Using underwater video observations to improve capture efficiency of fishing gear

by

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ABSTRACT

High incidental catches of Greenland shark (*Somniosus microcephalus*) in Greenland halibut (*Reinhardtius hippoglossoides*) longline fisheries has led to studies on the feasibility of capturing halibut with baited pots. In this study I compare catch data among six experimental pots and examine video of halibut interacting with pots. Catch rates of halibut did not differ among treatments and pots did not produced substantial amounts of bycatch. Video observations revealed that halibut become entangled by their teeth significantly more often in entrance funnels constructed with 50 mm than with 19 mm netting, resulting in 45% higher entry rates in the latter. Most (80%) halibut approached pots against the current following the scent of the bait. I recommend that future studies consider a four-entrance pot to ensure an entrance is aligned with bottom currents. To reduce likelihood of entanglement, I recommend 19 mm netting for entrance funnels, 100 mm polyethylene for exterior panels, and 19 mm polypropylene for parlour entrances for pots targeting halibut.

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CO-AUTHORSHIP STATEMENT

The research described in this thesis was carried out by Maggie Folkins, with guidance from Drs. Scott Grant, Paul Winger, Kevin Hedges, and Mr. Philip Walsh.

Maggie was responsible for data analysis and the manuscript resulting from this thesis was prepared by Maggie Folkins with editing assistance and intellectual input from Drs. Grant, Winger and Hedges. Dr. Grant and Mr. Walsh contributed significantly to the study design and carried-out the field data collection components of this research.

Maggie Folkins is the lead author for all chapters. Mr. Walsh and Dr. Grant are second and third authors for Chapter 2 respectively.

CHAPTER 1

General introduction

Currently, the most common types of gear used to fish groundfish are bottom trawls for mobile gear, and bottom gillnets or bottom longlines for fixed gears. Mobile gears towed along the seafloor account for 50% of total global annual fishery landings (Broadhurst et al., 2006) and, as a result, are responsible for 46% (4.2 million tonnes) of the global annual weight of bycatch (i.e. non-targeted species) in demersal finfish fisheries (Roda et al., 2019). Catch rates tend to be higher in mobile gears, but fixed gears are sometimes preferred by commercial fishers due to protective measures set to decrease seabed impacts or bycatch (Thomsen et al., 2010; Blyth et al., 2002). Factors outside of fishing pressures, such as climate change and pollution, affect species dispersal and habitat loss, so many research groups are striving to protect fish stocks by creating innovative ways to fish sustainably (Hughes et al., 2005; Fuller et al., 2008; Winger et al., 2016). This has led to the use of more environmentally friendly gear types that can efficiently capture target species while reducing the unintentional capture of or harm to non-target species.

Bottom longlines and gillnets (fixed gears) used in finfish fisheries are considered to have relatively low impacts on bottom habitat, and require less fuel to operate, compared to mobile gears (Suuronen et al., 2012). However, other impacts in terms of bycatch and product quality arise with fixed gear types. For example, gillnets can produce poor quality fish and contribute to ghost fishing when gear is lost or abandoned at sea (He, 2005; Savina et al., 2016). Moreover, the cost of longline fisheries can make fishing uneconomical as fishers need to bait every hook, which is both labour-intensive and costly (Løkkeborg & Bjordal, 1992; Valdemarsen et al., 2007). In addition to these economic factors, bottom longline and gillnet fisheries can have high bycatch of seabirds, marine mammals, and sharks (He, 2005; Young, 2010; Fangel et al., 2015; Hedd et al., 2016).

As a group, elasmobranchs (i.e. sharks, skates, and rays) are common bycatch in many commercial fisheries, which can cause declines in their populations. Elasmobranchs grow slowly, mature at a late age, and produce few young; traits that make their populations particularly vulnerable to high fishing mortality (Cosandey-Godin & Morgan, 2011). Bottom longlines and gillnets have been linked to high mortality rates in some shark species, particularly when gear is left deployed (i.e. soak time) for a long period of time (Morgan & Burgess 2007; Morgan & Carlson 2010). Many preventative measures to reduce shark bycatch have been attempted, such as; decreasing soak times for gillnets, using circle hooks rather than J hooks, and alternative bait options in longlines. However, research is still needed to reduce shark bycatch in many fisheries. Baited pots are one type of fixed gear that have, in some known cases, effectively reduced shark bycatch (Fuller et al., 2008).

Baited pots reduce ecological impacts in some crustacean and finfish fisheries (Thomsen et al., 2010; Major et al., 2017). Like gillnets and longlines, baited pots are considered a “Low Impact and Fuel Efficient (LIFE)” fishing tool, meaning they require low amounts of fuel and have low environmental impacts (Suuronen et al., 2012). Pots are a passive fishing gear and therefore are not actively dragged along the seafloor to capture fish, unlike mobile fishing gears (i.e.;bottom trawls and dredges). Therefore, pots are less likely to affect sensitive species in bottom habitat, where groundfish fisheries takes place. Moreover, fish that are caught in pots are less susceptible to predation since they are in an enclosed area and are not left in the open, as in gillnets or longline fisheries (Stavenow et al., 2016). Since catches from pots are most often alive and in good condition upon haul back, they can yield a quality catch resulting in higher profit (Övegard et al., 2011; Königson et al., 2015). Further, the degree of pre-slaughter stress experienced by fish has been linked to quality (Bjørnevik & Solbakken, 2010) and pot caught fish have been shown to exhibit less stress during capture and handling than fish captured on longlines (Humborstad et al., 2016). Pots are being introduced to more fisheries world-wide as an alternative gear type. However, often the successful introduction of a new gear type to an existing fishery can depend on knowing how the target species or non-target species react to this gear.

In fixed-gear fisheries, the capture of fish is completely dependent on their voluntary behaviour to either enter a trap or gillnet or to bite a baited hook (Fernö et al., 1986; Rose et al., 2005). Without the use of submersibles to observe behaviour directly, most conclusions on gear efficiency, catch per unit effort, predation on catch, and bait effectiveness is derived once gear is retrieved at the surface, thus missing important visual information prior to gear haul-back (High, 1980). Acoustic tagging and acoustic imaging both allow a wide area to be surveyed and can provide information on fish movement around fishing gears (Kallayil et al., 2003; Rose et al., 2005). Moreover, underwater video allows the observation of smaller areas but can give more specific visual information on behaviour around fishing gears (Beutel et al., 2008). These specific differences in behaviour can lead to gear modifications that improve capture efficiency or decrease bycatch of certain species (Løkkeborg et al., 1989; He 1996; Beutel et al., 2008). The Eliminator Trawl designed by Beutel et al. (2008) to avoid the bycatch of Atlantic cod (*Gadus* *morhua*) in the haddock (*Melanogrammus aeglefinus*) fishery is one example which validates incorporating this type of visual data into gear studies. Through video observations it was noted that cod swim downward when encountering haddock trawls whereas haddock swim upward. The introduction of a simple exit hole located in the bottom of the trawl allowed cod that encountered the trawl to easily escape (Beutel et al., 2008).

Underwater video used for *in situ* observations of deep-water species has become a convenient tool for studying marine life and has proven useful in answering many questions related to fisheries (Underwood et al., 2012; Favaro, 2016). Camera deployments eliminate limitations of duration and depth associated with scuba-diving surveys (Stobart et al., 2015). Further, video recordings can be easily revisited as many times as necessary, making it simple to train observers to analyze these recordings and allow for a more cost effective approach to certain types of data collection (Favaro et al., 2012). In fisheries, understanding undesired behaviour of fish (i.e. escapement, stress, or bycatch) in response to different gear features (i.e. types of netting, frames, or bait) can give us insight on how to modify and improve the efficiency of fishing gear.

