(\mu_{ij}) \\
&E(\text{CatchPerDeployment}) = \mu_{ij} \\
&\text{CatchPerDeployment} = \beta_1 + \beta_2 \text{ x PotType}_{ij} + \beta_3 \text{ x SoakDuration}_{ij} + \beta_4 \text{ x PotType}_{ij} \\
&\text{x SoakDuration}_{ij} + \text{GroupID}_i \\
&\text{GroupID}_i \sim N(0,\sigma^2)
\end{aligned} \tag{Eqn 2}$$

We then tested whether pot type affected the mean length of cod that we caught using a general linear model. Mixed effects were not used in this analysis because visual inspection of the data demonstrated no relationship between the sizes of caught fish and group ID, therefore we did not include group ID as a random effect. Body lengths were normally distributed. Therefore, we conducted an ANCOVA on the mean length of cod caught per pot as modeled by a normal distribution. Residuals met the assumptions for homogeneity, normality, and independence. We did all analysis using R statistical software (R Core Team, 2017).

3.3.7 Grading receipts (Year 2 – 2016)

To determine the quality of the cod caught using pots during our field study, we were provided with a small sample of anonymous grading receipts for landings of cod provided to us by the Fogo Island Cooperative Society within the duration of our field study. The grading receipts contained an overall quality score (A, B, or C, in declining order of overall quality), which was based on an assessment of the fillet quality of landed fish. Many factors are considered in these assessments, including parasites, odour, texture, bruising, and colour (Standing Fish Price-Setting Panel, 2016). The grading receipts we obtained were for the landings of cod caught off the coast of Fogo Island between August 22 and August 25, 2016 and represent 78 landings of cod from 57 different fishers. Using these grading receipts we were able to calculate the proportion of catch that was considered grade A, B, and C, for landings of cod, using three different fishing gears (pots, gillnets, and hooks) during the duration of our field study.

3.4 Results

3.4.1 Catch comparison (Year 1 – 2015)

We deployed a total of 41 NL pots, and 12 fleets of NOR pots (N = 72 NOR pots). We soaked the pots between 4.4 and 119.7 hours (mean ± 1 S.E. = 48.7 ± 2.5). Pot soak times ranged from 19.1 to 95.5 hours (mean ± 1 S.E. = 50.4 ± 2.9) for NOR pots, and 4.4 to 119.7 hours for NL pots (mean ± 1 S.E. = 46.5 ± 4.3). Deployment depths ranged from 25 to 48 m (mean ± 1 SE = 36.7 ± 0.4).

NOR pots caught between 1 and 54 cod (mean ± 1 S.E. = 24.74 ± 1.33) and NL pots caught between 1 and 40 cod (mean ± 1 S.E. = 18.71 ± 1.61; Table 3.1, Figure 3.4 A). Mean body length of cod did not differ significantly between pot types (p = 0.0792, Figure 3.4 A). Body lengths ranged from 16 to 105 cm (mean ± 1 S.E. = 57.38 ± 0.27) for the NOR pot and 33 to 100 cm (mean ± 1 S.E. = 58.24 ± 0.39) for the NL pot.

We found that there was no interaction between pot type and soak duration (β = -0.031, S.E. = 0.090, t = -0.34 p = 0.73). Therefore, we dropped the interaction term from the model. In the next model, which did not include the interaction term, we found that effect of soak duration on total catch per pot, was still non-significant (β = 0.00019, S.E. = 0.045, t = 0.0040, p = 0.997). In other words, pots deployed for two or more overnight periods did not catch more cod than pots soaked overnight. Therefore, for the remainder of our analysis, we dropped soak duration as a term in the model, and treated 'cod per pot, per deployment' as our metric of CPUE.

We found that NOR pots caught 32% more cod on average than NL pots (Table 3.2, Figure 3.4 A, $\beta = 0.28$, S.E. = 0.11 $t = 2.60$, $p = 0.0092$). The NL pots caught a total of 67 cod ≤ 45 cm TL (8.7% of catch), and NOR pots caught 278 cod ≤ 45 cm TL (15.6% of catch).

Over the course of this study, we captured six different bycatch species including toad crab, eel pout, rock cod, sculpin, urchin, and whelk (Table 3). The most frequently caught bycatch species, for both pot types was Toad crab (*Hyas araneus*), with 847 caught across all 113 pot deployments.

3.4.2 Catch comparison (Year 2 – 2016)

Over the course of the two-week study period (August 20 to Sept 3, 2016), we deployed a total of 125 pots, consisting of 25 deployments each of NL, NOR, NL-mod, NOR-mod, and 4-ent pots, nested within 25 groups. On August 30, 2016, during our fieldwork, a heavy windstorm affected five groups of deployed pots. Therefore, we removed these five groups (N = 25) from our analysis. We excluded two additional pots from analysis due to damage that occurred during deployment. Therefore, our final analysis included data from 98 pot deployments, nested within 20 groups, consisting of 20 NL, 20 NOR, 20 NOR-mod, 19 NL-mod, and 19 4-ent pot deployments. Soak times for pot deployments ranged from 14.6 to 98.8 hours (mean ± 1 SE = 42.1 ± 2.9).

The minimum number of cod caught in any single pot over the whole study period was one, occurring only once in a NL pot. The minimum number of cod caught for each other pot type was, six for NOR pots, three for NOR-mod pots, seven for NL-mod pots, and six for 4-ent pots. The maximum number of cod caught in any single pot occurred in an NL-mod pot, which had 64 individuals, and the maximum number of cod caught in the other pot types were 37 in NOR pots, 35 in NL pots, 41 in NOR-mod pots, and 55 in 4-ent pots (Table 3.4, Figure 3.4 B).

We found that there was no interaction between pot type and soak duration (p = 0.0659) (Table 3.4, Figure 3.4B). Therefore, we dropped the interaction term from the model. In the reduced model, which did not include the interaction term, we found that soak duration was still non-significant ($\beta = 0.030$, S.E. = 0.045, t = 0.670, $p = 0.503$). Therefore, for the remainder of our analysis, we dropped soak duration as a term in the model, and treated cod catch per pot, per deployment as our metric of CPUE.

Statistically, we found that the NL-mod pots caught significantly (145%) more cod on average than the standard NL pot (Table 3.5, Figure 3.4 B, $\beta_1 = 0.8949$, S.E. = 0.1756, $t = 5.096$, $p = 2.34\text{e-}07$). We found that the 4-ent pot, caught significantly (83%) more cod on average than the NL pot (Table 3.5, Figure 3.4 B, $\beta_1 = 0.604$, S.E. = 0.177, $t = 3.407$, $p < 0.001$). We also found that both the NOR and NOR-mod pots did not catch significantly more or less cod than the NL pot (Table 3.5, Figure 3.4 B, $\beta_1 = 0.213$, S.E. = 0.178, $t = 1.198$, $p = 0.231$) and (Table 3.5, Figure 3.4 B, $\beta_1 = 0.248$, S.E. = 0.177, $t = 1.396$, $p = 0.163$) respectively.