In the following chapter, I demonstrate the use of underwater video to study fish behaviour in response to a new potting technology in the existing Greenland halibut (*Reinhardtius hippoglossoides*) fixed-gear fishery. By combining catch data from six pot treatments, and behavioural data for two pot treatments designed to target Greenland halibut, I assess these pots for their best features. This chapter will determine whether it is possible to capture appreciable quantities of Greenland halibut with baited pots, and will further contribute to our knowledge of using underwater video to better understand fish behaviour in response to fishing gear. I suggest that the use of underwater video will reveal information not available to us by using catch rate data alone, and will use the video information gathered to make suggestions on how to improve the success of this experimental fishing gear.

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CHAPTER 2: Can Greenland halibut (*Reinhardtius hippoglossoides*) be captured using baited pots? Answering fisheries-related questions using underwater video observations of fish behaviour

Introduction

The Greenland halibut (*Reinhardtius hippoglossoides*) is the most valuable groundfish fishery in the inshore territorial waters of Nunavut, Canada (i.e., Nunavut Settlement Area; NSA) and adjacent offshore waters within Baffin Bay and Davis Strait (i.e., NAFO Divisions 0A and 0B) (Figure 1) (DFO, 2014). The NSA includes waters directly adjacent to Nunavut, extending to the 12-mile limit of Canada's territorial zone. Greenland halibut have a pan-arctic distribution, occurring in cold boreal waters on both sides of the North Atlantic Ocean, with peak abundance in a depth range of 400-1,000 m (Bowering & Nedreaas, 2000). In the Northwest Atlantic, including NAFO Divisions 0A and 0B, gillnets and longlines are the fixed gears used to capture Greenland halibut (DFO, 2014). Longlines are used in the NSA while gillnets and to a lesser extent longlines, are used in adjacent offshore waters. Nunavut communities are highly dependent on their marine resources for survival and economic prosperity (DFO, 2006; Treble & Stewart, 2009). However, pressures from fishing industries can cause adverse impacts to the marine environment that can have negative impacts on ecosystems and threaten the long-term sustainability of fishery resources (Innes & Pascoe, 2010). Areas of concern include the capture of non-targeted species and destruction of seabed habitat (Fangel et al., 2015; Cashion et al., 2018). Research on methods to mitigate these impacts is of value from both industry and environmental perspectives (Fuller et al., 2008; NOAA, 2017).

Although longline and gillnet fisheries are efficient at capturing Greenland halibut, non-targeted species, including many species of invertebrates, fish, seabirds, and cetaceans are also vulnerable to capture (He, 2005; Young, 2010; Fangel et al., 2015). For example, gillnets are banned in the Greenland halibut fishery in Cumberland Sound, Nunavut as a result of concerns about potential bycatch of large marine mammals and Greenland shark (*Somniosus microcephalus*); (DFO, 2014). Moreover, high bycatch rates of Greenland shark in exploratory Greenland halibut longline fisheries within the NSA (Walsh, 2008; Young, 2010) have led to research into modifying longline gear to avoid its capture (Grant et al., 2018; Grant et al., 2019). In addition to capture of non-target species, long soak times in the Greenland halibut gillnet fishery (≥ 5 days) can often lead to the capture of fish of lower quality, including partially eaten or decomposed fish, resulting in lower profits to industry (Savina et al., 2016). Indeed, extended soak times in the Northwest Atlantic and Davis Strait Greenland halibut gillnet fishery have led to high capture rates of non-targeted species (He, 2005), and discarding of dead decomposing Greenland halibut (S. Grant, personal observations, 2014 and 2015) likely leading to loss of revenue.

One of the common predators of Greenland halibut that also causes damage to fixed fishing gear in Arctic and sub-Arctic waters is the Greenland shark (Pike, 1994; Yano et al., 2007). The Greenland shark is the only species of shark that is a permanent resident in Arctic waters, where it is an opportunistic feeder. It is a generalist benthic and pelagic feeder, a known scavenger, and top predator that consumes fish and marine mammals (Ridoux, et al., 1998; Fisk et al., 2002; Yano et al., 2007; McMeans et al., 2010; Leclerc et al., 2011; 2012; Idrobo & Berkes, 2012, Devine et al., 2018). The Greenland shark is the most common bycatch species by biomass in established and exploratory longline fisheries for Greenland halibut in the NSA on the east coast of Baffin Island. Bycatch rates of 6.3 sharks/1000 hooks (90,500 hooks total) have been reported in exploratory longline fisheries during the ice-free season (Young, 2010) and as high as 6.9 sharks/1000 hooks (4,200 hooks total) during exploratory winter longline fisheries (Walsh, 2008). Greenland sharks captured on longlines are often severely entangled (Pike, 1994; Grant et al., 2018) which results in sharks being killed by fishers (Young, 2010, Idrobo & Berkes, 2012;) or released with trailing fishing gear (Grant et al., 2018) which has been demonstrated to lead to high unaccounted fishing mortality in some species of sharks (Sepulveda et al., 2015).

Past studies aimed at mitigating harm or the unintentional capture of Greenland sharks in Nunavut's Greenland halibut longline fishery have proved challenging. For example, magnetic and electropositive metal-treated hooks did not deter Greenland sharks from feeding on longlines (Grant et al., 2018). Some evidence suggests that switching from multifilament to monofilament fishing line in gangions can reduce the capture of Greenland shark in Greenland halibut longline fisheries (Grant et al., 2019). However, the reduction in catch rates was attributed in part to increased hook bite-offs by Greenland sharks. Hook bite-offs could influence unaccounted fishing mortality when hooks are swallowed or left hanging by the mouth to interfere with normal feeding behaviour (Borucinska et al., 2002). In addition to these mitigation plans, the introduction of baited pots was seen as an alternative to mitigating the capture of Greenland shark during the open water season in Nunavut's Greenland halibut fixed gear fisheries.

The introduction of baited pots in Greenland halibut fixed gear fisheries in Nunavut's inshore territorial waters and adjacent offshore waters has the potential to provide substantial environmental benefits as well as economic gains to the fishing industry. For example, many of the non-targeted species captured in pots can be released alive and unharmed (Grant, 2015). In the event of inclement weather, soak time has limited influence on market quality of pot-caught fish, and ghost fishing of lost pots can be prevented with the use of biodegradable materials (Thomsen at al., 2010; Suuronen et al., 2012). Discarding of targeted species captured in gillnet and longline fisheries, resulting from death, decomposition, and damage from scavengers, is reduced in potting fisheries and pots can be modified to avoid harvesting of undersized fish by adjusting mesh size (Ovegård et al., 2011; Königson et al., 2015a;2015b; Hedgärde et al., 2016). By introducing pots, loss of product from Greenland shark or cetacean depredation (Pike 1994; Dyb, 2006; Mesnick et al., 2006) can be eliminated and costs can be reduced as less bait is needed and tending baited pots is less labour-intensive than methods currently used in Nunavut's Greenland halibut fixed gear fisheries (Grant, 2015).

Initial efforts to use baited pots to capture Greenland halibut in Canadian waters was done using Newfoundland-style cod pots (Newfoundland pot, hereafter) (Murphy, 2014). However, the pots used by Murphy (2014) failed to capture appreciable quantities of Greenland halibut in Newfoundland waters. Because Atlantic cod and Greenland halibut differ considerably in morphology and behaviour, the ability to capture large numbers of each species may require different pot designs and potting strategies. More recent potting studies attempted the use of Norwegian-style cod pots (Norwegian pot, hereafter) (Grant, 2015) which are smaller, cheaper, and light weight, therefore can be fished more easily in large numbers. Having several smaller pots in a string allows Greenland halibut fishing industry to cover a greater area of the seabed, similar to longline and gillnets. Results from the Norwegian pots were encouraging, with up to 20 Greenland halibut (32 kg) captured in a pot in overnight sets (Grant, 2015). Moreover, pots were found to outperform longlines, capturing five times more Greenland halibut when catches were standardized for the linear distance of the fishing gears on the seabed (Grant, 2015).

Globally, fishing gear technologists and fisheries scientists developing potting technologies are struggling to find ways to maximize catch rates in order to make pots more commercially appealing (Suuronen et al., 2012; Esyrs & Pol, 2018). When fishing gear studies are based on catch rate data alone they suffer from a lack of knowledge with regard to the capture efficiency. For example, 100 fish may approach a baited pot but if only 10 are landed then the capture efficiency is only 10%. By observing the number of fish that approach a baited pot and the behaviour of these fish as they interact with a pot, we can assess the effects of varying the design features and construction materials so as to maximize the number of fish that enter a pot and minimize the number escaping (Anders et al., 2016; Winger et al., 2016; Meintzer et al, 2018). Thus, it is hypothesized that underwater video camera observations investigating factors influencing the rate at which Greenland halibut approach, enter, and exit a pot could be used to better design a pot and improve fishing methods that will maximize catch rates. For example, a preliminary study involving underwater video camera observations of Greenland halibut interacting with a Norwegian pot revealed that halibut became entangled by their teeth in the monofilament diamond netting of the entrance funnel and square mesh netting in the side panels of the pot (S. Grant, 2015, unpublished data). Based on these observations, it was hypothesized that modifications to a pot that are designed to reduce entanglement would increase capture efficiency of this species.

In this study, I investigate whether modifications to the Norwegian pot, designed to reduce the likelihood of entanglement in the entrance and side panels, affect capture rates of Greenland halibut while avoiding the capture of Greenland sharks. All species captured incidentally are also reported. Strings of experimental pots were deployed on Greenland halibut fixed gear commercial fishing grounds located in offshore waters of NAFO Division 0A (Figure 1). A large part of the success of experimental fishing gear relies on knowing how target and non-target species react to a new fishing gear so that potential obstacles to acceptance on the part of industry can be addressed (Fernö, 1993; Anders et al., 2016). In the current study, I use analysis of video observations to improve our knowledge of Greenland halibut behaviour in response to existing elements and modifications made to the entrance of the Norwegian-style cod pot.

Goals

- To determine whether modifications made to the Norwegian pot increase catch rates and capture efficiency of Greenland halibut.
- Demonstrate the value of video observations in identifying obstacles that negatively influence behaviour and capture efficiency of fish as they interact with different components of a pot.
- Demonstrate value of video observations when interpreting catch results.

These goals will be addressed by answering the following research questions:

1. Does CPUE (by total counts or total weight) of Greenland halibut captured in pots differ among pot treatments or by the number of overnight sets (soak time)?
2. Does the percent bycatch captured in baited pots differ among pot treatments?

3. Does Greenland halibut behavior (i.e. aggressiveness, number of entanglements, or interaction rates) differ among pot treatments?
4.

Materials and Methods

Fishing Trials

All pot treatments tested during this study were based on a commercially available two entrance Norwegian pot designed by the Institute of Marine Research (IMR) in Bergen, Norway to target Atlantic cod (Furevik et al., 2008; Ovegård et al., 2011) (Figure 2). The Norwegian pot is fully collapsible and there is a horizontal panel (i.e. parlour entrance) that separates the pot into two chambers; a lower entrance chamber and an upper fish retention zone referred to here as the parlour. The parlour entrance is constructed with buoyant 58 mm black polypropylene netting, with a longitudinal slit in the center of the netting that allows fish to swim into the parlour, while making it difficult for fish to find their way back into the entrance chamber. Entrance funnels are constructed with 50 mm clear diamond monofilament nylon netting. The entrance hole measures 28 cm × 16 cm (width × height). Pot dimensions are 1.5 m x 1.0 m x 1.2 m (length × width × height) with 12 mm galvanized round steel in the lower frame and 10 mm aluminum in the mid and upper frames. The exterior netting in the side and end panels of the pot are constructed with 58 mm black square nylon netting. The six shallow water Rosendahl floats described by Furevik et al. (2008) were replaced with two 20 cm diameter deep-water trawl floats with a working depth rating of 1,700 m and buoyancy rating of 2.3 kg. In addition, all salvages and mesh attachments to the frame of the pot were reinforced with 2 mm black mending twine.

This study tested three different diamond nylon netting mesh sizes (i.e., 3 mm green twine, 19 mm clear monofilament, and 50 mm clear monofilament) in the entrance funnel of the Norwegian pot. Fishers expressed concern that the light weight construction of the Norwegian pot would not withstand the rigors of fishing in deep water environments (i.e., >900 m) where they targeted Greenland halibut (Grant, 2015). For this reason, three entrance funnel mesh sizes were also tested in a more durable, partially collapsible pot. The lower entrance chamber of these pots were constructed with 35 mm bar length × 3.5 mm diameter square PVC coated rigid wire mesh. Pots constructed with wire mesh are referred hereafter as wire pots, while pots constructed entirely with the original black nylon mesh will continue to be referred to as the Norwegian pots. Fabrication of the wire pot simply involved attaching the horizontal separator panel and upper chamber from a Norwegian pot onto a lower chamber constructed of wire mesh. The wire mesh lower chamber was strengthened by attaching the 12 mm diameter galvanized round steel frame from a Norwegian pot to the base. All dimensions (i.e., length × width × height) were the same for each chamber of the wire pot and original Norwegian pots used in this study. Allowing the pot to be partially collapsible by maintaining nylon mesh in the upper chamber was seen as a means of conserving space on board commercial vessels, thereby allowing vessels to carry more pots.

Treatment codes for Norwegian (N) and wire (W) pots with varying entrance meshes are as follows:

N_{3mm} = Norwegian pot with 3 mm green nylon entrance

N_{19mm} = Norwegian pot with 19 mm clear monofilament nylon entrance

N_{50mm} = Norwegian pot with 50 mm clear monofilament nylon entrance

W_{3mm} = Wire pot with 3 mm green nylon entrance

W_{19mm} = Wire pot with 19 mm clear monofilament nylon entrance

W_{50mm} = Wire pot with 50 mm clear monofilament nylon entrance

Two strings of pots containing five replicates of each of the six experimental pot treatments spaced at 55 m intervals were fished for a total of 30 pots per string. Space limitations on board the fishing vessel led to preparing the strings with 15 wire pots on one end and 15 Norwegian pots on the other end of a string with the three wire and Norwegian pot treatments randomly distributed within each group of 15 pots. Each pot was baited with 1 kg of frozen squid (*Illex sp.)* cut in pieces and placed in small mesh (2 mm) bait bags that were hung in the center of the lower entrance chamber of the pot mid-way between the two entrances (i.e., approximately 0.3 m above the seabed). The pot strings were deployed on offshore Greenland halibut fixed gear fishing grounds in NAFO Division 0A from 18-29 October 2016 (Figure 1).

This study took place on board a commercial fixed gear fishing vessel (*MV Kiviuq I*) and all pot strings were deployed and tended by experienced longline fishers. Potting experiments took place at the same time as the commercial gillnet fishery for Greenland halibut. To compare catch rates among fixed fishing gears, at the request of the fishing industry, experimental strings of pots were deployed in an approximately 4-5 km wide corridor between strings of baited gillnets that were set by fishers in the Greenland halibut fishery. Commercial vessels fishing in the area deployed ten strings of 50 gillnets baited with squid immediately north and south of the potting corridor (i.e., 20 strings total). Strings of gillnets and pots were set in an east to west orientation and distance between the strings was about 1 – 2 km. Each gillnet was 91.4 m in length. Small mesh bait bags (n=5-10) containing approximately 1 kg of squid were evenly spaced along the head rope, corresponding to a vertical distance of approximately 2.5 m above the seabed and a bait bag every 9-18 m (S. Grant, unpub. data). Each string of gillnets was 4.6 km in length and left to soak for five or more days. Prior to our experiments, commercial gillnet vessels had been fishing on these grounds for over two months.