Mean body length of cod did not differ significantly between pot types in comparison to the standard NL pot for all five pot types (Figure 3.4 B), NL-mod (p = 0.390), NOR (p = 0.101), NOR-mod (p = 0.697), and 4-ent pot (p = 0.503). Body lengths of cod are presented in Figure 3.4 B.

The proportion of catch below 45 cm was 2.55% for the NL pot, 0.63% for the NL-mod pot, 7.37% for the NOR pot, 0.39% for the NOR-mod pot, and 0.00% for the 4-ent pot. The standard NOR pot had the greatest proportion of catch < 45 cm (Figure 3.4 B), whereas the 4-ent pot had no catch below 45 cm. We reduced the undersized catch (< 45 cm) by 95% by switching to a bigger mesh size in NOR pots.

Over the course of the second field study, we captured seven different bycatch species including toad crab, eel pout, rock cod, sculpin, urchin, whelk, and seal (Table 3.6). The most frequently caught bycatch species for all five pot types was toad crab. A single seal (*Phoca vitulina*) was caught in one deployment within an NL-mod pot, which had an unusually long deployment (4 days) due to poor weather inhibiting our ability to retrieve the pot.

3.4.3 Grading sheets

A total of 94% of the landings from cod pots were ranked as grade A, while hooks produced 91% grade A landings. Gillnets produced only 58% grade A catch (Figure 3.5).

3.5 Discussion

In our 2015 study, we found that the NOR pot clearly outperformed the NL pot. This provided the first evidence that lightweight pots could be useful in the NL cod fishery. The difference in CPUE may have been a result of design features of the NL pot such as the metal retention triggers, which, as previously reported, appear observed to deter the entry of cod (Meintzer et al., 2017; Olsen, 2014). The mean body length of cod did not differ significantly between the NOR and NL pots, but since the NOR pots caught more fish overall, the pots accumulated a larger absolute number of undersized (< 45 cm) cod than the NL pots. This was our primary motivation for increasing the mesh size for the NOR pot in our second field study in 2016, through the NOR-mod pot. Regardless, our conclusion from year 1 was that NOR pots were clearly more effective at catching cod than the NL pots.

In the second year, we found that the modified NL pot was the best performer – even outperforming the 4-ent pot. Our expectation was that the presence of entrances on all sides of the 4-ent pot would result in an entrance always facing the down-current direction, thereby making it easier for cod to enter pots (see: Meintzer *et al.*, 2017). While that likely worked, the addition of extra openings also facilitates exit, and it is possible that the exit rate increased more than the entrance rate. In another field study in the Barents Sea, researchers found that floated pots – which could reorient themselves based on current direction – with two entrances caught 82% fewer cod per deployment than one-entrance pots (Jørgensen et al., 2017), thus demonstrating the importance of exit rate as a determinant of final catch. A second possible explanation for the higher CPUE of the NL-mod pot is that cod tend to swim upwards inside pots (Meintzer et al., 2017). Each entrance had associated twine that crisscrossed the interior of the pot, and having four entrances potentially created barriers to trapped cod's ability to swim upward and into the cod-end.

The modifications made to the NL pot had a major impact on catch rates, particularly versus the unmodified NL pots. By removing the metal retention triggers, changing the entrance funnel design, and adding the mesh separator, we were able to substantially increase the catch of the NL-mod pot relative to the standard NL pot. The key modifications to the NL pots were inspired by features from the NOR pots. The design factor that we believe was most responsible for the improved catch rates was the inclusion of the mesh separator panel as the primary retention mechanism for trapped cod.

Overall, we found that all five pot types were effective at catching substantial quantities of Atlantic cod off the coast of Fogo Island during the commercial fishing season. However, NL-mod and 4-ent pots produced highest CPUE of cod, and that increasing the mesh size in NOR pots essentially eliminated undersized catch. There are two main implications of these findings. First, there is substantial opportunity for variation among potentially effective pot designs, in terms of size, shape, and dimension. This suggests that fishers can have a degree of flexibility in building and deploying pots that work well for their fishing vessel's deck configuration. Second, to maximize catch rate while minimizing impact on habitat and non-target species, designs should incorporate several features. First, pots should use monofilament entrance funnels, with bait bags suspended on the interior end in line with the entrances. Second, pots should be built with 100 mm mesh on the exterior of the pots to reduce undersized bycatch. Third, a mesh separator panel that divides the pot into two chambers should be included at the midway point of the interior of the pot, with a slit that allows the movement of fish between chambers.

In other studies that employed field tests of cod pots, researchers have noted lower CPUE's for the NOR pots than we experienced here. Specifically, (Marcella et al., 2016) caught only 231 cod across 377 deployments of NOR pots, resulting in a CPUE of only 0.61 cod per pot per deployment, in contrast to our observed NOR pot CPUE's of 24.7, and 17.0 cod per pot per deployment for our 2015, and 2016 field studies respectively. Likewise, floated NOR pots with two and one entrances caught 2.70 and 4.11 cod per deployment, respectively (Jørgensen et al., 2017) – with both values being lower than our 17.0 cod per deployment for two-entrance NOR pots in 2016. Clearly, these studies were conducted at different times, in different ecosystems, and on different populations of Atlantic cod. Nevertheless, these differences may indicate that fishers may expect to see variable catch rates across ecosystems, and it is possible that pot designs may need to be customized for the system in which they are used. Therefore further research into the optimal design of cod pots for different populations will be an ongoing effort.

It remains unclear what the optimal soak duration is for cod pots in NL. In our study, there was no relationship between soak duration and catch per unit effort – 24 h was just as effective as longer deployments, across the range of deployment durations we tested. However, longer soak durations have been associated with higher catch rates in other fisheries (S. J. Königson et al., 2015). Nevertheless, an advantage of pots over other fishing gears is that fish trapped within pots do not die until retrieval. This means that if fishers are unable to retrieve pots (e.g. due to bad weather) they will not lose quality of catch due to *in situ* decomposition. This provides fishers the ability to catch quotas quickly (with short soak times and daily retrieval of gear) or to stretch out the fishery over a longer time period, with long soak times and sporadic retrieval of gear. Either strategy could potentially be used without compromising fish quality.

The amount of pre-slaughter stress experienced by fish has been linked to quality (Bjørnevik and Solbakken, 2010), and stress varies depending on the fishing gear (Chopin and Arimoto, 1995; Humborstad et al., 2016). To ensure high quality catches, capture techniques that minimize stress are desirable. Recent findings have suggested that pot-caught cod suffered from less stress during capture and handling procedures than longlines based on physiological and stress measurements (Humborstad et al., 2016). In addition, in a previous study we found most cod exhibited positive rheotaxis (i.e. swam against the direction of the current) within pots, and no showed no obvious visual signs of stress (Meintzer et al., 2017), which is supported by a study that observed captured cod resting within pots (Olsen, 2014). The data provided to us by the processor suggested, at least within the limited sample size examined, that professional fish graders were reporting higher quality among pot-caught cod than cod caught using gillnets. This is unsurprising, because previous research has also demonstrated that cod caught using gillnets consistently received the lowest prices compared to other gears (Lee, 2014). Stress in fish has been correlated with reduced market quality (Bjørnevik and Solbakken, 2010) and so the higher quality grades in pot-caught-cod during the duration of our study period, suggests the possibility that these fish were not subject to high stress during the capture process.