Strings of experimental pots were intended to soak for one night, but soak times ranged from 1 to 3 nights due to inclement weather. Mean depth at the potting sites ranged from 1,008-1,278 m, however because the gear was set on sloped seabed the depth range varied from 35 to 104 m at a potting site. Weather conditions and working within a narrow corridor resulted in the wire pots being deployed within the deeper waters at a potting site in 75% of the deployments.

All fish caught in pots were identified to species (Scott & Scott, 1988; Kulka et al., 2007). Total mass (± 1 kg) of each species was weighed using a scale and individual body lengths (± 1 cm) were measured using a fish board. Total-length was measured for fish without forked tails and fork-length was measured for fish with forked tails. Catch per unit effort is expressed as the total weight ($CPUE_W$) and total number ($CPUE_N$) of Greenland halibut captured in a pot. The contribution of each non-targeted species to the total catch weight was calculated for each pot.

All pots were visually inspected prior to redeployment. Damage such as torn netting or bending of the frame was recorded, and pots were repaired or replaced prior to deployment. When damage was severe enough to allow escapement of fish, the data from that pot were excluded from further analysis.

All data analysis was done using the software R (R Development Core Team, 2009), therefore all "packages" mentioned hereafter refer to data packages loaded in R. Each pot treatment was sampled though multiple deployments for each fleet of gear, therefore, for the CPUE data, Generalized Linear Mixed Models (GLMM) were used. GLMMs are able to handle unbalanced data that include a mix of random and fixed independent variables. Independent variables were pot type (fixed), soak time (fixed), and fleet (random) which was nested within deployment (random). Soak time was treated as a categorical covariate (1 night, 2 nights, and 3 nights), which corresponded to soak codes 1, 2 or 3 (Eq 1). Equations are presented as outlined in Zuur & Ieno (2016).

Eq 1: $CPUE_{Wijk} \sim Gaussian\ (\mu_{ijk})$

$E(CPUE_{Wijk}) = \mu_{ijk}$

$CPUE_{Wijk} = PotType_{ijk} + SoakCode_{ijk} + PotType_{ijk} \times SoakCode_{ijk} + Fleet_{jk} + Day_k$

$Fleet_{jk} \sim N(0, \sigma^2)$

$Day_k \sim N(0, \sigma^2)$

where $CPUE_{Wijk}$ is the jth observation in fleet jk and day k, and Fleet and Day are the random intercepts, which is assumed to be normally distributed with mean 0 and variance σ^2. When comparing $CPUE_N$ among treatments, the same variables previously described were used; however, a GLMM with a negative binomial error structure was found to be more fitting for counts data (Eq 2).

Eq 2: $CPUE_{Nijk} \sim \text{Negative Binomial}\ (\mu_{ijk})$

$$E(CPUE_{Nijk}) = \mu_{ijk}$$

$$CPUE_{Nijk} = PotType_{ijk} + SoakCode_{ijk} + PotType_{ijk} \times SoakCode_{ijk} + Fleet_{jk} + Day_k$$

$$Fleet_{jk} \sim N(0, \sigma^2)$$

$$Day_k \sim N(0, \sigma^2)$$

where $CPUE_{Nijk}$ is the jth observation in fleet jk and day k, and Fleet and Day are the random intercepts, which is assumed to be normally distributed with mean 0 and variance σ^2. The lme4 R package in version 1.1-17 (Bates et al., 2014) was used to for the models in equations 1 and 2. Analysis of percent bycatch per pot treatment was ran using the same independent variables, but a beta error structure was required to fit the model since the dependent variable was now a proportion (percent bycatch) (Eq 3).

Eq 3: $Bycatch_{ijk} \sim \text{Beta}\ (\pi_{ijk})$

$$E(Bycatch_{ijk}) = \pi_{ijk}$$

$$Var(Bycatch)_{ijk} = \pi_{ijk} \times (1 - \pi_{ijk})/(1 + \Theta)$$

$$Logit(\pi_{ijk}) = PotType_{ijk} + SoakCode_{ijk} + PotType_{ijk} \times SoakCode_{ijk} + Fleet_{jk} + Day_k$$

$$Fleet_{jk} \sim N(0, \sigma^2_{Fleet})$$

$$Day_k \sim N(0, \sigma^2_{Day})$$

where $Bycatch_{ikj}$ is the *j*th observed rank difference between fleet *jk* and day *k*, and ϴ is an unknown parameter controlling the variance. This model was built using the package glmmTBM version 0.2.3 (Brooks et al., 2017).

To compare mean body lengths of halibut captured among pot treatments, a Generalized Mixed Model (GLM) was used to fit the data. The dependent variable was length (continuous), and independent variables were pot type (fixed) and fleet (random). All model assumptions were verified by plotting residuals versus fitted values, versus each covariate in the model and versus each covariate not in the model. Model validation indicated no problems.

Video Observations

Most video sets were recorded at the same time and in the same area as fishing trials in NAFO Division 0A at a depth range of 828-1,254 m. Additional underwater video observations were conducted at depths of 914-1,234 m on offshore Greenland halibut fixed gear fishing grounds in NAFO Divsion 0B from 7-13 October 2016 (Figure 1). Commercial fishing had ceased in NAFO Division 0B for the year during our study. Due to the challenges of recording usable video in deep water, we were only able to obtain sufficient video of Greenland halibut interacting with two pot treatments, N_{50mm} and N_{19mm}.

Pots were attached to an aluminum observation frame (Meintzer et al., 2017) (Figure 3) to permit observations of the pot from above (Favaro, 2016). Two red LEDs built for deep-water observations were used for lighting. Red light is commonly used for deep-water observations since it is known to be less visible to fish and crustaceans than white light (Rooper et al., 2015; Nguyen et al., 2017). A 1Cam Alpha HD video camera and battery packs were securely attached to the frame, with the camera pointed downward toward the pot, giving an overhead view of the activity within 1 m of the pot. To avoid obstructing the overhead view of fish within a pot, the floats were removed before it was mounted to the camera frame. To keep the pot open, twine was used to tether the pot to the camera frame. Underwater video was recorded up to 20 hours per day and the system was set to film in 30 minute intervals, downloading video to an internal USB hard drive between sets to avoid data loss. In total, 8 camera sets (83 hours of video) of the N_{50mm} pot and 4 camera sets (55 hours of video) of the N_{19mm} pot were analyzed. The information gathered included, but was not limited to:

1. Approach - when a fish entered the camera field of view.
2. Direction of the approach relative to current direction ascertained from movement of particles in the water column.
3. Encounter - a fish contacted the frame or netting.
4. Entry attempt - a fish entered an entrance funnel.
5. Entanglements and entanglement location - a fish became entangled in the netting in the entrance funnels, parlour entrance, or side panels.
6. Entry - a fish entered the entrance chamber.
7. Escape - a fish exited through an entrance funnel after entering.

8. Aggressive (appeared to be seeking escape route) or neutral (resting on the floor of the entrance chamber or parlour) behaviour within the first 30 seconds of entering the lower entrance chamber or upper parlour

Observational data was used to look at the relationship between the number of entanglements and the location in the pot where entanglements occurred. The model was fit using a GLMM with a negative binomial error structure in the lme4 package version 1.1-17 (Bates et al., 2014). The independent variables were the fixed variables location (entrance funnel, entrance chamber, parlour entrance, or parlour), pot type (N_{19mm} or N_{50mm}) and the random factor day, in which entanglement location was nested in. Further, chi-square tests were used to determine whether aggressive or neutral behaviour were related to entrance type (19 mm or 50 mm monofilament) or location (entrance chamber or parlour).

Scores on halibut behaviour were used to calculate:

Encounter rate = n_{fov}/n_{enc},

Entry rate = n_{cap}/n_{entr},

Escape rate = n_{esc}/n_{cap},

Parlour entry rate = n_{upp}/n_{cap}, and

Capture rate = $(n_{cap} – n_{esc})/n_{entr}$

where: n_{enc} = number that entered the video camera field of view; n_{fov} = number that came in contact with the frame or netting; n_{entr} = number that attempted to enter an entrance funnel; n_{cap} = number that successfully entered; n_{esc} = number that escaped; and n_{upp} = number that entered the parlour. T-tests were used to compare the mean capture rates between the two pot treatments.

Since one fish could entangle multiple times, I explored the relationships among the number of entanglements observed at the pot entrance to the subsequent entanglements that occurred once fish were inside the pot. On top of this, I then considered if a relationship between entanglements and escapement existed. These two models were analyzed using linear mixed models (LMM) fit by restricted maximum likelihood. For the relationship of entrance entanglement and subsequent entanglements within a pot, the dependent variable was number of observed entanglements after entering a pot, fixed effect was entanglement at the pot entrance, and the random effect was pot. For the effect of number of entanglements in a pot on escapement the dependent variable was number of entanglements within the pot, fixed effect was escapement, and random effect was pot. This model was also fit using the lmer function in the lme4 package version 1.1-17 (Bates et al., 2014). For all boxplot figures (comparing more than two groups) in the results section, the letters “A” and “B” are used to represent variables that differ significantly.

This project was reviewed and approved by Memorial University’s Institutional Animal Care Committee (Project # 15-04-SG).

Results

Fishing Trials

A total of 2,439 Greenland halibut were caught in the 12 potting sets in NAFO Division 0A. Fifty-eight of these fish were omitted from the catch data because they were captured in damaged pots. Catches were highly variable within and among treatments (Figure 4). Mean catch per unit effort based on weight ($CPUE_W$) and counts ($CPUE_N$) did not differ significantly among treatments ($F_{5,304} = 0.88$, $p = 0.497$ and $F_{5,304} = 2.18$, $p = 0.056$, respectively) (Figure 4). However, since $CPUE_N$ was marginally insignificant, a Tukey post hoc analysis was carried-out which revealed the number of fish caught in the N_{19mm} and W_{3mm} pots did differ ($p = 0.042$), with the former capturing a significantly higher mean number of Greenland halibut than the latter (i.e., 8.8 fish/ pot versus 6.4 fish/pot, respectively) (Figure 4b).

When $CPUE_W$ was pooled across the wire and Norwegian pots for each entrance mesh size, catches differed significantly between entrance mesh sizes ($F_{2,307} = 3.53$, $p = 0.031$). Tukey post-hoc analysis revealed the only difference was a higher mean $CPUE_W$ in pots with the 19 mm entrance over that of the 3 mm entrance ($p = 0.019$) (Figure 5). When $CPUE_W$ was pooled across all entrance mesh sizes for the wire and Norwegian pots, catches did not differ significantly ($F_{1,308} = 0.97$, $p = 0.326$) (Figure 6).

Body length differed significantly between treatments ($F_{5,2433} = 2.408$, $p = 0.035$). Post-hoc analysis revealed the difference was only between catches in the N_{19mm} and W_{3mm} treatments, with halibut in the former having higher body length than the latter ($p = 0.027$). A comparison of the mean body length among all wire pots combined (i.e., 56.5 ± 6.5 cm, n = 1215) and all Norwegian pots combined (i.e., 57.1 ± 6.8 cm, n = 1224) found a significant difference between body lengths of fish between Norwegian and wire pots ($t_{2437} = 2.21$, $p = 0.027$) (Figure 7). No significant difference in body length was found among pots with different entrance mesh sizes ($F_{2,2436} = 0.83$, $p = 0.438$). The mean total body length of all Greenland halibut captured in pots was 56.8 cm.

In total, 31 of the 2,439 Greenland halibut captured during this study were dead when the pots were hauled aboard the vessel (1.3%). Most mortalities (77%) were entangled by their teeth in netting. An additional 19 Greenland halibut were entangled in the netting when pots were hauled and, although they were not dead, they exhibited a limited physical response when grasped by the caudle peduncle. Overall, 43 (1.8%) of the Greenland halibut captured were entangled in the netting when pots were hauled. Thirty-five of these fish were entangled in nylon netting in the side and end panels and the parlour entrance; eight were entangled in the 50 mm entrance funnel. There were no Greenland halibut entangled in the 19 mm or 3 mm entrance funnels. All remaining Greenland halibut captured in pots were alive and active when the pots were hauled, and exhibited an active response when grasped by the caudal peduncle. We did however record 12 Greenland halibut that exhibited gillnet scars, mucus loss, scale loss, and bruising patterns, which is indicative of escaping or falling out of gillnets that were set in close proximity to the potting sites.

No interaction was found between soak time codes and pot treatments for $CPUE_N$ ($F_{10,294} = 0.59$, $p = 0.819$) or $CPUE_W$ ($F_{10,294} = 1.28$, $p = 0.243$). However, soak time code did have a significant effect on $CPUE_W$ ($F_{2,307} = 19.73$, $p < 0.001$). Tukey pots-hoc analysis revealed catches in the 25-48 h and 0-24 h soak time intervals differed, with the former exhibiting significantly higher catches than the latter ($p < 0.001$) (Figure 8). Our results indicate strings set for two nights with the best performing pot (N_{19mm}) would yield a mean $CPUE_N$ of 11.8 and mean $CPUE_W$ of 21.1 kg of Greenland halibut per pot.

Torn nylon netting in the floor of the entrance chamber was recorded with three of the Norwegian pots. Two tears were large enough to allow Greenland halibut to escape, and appear to have resulted from contact with the seabed during haul-back. Thirteen of the wire pots had tears in the nylon meshes of the parlour. Most (11) of these were minor and not large enough to allow fish to escape. The tears resulted from the nylon netting hooking on the wire framing of the entrance chamber during deployment and in one case the upper chamber (parlour) did not open fully when a pot was deployed. Hooking of the nylon mesh on the wire frame was common and created a hazardous situation for fishers during deployment. The framing was not bent on any of the Norwegian pots. However, in two of the wire pots, the wire mesh in the entrance chamber at the lanyard end was bent and clips holding sections of wire mesh together were broken. The wire was bent back into place and wire sections lashed together with twine. The damage continued during subsequent deployments and because suitable equipment was not available to reattach the wire sections these pots were replaced. The damage occurred as the wire pots were dragged across the seabed during haul back. The broken attachments did not influence escapement of fish but continued use would compromise the integrity of the pot and increase the chances of the pot being lost on the seabed.

Bycatch

Eight species were captured incidentally during the experiments (Table 1). Bycatch of all non-targeted species combined expressed as a percentage of total catch weight in a pot did not differ significantly among the six treatments ($F_{5,304} = 0.29$, $p = 0.918$). Atlantic wolffish (*Anarhichas lupus*), threebeard rockling (*Gaidropsarus ensis*), and silver rockling (*Gaidropsarus argentatus*) dominated the bycatch by weight accounting for 39%, 31%, and 13% respectively of all non-targeted species. The rocklings were most prevalent in numbers, exhibiting the highest frequency of occurrence among pot treatments followed by the Atlantic wolffish. Three large (2-3 m) Greenland sharks were observed interacting with the pots in the video analysis, however none tried to bite or break into pots, nor did they become entangled in or damage the pots.