While the environmental case for a shift from gillnets to less impactful gears is clear, environmental benefits alone are rarely sufficient to motivate change within an industry. When adopting alternative fishing gears, achieving greater, or at least comparable catches, with similar input effort is an important factor for fishers to consider abandoning traditional gears (S. J. Königson et al., 2015). There are three non-environmental reasons that a shift to using pots would make sense for a fishing operation. First, the presence of zippers and a cod-end in the design of pots means that there is less labor required to remove the catch from pots, in contrast to gillnets which require greater effort (Rouxel and Montevecchi, 2017). Second, because the fish are freely swimming within the pots until recovery, fishers have the flexibility to retrieve their gear at their own convenience, avoiding the risk of hauling their gear during inclement weather. Thirdly, if a market could be established for higher quality cod, and fishermen rewarded with a greater price-per-kilogram for high quality fish caught using pots (e.g. Guy, 2017; The Shorefast Foundation, 2016), then the financial gains a fisher could make from pots would be substantial when compared to gillnets.

Over the course of our two studies, we caught a low diversity of non-target species (n = 7), with our only major bycatch by count being toad crab. In contrast, a similar study between NL and NOR cod pots in Massachusetts caught an increased diversity of bycatch with 15 different species caught during their study period (Marcella et al., 2016). Toad crab is currently classified as Least Concern by the International Union for the Conservation of Nature (IUCN, 2017), and is likely robust to capture (e.g. Moiseev et al., 2013). Nevertheless, it is good practice to minimize impacts on non-target species, even if they are least concern. One option would be to focus further gear modification efforts to reduce crab bycatch, such as using floated pots which were observed to reduce the bycatch of king crabs in the Barents Sea (Furevik et al., 2008), while another would be to acknowledge this bycatch within the conditions of fishing licenses, and manage as a multi-species fishery (Gislason et al., 2000; Grafton et al., 2004).

Despite signs of a limited recovery (Rose and Rowe, 2015), the northern cod stock remains depressed (Simms, 2017). It is critical that any decision made about exploitation of northern cod be precautionary in nature and considered in an ecosystem context (Rowe and Rose, 2017). Empowering managers and fishers to use gears, such as pots, that produce reduced impacts on ecosystems while meeting the needs of industry is a key aspect to promoting sustainable management of cod. These results show that pots are effective at catching cod while minimizing catch of non-target species, and that modifications to gear can increase catch efficiency while decreasing bycatch. Different pot types can produce substantially different catch rates. The different catch rates we observed across pot designs, fishing at the same time of year in the same locations, demonstrates that innovation within this class of fishing gear can substantially improve its usability as a tool for industry.

3.6 Tables

Table 3.1. Summary of cod caught per pot type from our 113 deployments.

Pot type	Total caught	Min	Max	Mean CPUE	SE	N
NOR	1781	1	54	24.74	1.33	72
NL	767	1	40	18.71	1.61	41

Table 3.2. Estimated regression parameters, standard errors, z-values, and P-values for the Negative Binomial GLMM presented for catch-per-deployment from our 2015 field study.

	Estimate	Std. error	z value	P-value
Intercept	2.92891	0.08631	33.93	<2e-16
PotTypeNor	0.27936	0.10729	2.6	0.00922

Table 3.3. Bycatch comparison between the NL and NOR pots for our 2015 field study. Values represent the total number of individuals caught out of 41 NL and 72 NOR deployments.

Common Name (Species)	NOR	NL	Total Catch
Whelk (*Buccinum* sp.)	5	0	5
Greenland cod (*Gadus ogac*)	0	22	22
Sculpin (*Myoxocephalus* sp.)	8	2	10
Sunstar (*Crossaster* sp.)	3	0	3
Toad crab (*Hyas araneus*)	797	50	847
Eelpout (*Lycodes* sp.)	0	1	1

Table 3.4. Summary of cod caught across all pot deployments for each pot style. N represents the number of pots deployed per pot type.

Pot Type	Total cod caught	Min	Max	Mean CPUE	SE	N
NL	274	1	35	13.7	2.3	20
NOR	339	6	37	17.0	1.8	20
NL-mod	637	7	64	33.5	3.3	19
NOR-mod	351	3	41	17.6	2.2	20
4-ent	476	6	55	25.1	2.9	19

Table 3.5. Estimated regression parameters, standard errors, z-values, and P-values for the Negative Binomial GLMM presented for catch-per-deployment from our 2016 field study.

	Estimate	Std. error	z value	P-value
Intercept	2.6174	0.127	20.606	< 2e-16
PotType4-ent	0.6036	0.1771	3.407	0.000656
PotTypeNLMod	0.8949	0.1756	5.096	3.48E-07
PotTypeNOR	0.2129	0.1777	1.198	0.230875
PotTypeNORMod	0.2477	0.1774	1.396	0.162679

Table 3.6. Bycatch comparison between all five pot types. Values represent the total number of individuals caught out of 20 NL, 20 NOR, 19 NL-mod, 20 NOR-mod, and 19 4-ent pot deployments (98 pot deployments total).

Common Name (Species)	**NL**	**NL-mod**	**NOR**	**NOR-mod**	**4-ent**	**Total Catch**
Toad crab (*Hyas araneus*)	54	401	512	589	810	2366
Eel Pout (*Lycodes* sp.)	0	0	1	2	1	4
Greenland cod (*Gadus ogac*)	1	8	3	6	3	21
Sculpin (*Myoxocephalus* sp.)	15	8	13	14	17	67
Green sea urchin (*Strongylocentrotus* sp.)	0	0	2	0	0	2
Whelk (*Buccinum* sp.)	0	0	0	0	2	2
Seal (*Phoca vitulina*)	0	1	0	0	0	1

3.7 Figures


55
50
45
40
Latitude
-70
-60
-50
Longitude
NEWFOUNDLAND AND LABRADOR
QUÉBEC
Gulf of St Lawrence
St. John's
Saint Pierre and Miquelon
Québec City
NEW BRUNSWICK
PRINCE EDWARD ISLAND
Ottawa
Montreal
MAINE
NOVA SCOTIA
VERMONT
NEW HAMPSHIRE
NEW YORK
MASSACHUSETTS
CT
RI
New York
Philadelphia
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Map data ©2017 Google

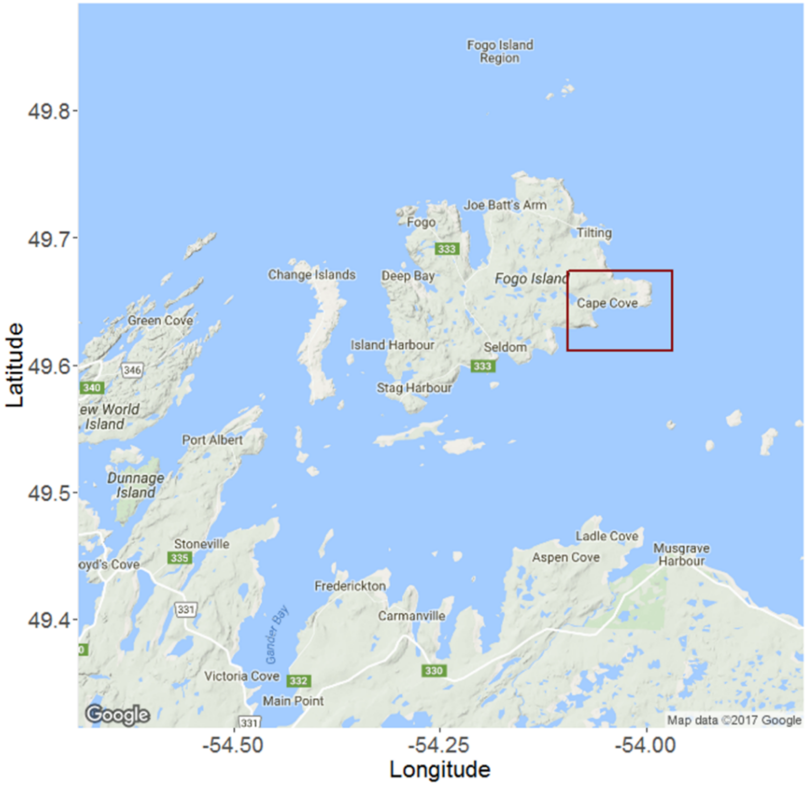
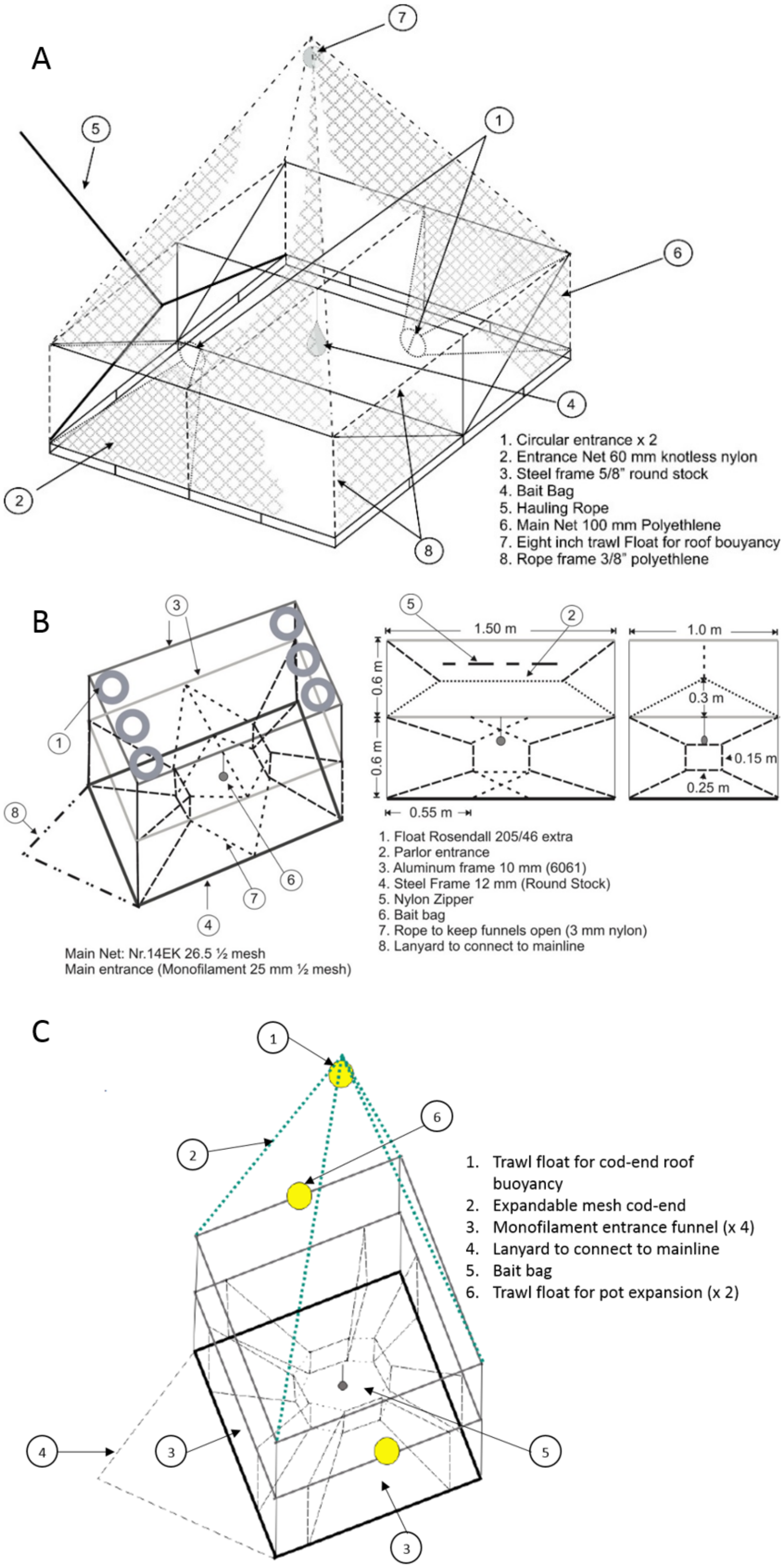

49.8
49.7
49.6
49.5
49.4
Latitude
-54.50
-54.25
-54.00
Longitude
Fogo Island Region
Joe Batt's Arm
Fogo
333
Tilting
Change Islands
Deep Bay
Fogo Island
Cape Cove
Green Cove
Island Harbour
Seldom
346
340
Stag Harbour
Port Albert
Dunnage Island
Stoneville
335
Ladle Cove
Aspen Cove
Musgrave Harbour
Fredericton
331
Carmanville
Gander Bay
Victoria Cove
332
330
Main Point
Google
Map data ©2017 Google

Figure 3.1. Map of our research site, off of the southern coast of Fogo Island, NL, for both field studies in 2015 and 2016. The red rectangle on the top map indicates Fogo Island's location relative to eastern Canada and the United States, and the red rectangle on the bottom map encompasses the greater fishing area where we deployed our cod pots during both field studies.