All wolffish captured in baited pots were alive, active (exhibiting physical resistance and biting reflex when grasped by the caudal peduncle), and in good physical condition with no external wounds. Similarly, threebeard rockling, silver rockling, spinytail skate (*Bathyraja spinicauda*), polar eelpout (*Lycodes polaris*), and polar sculpin (*Cottunculus microps*) captured in baited pots were alive and active when handled and did not exhibit external wounds. When handled, spinytail skates curled their tails over the body and they maintained this posture as they descended through the water column when returned to the ocean. Apart from the roughhead grenadier (*Macrourus berglax*), all remaining species were observed to descend and swim away when quickly returned to the ocean. Due to the presence of a swim bladder, roughhead grenadier experienced barotrauma during haul-back, were moribund, and did not descend when returned to the ocean.

Video observations

A summary of the visual information gathered for each pot treatment is illustrated in Table 2. Overall, fewer Greenland halibut were observed to approach the $N_{19\ mm}$ pot treatment and mean approach rates were 1.1 fish/h compared to mean approach rates of 5.6/fish per hour in the $N_{50\ mm}$ pot treatment. These differences in approach rates are attributed to all of the observations with the $N_{19\ mm}$ pot treatment being carried out at sites immediately adjacent to 4.6 km strings of heavily baited gillnets in NAFO Div 0A. Observations with the $N_{50\ mm}$ pot treatment were made in NAFO Div 0B on fixed gear fishing grounds that had been abandoned for the season. In addition, to avoid gear conflicts with gillnet fishers in 0A and strings of experimental pots within the narrow fishing corridor provided for our study, the camera system was deployed at suboptimal depths outside of the primary fixed gear fishing grounds for two deployments. However, even when the camera system was deployed within the optimal depths on the fixed gear fishing grounds in 0A the maximum encounter rates were 1.2-1.7 fish/h in the $N_{19\ mm}$ pot treatment compared to maximum encounter rates of 7.3-9.3 fish/h in the $N_{50\ mm}$ pot treatment in 0B.

Most (80%) of the Greenland halibut approached pots against the current (Table 3). The downstream entrance of the experimental pots was aligned with the bottom current in 52% of the approaches. Overall, 70% of entry attempts and 67% of successful entries occurred when the entrance was aligned with the current and when fish approached a pot against the current. Analysis indicated there was no significant difference in encounter rate ($t_{11} = 0.84$, $p = 0.418$), successful entry rate ($t_8 = -0.83$, $p = 0.431$), escape rate ($t_8 = 0.80$, $p = 0.449$), parlour entry rate ($t_8 = -0.87$, $p = 0.412$), or capture rate ($t_8 = -2.09$, $p = 0.070$) between the N_{50mm} and N_{19mm} pot treatments (Figure 9). Nevertheless, in the N_{19mm} pot treatment, successful entry rates were 45% higher and escape rates were 56% lower which resulted in a 109% increase in capture rates compared to the N_{50mm} pot treatment.

Greenland halibut commonly entangled in the nylon netting in the pots and most of the entanglements were by their teeth (Table 2). However, two fish were also observed to become entangled by their tail in the parlour entrance. The majority of entanglements by the teeth occurred in the entrance funnel and the entrance to the parlour (Table 2). Analysis indicated Greenland halibut entangled significantly more often in the entrance funnel of the N_{50mm} pot treatment than in the N_{19mm} pot treatment ($F_{1,11} = 5.82$, $p = 0.034$) (Figure 10).

All of the fish that became entangled in the entrance funnels of both pot treatments exhibited active behaviour, rapidly twisting and turning and moving forward and backward until they were able to free themselves within 6 to 187 seconds (mean = 43 seconds) with 41% exiting the entrance funnel and rapidly swimming out of the camera's field of view. The other 59% entered the entrance chamber with 77% continuing to exhibit active behaviour by rapidly swimming about. Linear mixed model analysis revealed the number of entanglements observed after a fish entered a pot was significantly related to entrance entanglement ($p = 0.004$) but the number of entanglements that occurred after fish entered a pot did not appear to influence escapement ($p = 0.654$). However, I was not able to track all fish individually throughout their residency within a pot. Rather my observations of behaviour of escapes were limited to immediately prior to escapement. Overall the number of entanglements of Greenland halibut by their teeth ranged from 1 to 12 (mean = 4.6) per pot.

Overall, 37% of the Greenland halibut that entered the pot treatments were observed to escape through the entrance funnel (Table 2). Eleven of the 18 fish (61%) exited within one minute of entering a pot, three exited within an hour (17%), and the remainder (22%) exited over the next 1-4 hours. Four of the fish that exited within one minute were observed to enter one entrance and swim directly out the opposite entrance. Of the fish that exited a pot, 67% (12/18) exhibited aggressive behaviour immediately prior to exiting and 42% (5/12) of these fish were observed to entangle in the netting immediately prior to escapement. Aggressive fish were observed to intermittently swim about rapidly within a pot bumping into the netting in the side panels and parlour entrance. Chi-square tests revealed no significant difference in aggressive behaviour within the first 30 seconds upon entering a pot among fish in the N_{50mm} and N_{19mm} pot treatments ($X^2_{(2, N = 70)} = 2.34$, $p = 0.126$). Sixty one percent of fish were aggressive in the N_{50mm} pots and only 41.7% were aggressive in the N_{19mm} pots. Conversely, fish in the entrance chamber (where 66.7% of all fish showed aggression) were found to show significantly more aggression than those in the parlour (where 27.3% behaved aggressively) ($X^2_{(2, N = 70)} = 9.43$, $p = 0.002$).

On four separate occasions I was able to observe the behaviour of Greenland halibut as a pot was hauled to the surface. When fished in a string, pots are attached to the ground line by a lanyard that is tied to the steel frame on the bottom of a pot which results in pots ascending through the water column at about 45°. This resulted in the fish falling back into the lowest section of the parlour or entrance chamber of a pot. None of the Greenland halibut made any effort to escape when hauling commenced or as a pot ascended to the surface.

Discussion

This study was part of an ongoing effort to develop a deep-water pot that is suitable for capturing large quantities of Greenland halibut while minimizing the incidental capture and gear depredation caused by non-targeted species including Greenland shark. I hypothesized that the use of alternate netting materials in various components of the original Norwegian pot would prevent entanglement of Greenland halibut and increase the number of Greenland halibut that successfully entered a pot. Video observations disclosed that significantly fewer Greenland halibut entangle in the entrance funnel of the $N_{19\ mm}$ pot treatment compared to the $N_{50\ mm}$ pot treatment. Further, mean entrance rates were 45% higher, and mean capture rate was 109% higher in the $N_{19\ mm}$ pot treatment. Overall, 41% of the fish that entangled in the entrance funnels, irrespective of netting mesh size, did not successfully enter a pot and of those fish that entangled in the entrance prior to entry, a high percentage (79%) exhibited aggressive behaviour that led to substantial additional entanglements upon entering a pot. Video observations revealed a surprisingly high rate of escapement but the total number of entanglements observed by Greenland halibut once they entered a pot did not appear to influence escapement. I was however unable to track individual fish throughout their residency in a pot so it is unclear to what extent entanglement in the side panels of the entrance chamber contributed to escapement. Video observations also revealed that the majority of Greenland halibut approached a baited pot against the current providing evidence of chemically mediated rheotaxis (Løkkeborg et al., 1989). This study also demonstrates the importance of having the entrance funnel aligned with the prevailing bottom current as the majority of the entry attempts and successful entries occurred when Greenland halibut approached a pot against the current and when an entrance was aligned with the current.