1. Circular entrance x 2
2. Entrance Net 60 mm knotless nylon
3. Steel frame 5/8" round stock
4. Bait Bag
5. Hauling Rope
6. Main Net 100 mm Polyethlene
7. Eight inch trawl Float for roof bouyancy
8. Rope frame 3/8" polyethlene

1. Float Rosendall 205/46 extra
2. Parlor entrance
3. Aluminum frame 10 mm (6061)
4. Steel Frame 12 mm (Round Stock)
5. Nylon Zipper
6. Bait bag
7. Rope to keep funnels open (3 mm nylon)
8. Lanyard to connect to mainline

Main Net: Nr.14EK 26.5 ½ mesh
Main entrance (Monofilament 25 mm ½ mesh)

1. Trawl float for cod-end roof buoyancy
2. Expandable mesh cod-end
3. Monofilament entrance funnel (x 4)
4. Lanyard to connect to mainline
5. Bait bag
6. Trawl float for pot expansion (x 2)

Figure 3.2. Diagrams of the different pot types used during our 2015, and 2016 field studies. Figure 3.1A pictures a Newfoundland (NL) pot, as it would appear deployed on the sea bottom. Figure 3.1B pictures a Norwegian (NOR) pot, as it would appear deployed on the sea bottom. Figure 3.1C represents a 4-ent pot, as it would appear deployed on the sea bottom.

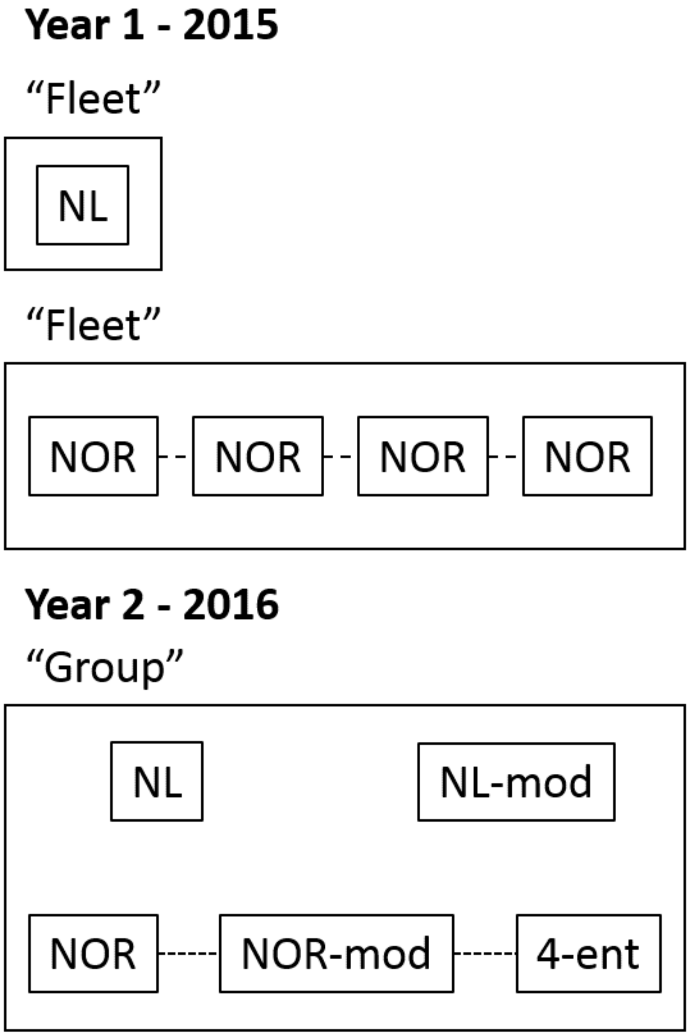


Figure 3.3. Diagram representing our experimental design for both 2015, and 2016 field studies.

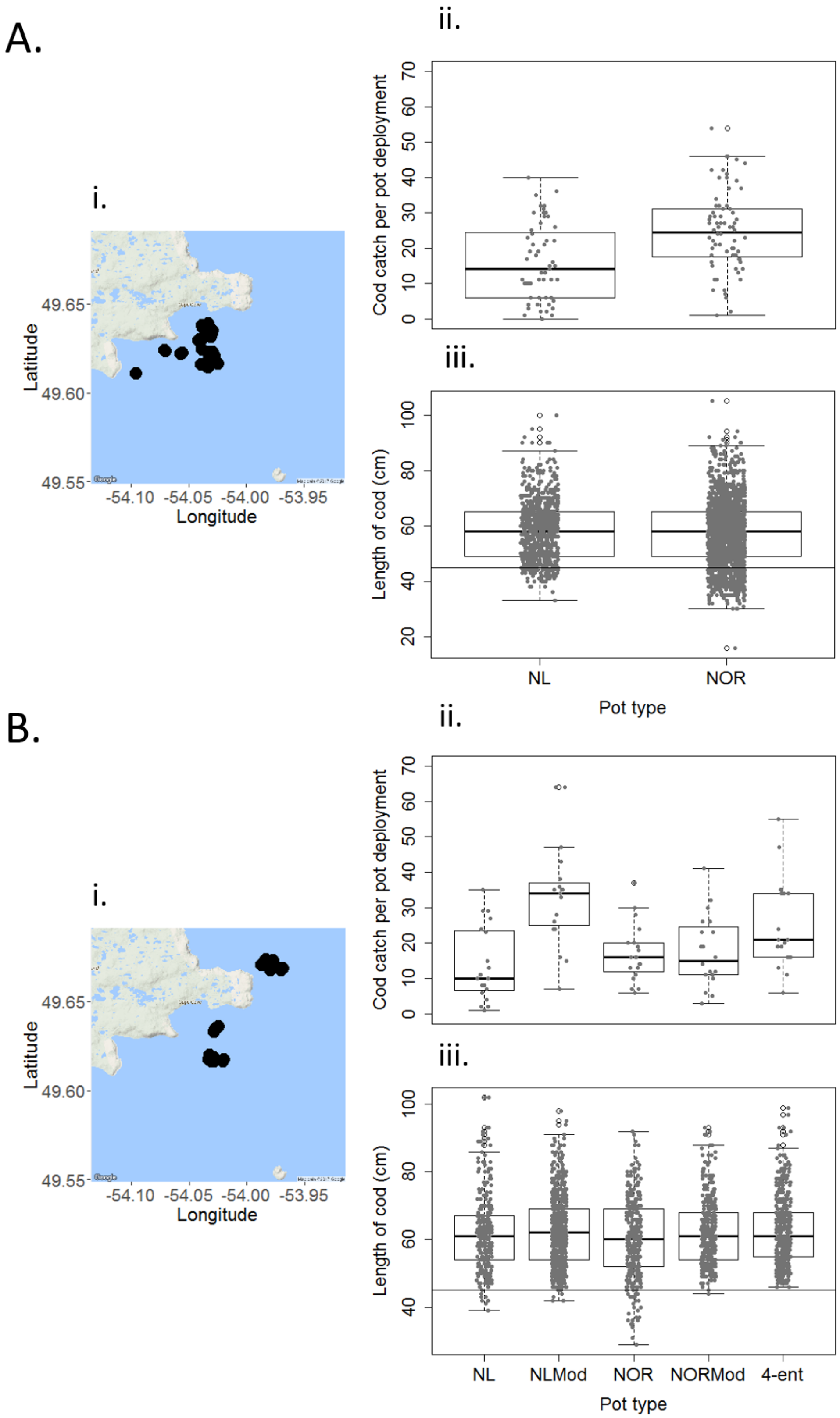

A.
i.
49.65
49.60
49.55
Latitude
-54.10 -54.05 -54.00 -53.95
Longitude
ii.
Cod catch per pot deployment
0 10 20 30 40 50 60 70
iii.
Length of cod (cm)
20 40 60 80 100
NL
NOR
Pot type
B.
i.
49.65
49.60
49.55
Latitude
-54.10 -54.05 -54.00 -53.95
Longitude
ii.
Cod catch per pot deployment
0 10 20 30 40 50 60 70
iii.
Length of cod (cm)
40 60 80 100
NL
NLMod
NOR
NORMod
4-ent
Pot type

Figure 3.4. A summary of our catch data, length data, and pot deployment locations, collected during both field studies (2015 and 2016). A and B present 2015 and 2016 data, respectively. Maps (Ai and Bi) present locations where we deployed pots. Top boxplots (Aii and Bii) compare mean catch-per-deployment of Atlantic cod across pot types, where each grey dot represents an individual pot deployment. Bottom boxplots (Aiii and Biii) compare the total lengths of cod caught between pot types, with each fish indicated as a grey dot. Points below the black line at 45 cm represent fish that were < 45 cm in length.

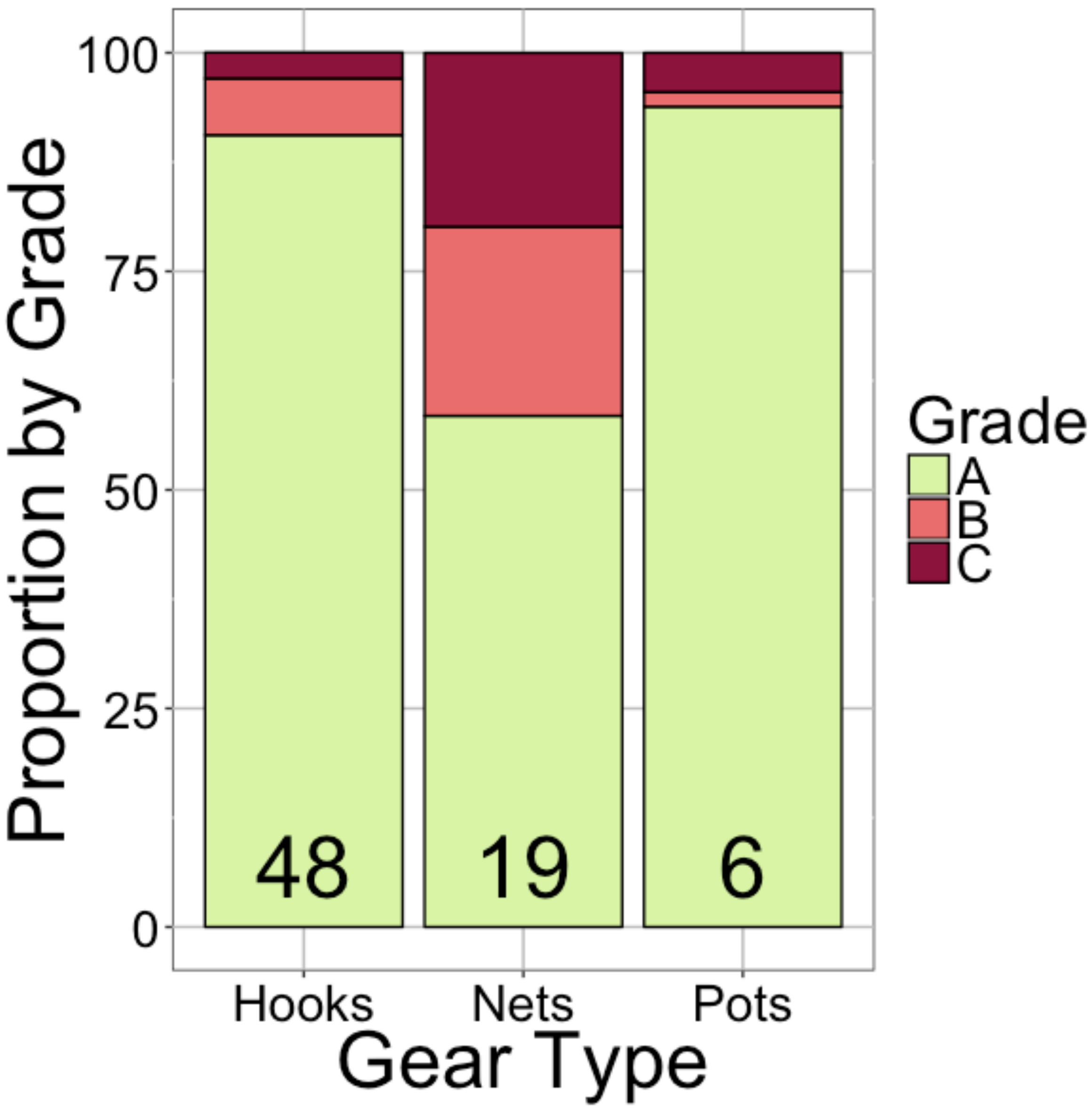


Figure 3.5. The proportion of cod landings considered grade A, B, or C quality for hooks, gillnets, and pots during our field study. Numerical values represent the sample size, which was the number of grading receipts for the respective fishing gear type within our study period.

3.8 Acknowledgements:

We thank Aubrey Payne, Marie Payne, and Rodney Budden for their invaluable contributions to this MS, including the use of their fishing vessels and assistance with fieldwork. We thank Gordon Slade and the Shorefast Foundation for logistical support. We also acknowledge Rennie Sullivan and Maggie Folkins for assistance in constructing our experimental cod pots.

We would like to respectfully acknowledge that the lands on which we conducted our fieldwork are situated in the traditional territories of the Beothuk indigenous group, and we acknowledge the diverse histories and cultures of the Beothuk of this province. We strive for respectful relationships with all the peoples of this province as we search for true reconciliation and honour this beautiful land together.

Chapter 4: General Discussion – The Potential for cod pots in Newfoundland

4.1 Summary

The findings in this thesis demonstrate that cod potting technology can be a useful tool for catching Atlantic cod in NL. Through two field studies, I observed that all five variations of cod pot design were able to successfully catch cod with minimal bycatch, indicating that fishers have the freedom to choose the cod pot design which best suits the needs of their fishing enterprise. This finding is important because all fishers do not have identical boats, hauling equipment, or crew sizes, and therefore some fishing operations may be better suited to the smaller, light-weight NOR and NOR-mod pots, whereas other fishers can deploy the larger NL, NL-mod, and 4-end pots with relative ease. Therefore, more fishers could be potentially encouraged to adopt pots as their primary fishing strategy for Atlantic cod, because they are not restricted by their boat size or equipment.

Chapter one demonstrated that although cod pots are able to successfully catch Atlantic cod, there is still vast room for improvement in potting technology as a whole. From the underwater videos, numerous cod were observed to make unsuccessful entry attempts, and the number of observed approaches by cod towards the pot greatly outnumbered the amount of successful entries. I observed that water direction in relation to entrance orientation was a critical factor influencing the efficiency of cod pots for target species, and this was supported by our findings presented in chapter 2, with the novel 4-ent pot design having increased catches relative to both the standard NOR and NL pots.