I found no differences in $CPUE_W$ among pot treatments, and the difference in $CPUE_N$ was limited to only two of the six treatments. The catch results demonstrate that a substantial quantity of Greenland halibut can be captured in two overnight soaks of a baited pot with a maximum $CPUE_N$ and $CPUE_W$ of 21 fish and 38 kg, respectively. However, catch rates were highly variable within pot treatments and the mean catch rates were well below those obtained in baited commercial gillnets set immediately adjacent to the potting sites.

Grant et al. (2015) demonstrated that baiting gillnets used to target Greenland halibut in offshore waters of Davis Strait (NAFO Div. 0B) increased catch rates by 240-350% over non-baited gillnets and catch rates of some non-targeted species were also significantly higher in baited gillnets. Indeed, Greenland halibut landings (i.e., catch excluding discards) in individual strings of 50 baited gillnets set adjacent to the potting sites during the current study were about 9,000-10,000 kg per string (Captain M. Letto, pers. comm.). This corresponds to 108-120 kg when standardized to a 55 m section of a string of gillnets which was also the distance between pots in a string. These standardized gillnet catch rates were 5.1-5.7× the maximum mean catch rate observed in two overnight soaks of the $N_{19\ mm}$ pot treatment during this study (21 kg). The higher catch rates in baited gillnets can be explained by a number of factors including: increased concentration of chemical attractants in the baited gillnets (i.e., a bait bag every 9-18 m in gillnets vs. every 55 m in a string of pots), horizontal range of attraction relative to increased chemical concentration and vertical distance bait was off the seabed (i.e., 2.5 m in gillnets vs. 0.3 m in baited pots), extended soak time of gillnets (i.e., five or more days vs. 1-3 days in baited pots), and continuous release of feeding attractants by self-baiting gillnets resulting from dead and decomposing Greenland halibut and non-targeted species. Further, depending on swimming direction, Greenland halibut would have to navigate through several 4.6 km long strings of baited gillnets before they encountered the baited pots. Lastly, gillnets entangle fish while pots trap fish, therefore the longer pots are fished could increase the likelihood of escapement thus reducing catch rates.

Atlantic cod can detect and locate the chemical bait source in longlines from distances of 600-700 m (Løkkeborg et al., 1989). Additionally, Kallayil et al. (2003) demonstrated that acoustically tagged Atlantic cod could be attracted to a string consisting of two baited gillnets from 400-800 m away. I suspect that during the current study, the increased level of baiting carried-out by Greenland halibut gillnet fishers and the length of a string of gillnets combined to not only attract halibut from even greater distances then those reported by Løkkeborg et al. (1989) and Kallayil et al. (2003) but also increased the density of halibut around the gillnets, negatively influencing the availability of halibut to the potting gear. These conclusions are supported by the lower mean approach rates of Greenland halibut (i.e., 1.1 fish/h) in my video observations when a baited pot was set in close proximity to baited gillnets in NAFO Div. 0A compared to mean approach rates (i.e., 5.5 fish/h) when a baited pot was set on fixed gear fishing grounds that had been abandoned for the season in NAFO Div. 0B.

Overall, the results of this study show catch rates that may not reflect real-world performance because of the presence of gillnets. In addition, fishing strings of pots in close proximity to baited gillnets may have disproportionately influenced the availability of Greenland halibut to the different pot treatments within a string of pots and subsequently catch rates among pot treatments. When it comes to the influence of baited gillnets on catch rates among the pot treatments the critical question is, would we expect to obtain the same trends in catch rates if these pot treatments were tested in the absence of direct competition from 100s of baited gillnets and the absence of prolonged heavy fishing pressure within the study area? All things considered, it is conceivable that conducting the potting experiments in such close proximity to heavily baited gillnets influenced the results in at least one manor. Therefore, ambiguity was created with the conclusions in regards to either the performance of the pots or potentially in the relationships between catch rate and pot type.

This study demonstrates the value of *in situ* observations for guiding decisions with regard to the best features to incorporate into a baited pot to minimize negative encounters and maximize catch rates of targeted species. By observing the number of fish that approach a baited pot and behaviour as they interact with various components of a pot we can assess the effects of varying design features and construction materials. We can never know how many fish approached and interacted with a pot when we assess suitability of various modifications using only catch rate data from strings of experimental pots. Ultimately, the use of catch rate data alone can increase the risk of drawing erroneous conclusions.

Unfortunately, I was unable to observe the effects of the 3 mm green nylon mesh on entanglement, entry success, and behavior for the current study. However, given the reduction in entanglement with a decrease in mesh size of the monofilament netting it stands to reason that the level of entanglement and aggressive behaviour should be reduced in pots with 3 mm entrance funnel netting. The significant decrease in entrance entanglements observed in the

N_{19mm} pot over the N_{50mm} pot contributed to a moderately higher entry rate. Subsequently, a reduction in entrance entanglements was shown to lead to a significant reduction in entanglements after entering a pot and is indicative of an overall reduction in aggressive behaviour. This can explain the increased capture rates in the N_{19mm} pot from a reduction in escapement. Video observation data confirmed halibut that entangled in entrances were more likely to entangle in additional pot locations once they entered. For this reason, I suspect that using a smaller mesh in entrance funnels (19 mm or smaller) would reduce entanglements in the entrance as well as subsequent entanglements. Entanglements in the parlour entrance (58 mm polypropylene netting) of the pots would also likely be reduced with the use of a smaller mesh. Decreasing the amount of entanglements in this location of the pot would facilitate movement into the parlour where fish were shown to exhibit less aggression than in the entrance chamber. It would not be recommended to reduce the size of the 58 mm nylon netting around the side and end panels at the risk of increasing the amount of undersize halibut captured. Meintzer et al. (2018) used a 3mm diameter 100 mm polyethylene mesh in the side and end panels of the Norwegian pot to target Atlantic cod which helped reduce the capture of undersized cod. Replacing the thin nylon netting with a thicker diameter polyethylene could help decrease entanglements, keep catches of undersized halibut low, and potentially reduce the incidental capture of small bodied rocklings and eelpouts that commonly dominate catches in the current study and in previous halibut potting studies (Grant, 2015). Further, polyethylene netting is positively buoyant and will assist in opening the collapsible pot on the seabed, also helping to keep the openings in netting fully open to facilitate escapement of small fish. Finally, the use of thick polyethylene netting could prevent potential damage to the netting from contact with the seabed.

Another potential negative aspect of halibut entangling in the mesh of pots is that fish in distress could be an attractant to predators such as wolffish and Greenland shark. Alternatively, a Greenland halibut in distress in the entrance of a pot could deter other Greenland halibut from entering the pot. Stress in fish due to entanglements most likely reduces fish quality, as capture stressors and physical injuries due to contact with gear or other fish are more likely to occur when fish are entangling (Chopin & Arimoto 1995; Humborstad et al., 2016). With that said, Meintzer et al. (2018) did not find that cod in pots were exhibiting stress induced behaviours, however morphological differences between cod and halibut may explain why halibut were entangling in the 50 mm entrances and cod were not. Greenland halibut have relatively large teeth that line the upper and lower jaw. These teeth are also found on the distal ends of the jaw and commonly protrude when the mouth is partially closed. By comparison, Atlantic cod also have teeth lining the upper and lower jaws but the teeth are smaller, set back farther on the jaws, and do not protrude when the jaws are partially closed. Further, Atlantic cod have not been observed to entangle by their teeth in meshes of the Norwegian pot (P. Walsh, pers. obs.). So, at this time I would suggest future pot designs use 19 mm mesh in both the entrance funnels and in the parlour entrance to avoid entanglement of halibut by the tail or protruding teeth.