Chapter 2 demonstrated the significant impact that modest modifications can have on the efficiency of cod potting gear, and that combining behavioural observations with commercial fishing experiments can produce substantial improvements for fishing gear. As a result of the underwater video analysis, in conjunction with the catch data I collected during the first field study in 2015, I modified the NOR pot by increasing its mesh size to the 100 mm mesh size legally required by Fisheries and Oceans Canada (DFO). This minor modification resulted in the NOR-mod pot catching 95% fewer cod under 45 cm in length, without negatively impacting the average catch per deployment. This indicates that the NOR-mod pot can be fished just as successfully as the standard NOR pot, without compromising catch, while avoiding undersized bycatch. The results of the modifications to the NL pot were more surprising than anticipated. Modifications were made to the NL pot to copy some of the beneficial design features of the NOR pot, as a means to increase the efficiency of the NL pot for fishers on Fogo Island, who had already invested heavily into this gear. However, as a result of these modifications, the catch efficiency of the NL-mod pot was significantly increased by 145% relative to the standard NL pot, and it caught the most cod per deployment of all five variations tested. The exact reason for this increase is unclear, because I added three different modifications (different entrance funnel, midway mesh divider panel, bait bags in front of entrances) from the standard NL pot, however future underwater video studies of the NL-mod pot *in situ* could help determine how these modifications, or which modification specifically increased the CPUE so greatly.

The novel design 4-ent pot was expected to catch the most cod per deployment, because I had increased the number of entrances compared to the NL and NOR pots, in an attempt to increase the probability that an entrance would be in-line with the downstream current direction, which I found to be an important factor influencing cod pot efficiency in chapter 1. The 4-ent pot caught significantly more cod per deployment than the NL, NOR, and NOR-mod pots, however the NL-mod pot had the greatest CPUE of all five pots tested. Possible reasons for the 4-ent pot not having the greatest CPUE is the smaller capacity compared to the NL-mod pot, as well as the presence of an increased number of entrances. Although increasing the number of entrances can result in an increased chance of lining up with the current, it could also increase the probability of a fish locating an exit to the pot once already caught. In chapter 1, I observed that 25% of successfully caught cod were able to exit the pot following capture, and this proportion could be greater with an increased number of entrances. Again, *in situ* underwater video studies of these modified and novel cod pot designs could be beneficial to understanding the mechanisms that underlie their respective CPUE determined in chapter 2, and the absence of *in situ* video recordings for these new pots is a limitation of this research project I would address if I were able to repeat this study.

4.2 Limitations of my Approach

As mentioned in chapter 2, when observing the underwater videos of deployed cod pots and recording all approaches by Atlantic cod towards the pot, I was unable to account for the actual number of individual cod in the vicinity of the pot, due to the limited field of view provided by our underwater camera and camera frame apparatus. In this chapter, we defined an approach as a cod entering the visible area of the video. Therefore, the limited field of view meant that if a fish was to swim towards the pot, swim away (off-camera), and then return to the visible area of the video, we recorded these actions as two separate approaches. Although knowing the population of cod in the vicinity of the pot was not essential to my specific research questions, knowing what proportion of nearby cod get caught by these fishing gears would be informative, and could provide valuable information towards the establishment of a sustainable cod fishery.

Another limitation within my second chapter was the lack of observable video for the over-night hours during each deployment. I decided to not use an external artificial light source for overnight deployments based on literature which observed artificial illumination having an positive effect on the CPUE for Atlantic cod in Norwegian cod pots (Bryhn et al., 2014), and I did not want to introduce another variable which might influence catch rates. Therefore, I was unable to observe and record the number of approaches, entry attempts, successful entrances, and escapes by cod (and bycatch) during the overnight period when ambient light was not sufficient to illuminate the videos.

In chapter three, it would have been valuable to have collected additional *in situ* underwater videos of the new and modified cod pots during deployment to try and determine the reasons behind their increased catch efficiencies when compared to the unmodified pots, however I was unable to access the same underwater camera which was used in the previous year's fieldwork during the 2016 field season. In addition, I think future research could analyze each individual modification made to the NL-mod pots (i.e. including a separator panel, removing metal triggers etc.) to compare the modifications in order to determine which specific adjustment was responsible for the increase in CPUE when compared to the standard NL pot. If a single specific modification could be determined to be responsible for the increased catch efficiency for cod, it could significantly reduce the time and labor required for fishers to modify their gears. The reason I had not addressed this question within my thesis was because we had not expected the modifications to have such a significant impact, and the decision to modify the NL pot was a made as a means to assist fishers who had already invested into these gears in the past, and was not part of my original research plan.

At the moment, the financial viability of cod pots as the primary harvesting tool for cod fishers in NL is uncertain. The current cod pots I tested were prototypes built for research purposes, and without a formal investigation into the economics (i.e. comparing procurement cost and longevity across gears, including bot pots and gillnets) we can't firmly make business recommendations. Determining the large scale viability of pots requires data on many variables, including the initial cost for purchasing a fleet of commercial cod pots, the average fuel costs to harvest a commercial fleet of pots, the average mass of cod collected from a fleet of pots, and the sale price of Atlantic cod paid to the fisher (which is variable depending on the quality of the caught cod).

4.3 Conclusion

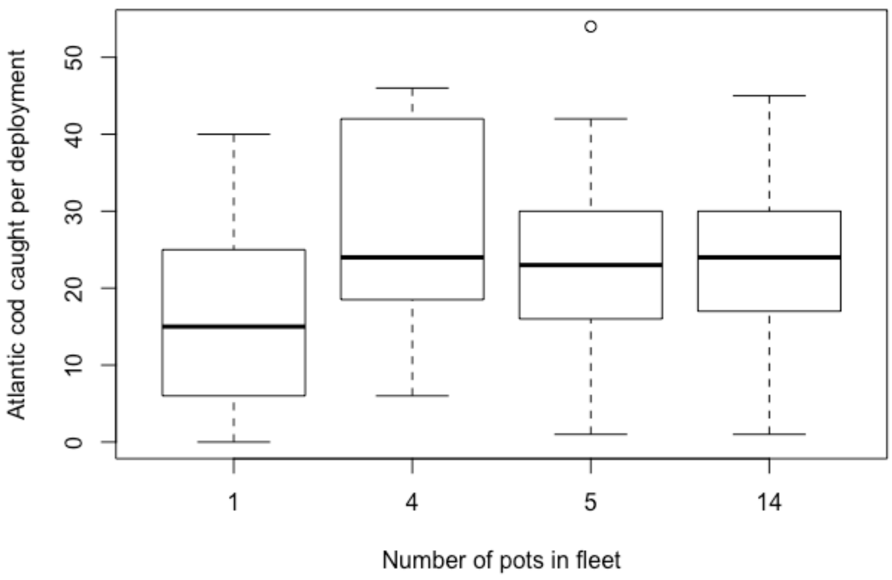
As a direct result of the research conducted for this thesis, during the fall of 2017, the provincial government of NL announced an investment of $1.8 million into their Seafood Innovation Transition Program (SITP), and as part of this program, approximately $400,000 was invested directly into the manufacturing and purchase of cod pots across 29 projects to assist fishers and communities across NL in the transition to sustainable cod fishing gears ("Groundfish Focus of 2017 Seafood Innovation and Transition Program," 2017).

If NL populations of Atlantic cod continue to increase, and the moratorium on the commercial cod fishery is lifted, it will be the responsibility of fisheries managers to regulate the types of gears allowed within the fishery. The most recent report on Northern cod, by the Canadian Standing Committee on Fisheries and Oceans suggests that for NL to be successful in a competitive global market for fish, eco-certification, as well as high quality products fished using sustainable methods will be required, and the use of cod pots was recommended as a possible higher quality alternative to gillnets (Simms, 2017). As a result of this research, NL based fishing gear manufacturers have begun to produce cod pots for sale to fishers, and a group of fishers on Fogo Island have committed to constructing approximately 400 cod pots throughout the summer of 2017 for use in the upcoming commercial cod fishery. The results presented in this thesis demonstrate that cod pots can function as a low-impact alternative to traditional fishing gears in NL, and could help promote a sustainable re-emergent cod fishery, for both North Atlantic marine ecosystems, and local fishing communities.

Appendix 1: Response to examiner comments

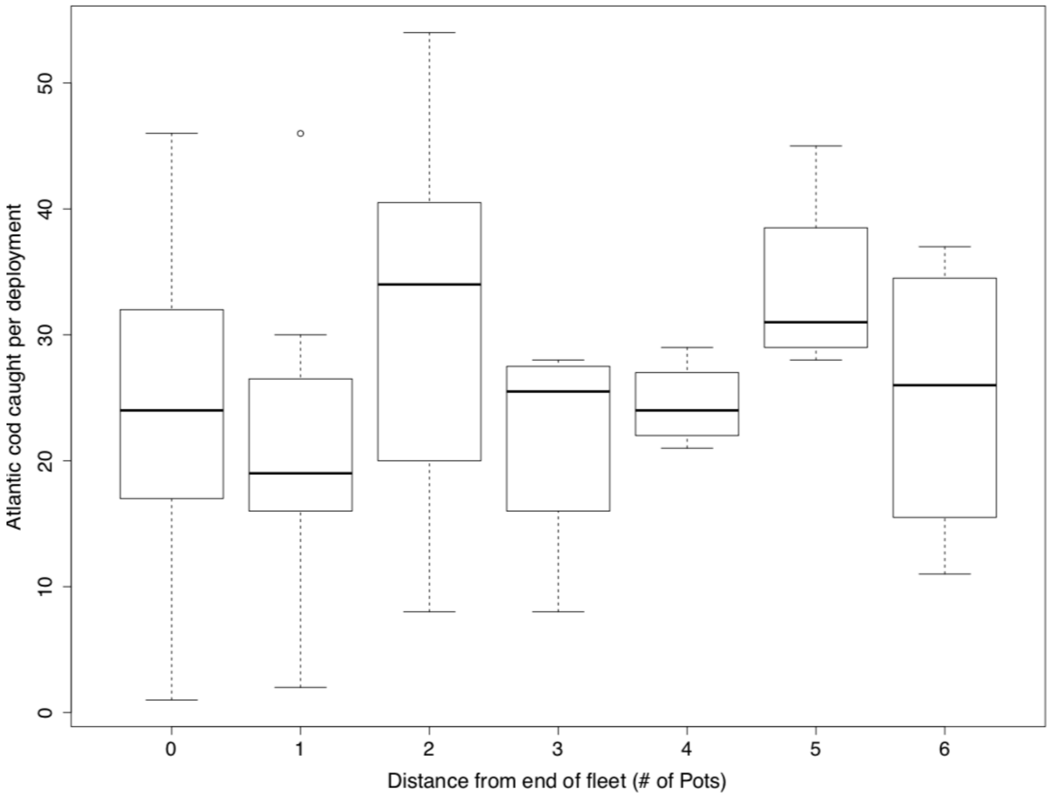
I have included this appendix to respond to the comments provided by the external examiner of my thesis, without detracting from the readability of the main body of text. All four comments are concerns from the examiner with regards to the experimental design of the first year (2015) field season of chapter 3, and are addressed below.

In comment one, the examiner introduced the concept that solitary pots can have a larger area where the scent of the bait is spread, and thereby have more cod approaching the pot. I was not able to observe the number of cod which approached each pot deployed during our fieldwork, however in response to this comment, I conducted a visual exploratory analysis of our data to see the difference in catch of Atlantic cod per pot deployment against the number of pots within fleets, including solitary pots. From the visual analysis, I did not observe any trend in the data supporting the idea that solitary pots have more cod approaching than pots within fleets, and the data indicates that our pots deployed in fleets caught slightly more cod per deployment. (Appendix Figure 1). There could be an interactive effect between catch rates and the number of pots within a fleet but I couldn’t test for it with the present design, because fleets were only composed of NOR pots during this field season, therefore fleet size was collinear with pot type.



Appendix Figure 1. Atlantic cod caught per pot deployment for solitary pots and fleets during the 2015 field season. Solitary pots are indicated by having only one pot per fleet, and all three fleet sizes deployed in our study (4, 5, and 14) have been included.

Comment two introduced the concept that the pots set at the beginning or at the end of fleets most often catch more fish than pots set in the middle of the fleet. To address this concern, I conducted a second visual exploratory analysis of my data to observe the difference between the catch per deployment of pots at the end of fleets compared to pots within. From the visual analysis, the pots located at the beginning and end of the fleets did not catch more cod per deployment than pots located within the fleet (Appendix Figure 2).



Appendix Figure 2. Comparing the number of Atlantic cod caught per deployment, at different locations within a single fleet (string) of NOR cod pots from our 2015 field season. A distance of zero indicates the pot was located at the start or end of the fleet.

The examiner's third comment raised the concern that all pots were not emptied at the same time, which can affect the results. I acknowledge this concern from the examiner, and I recognize that some pots soaked for longer or shorter durations than others, which could have an effect on the number of cod which could enter and escape. However, because of the large number of pots we had to deploy and recover each day with only a single fishing boat (not optimized for cod pot fishing) and a small crew size (four persons), we were unable to deploy and recover all pots at similar times. I tried to account for this difference in the statistical analysis of our data by including soak duration as an explanatory variable in our model (Eqn 1).

The examiner's final comment was regarding how the number of fish inside the pot can affect the catch, because the accumulation of fish within a pot could attract additional fish; or alternatively, too many caught fish could lead to a pot saturation affect and discourage the entry of additional fish (Anders, 2015). As a result of the experimental design for the 2015 field season, we were not able to test for the effect of the number of caught fish on the number of additionally caught fish, however, the use of underwater cameras attached to cod pots in future research could allow for this effect to be determined.

I would like to thank both examiners for their valuable feedback, which has been beneficial in the improvement of my thesis.

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