For the current study I was unable to collect video observations of fish interacting with wire pots. It was originally thought that the use of a rigid wire mesh in the lower chamber would both strengthen the section of the pot that was in contact with the seabed and eliminate entanglement of Greenland halibut. I was not able to observe whether there was a reduction in entanglements, however the damage wire pots sustained and suspected seabed impact due to weight could be reason enough to omit the design from further studies. Repairing damaged wire pots requires the use of specialized equipment, making them difficult and costly to mend at sea. Alternatively, damage to Norwegian pots, to either the frame or netting, is much easier to address. The frame of a Norwegian pot can be easily bent back to the original shape, and damage to netting can often be easily sewn. Further, fully collapsible pots take up less space on board, making them easier to accommodate on smaller vessels used in the NSA. In the future, collapsible pots could be strengthened to decrease damage to netting in the floor of the pot entrance chamber and bending of steel in the lower frame when dragged over seabed by welding two steel frames together as the bottom frame. This would lift the netting in the floor of the entrance chamber off the seabed, reducing contact, as has been achieved in the Newfoundland cod pot (P. Walsh, pers. comm.).

During the current study, 80% of the Greenland halibut approaches were from the upstream direction and the majority of the entry attempts and successful entries occurred when the downstream entrance of a pot was aligned with the current. These results are consistent with other groundfish species (e.g., Anders et al., 2017; Meintzer et al., 2017), demonstrating the importance of entry alignment with bottom currents for the success of this fishing gear. Unfortunately, during the current study the downstream entrance of a pot was only aligned with the bottom current in 52% of observed approaches. When targeting Atlantic cod in the Baltic Sea, providing adequate floatation to lift a single entrance Norwegian-style pot so that it floats about 0.5 m off the seabed has been shown to improve entry alignment (Königson et al., 2015b; Jørgensen et al., 2017). However, in the current and previous studies (Grant 2015) halibut were observed to approach the pots near the seabed and given the attenuation of light at the depth of capture these factors would combine to increase the likelihood of halibut swimming under the pot. Further, there would be considerable operational limitations of setting strings of several floating pots in deep waters inhabited by halibut.

Development of Greenland halibut pots with a greater number of entrances would increase the likelihood of at least one entrance aligning with bottom currents. Meintzer et al. (2018) developed a four-entrance pot and in experiments conducted in coastal waters of Newfoundland they demonstrated that this pot could capture about 30% more Atlantic cod than the traditional two entrance Norwegian cod pot. However, Meintzer et al (2018) speculated that exit rates may be equal to or even greater than entrance rates and in the current study I observed cases where halibut passed directly through the pot by swimming in one entrance and directly out of the opposite entrance. Further, given the total escape rates observed in the current study, use of a four-entrance pot would require additional modifications. For example, changing the configuration of the entrance funnels so that openings into the entrance chamber are vertically and horizontally offset from the adjacent opening to prevent fish from swimming directly out of an adjacent entrance. Alternatively, some trap fisheries use one-way entrance retention devices to prevent escapement of target species (Salthaug, 2002). These devices are placed at the end of the entrance funnel and have finger like projections or triggers that hang vertically and pivot in one direction (i.e., inward) or taper inward from the top and bottom. Triggers that taper inward are made of coloured plastic (usually red) while vertically hanging triggers are commonly made from steel but have also been made with light weight clear plastic. When fish enter a pot fitted with one way entrance retention devices they push through the moveable triggers and once they enter a pot they cannot move back out (Salthaug, 2002). Plastic tapering triggers require a greater amount of force to push through than hanging triggers and in the case of flatfish depending on trigger spacing several triggers can come in contact with the dorsal and ventral surface of a fish which may prevent entry into a pot. This would explain why Pacific cod (*Gadus microcephalus*) pots fitted with one-way entrance retention devices made with plastic tapering triggers were found to capture fewer Pacific halibut (*Hippoglossus stenolepis*) while catches of fusiform shaped Pacific cod were not affected (Carlile et al., 1997). Murphy (2014) used vertically hanging one-way entrance devices constructed of steel to target Greenland halibut. Although very few halibut were captured, the capture of several American plaice (*Hippoglossoides platessoides*) suggests vertically hanging triggers do not negatively influence the entry of flatfish (Murphy, 2014). It is notable that few halibut were also captured in gillnets at the study site and the study was conducted during autumn when seasonal movements of halibut out of the coastal potting site may account for the low catch rates.

To increase the likelihood of an entrance aligning with bottom currents I conclude that future Greenland halibut potting studies should consider the use of four-entrance pots fitted with one-way entrance devices constructed with vertically hanging triggers. Given the large dorsal and ventral surface of flatfish, the use of light weight plastic triggers may be more suitable than steel triggers and video observation studies should consider varying the spacing between triggers in the four entrances of a pot to determine whether this affects successful entry rates.

It is unclear whether setting pots in close proximity to heavily baited gillnets affected the incidental capture of non-targeted species. For example, Grant et al. (2015) demonstrated that significantly more rocklings (*Gaidropsaurus sp.*) and wolffish (*Anarhichas* sp.) were captured in baited versus non-baited gillnets. Greater densities of these species in the vicinity of baited gillnets would likely reduce the capture rates in baited pots. However, the same species were captured incidentally in Norwegian pots by Grant (2015) in the absence of baited gillnets. Further, both studies (current and Grant, 2015) show that apart from species that exhibit barotrauma (i.e., grenadier) all remaining species were unharmed (in good physical condition), alive, and active when the pots were tended suggesting high post-release survival. Lack of damage suggests a high probability of survival when returned to the ocean. Given the bycatch rates of the SARA listed spotted wolffish, future studies should seek to verify survival of pot caught wolffish when they are returned to the ocean (i.e., see Grant & Hiscock, 2014).

Suggestions for future potting strategies

The results of this study suggest that monofilament netting in entrance funnels and polypropylene in parlour entrances need to be substituted with smaller (i.e., 19 mm or less) mesh to prevent entanglement, increase the rate of capture, and reduce possible stress and reduction of fish quality. A substantial number of entanglements were observed in video analysis and documented in catches when pots were landed. These entanglements are also likely to negatively influence fish entering a pot and therefore could reduce catch rates. In addition, netting used in side and end panels should also be substituted but with a larger mesh size opening (i.e. 100 mm polyethylene) and thicker diameter (i.e. 3mm). A larger mesh opening will allow escapement of undersized Greenland halibut and small bodied bycatch. Larger diameter mesh will likely reduce damage to netting when it comes in contact with seabed. For the current study, although some pots were damaged, no pots were lost at sea. In the future, biodegradable twines could be considered for use in the side and end panels of the parlour of pots, to prevent possible ghost fishing.

Video data confirmed that due to chemical stimulus (i.e. rheotaxis), improving entry alignment with prevailing bottom currents will be important for improving capture rates of Greenland halibut in baited pots. The introduction of a four entrance pot with light weight vertically hanging triggers in entrances would ensure one entrance is aligned with bottom currents at all times, while preventing escapement of captured fish through entrance funnels.

In the future, it is recommended to test the effects of Greenland halibut potting within the NSA (inshore waters of Nunavut) where high numbers of Greenland shark have been observed in underwater video (Devine et al., 2018) and captured on longlines (Pike, 1994; Young 2010; Devine et al., 2018; Grant et al., 2018). The original Norwegian pot tested by Grant (2015) was found to outperform longlines, which happen to be the recommended fixed gear in inshore waters of Nunavut (DFO, 2014). Mean capture rates of 21.1 kg/pot in the N_{19mm} pots may not be expected to meet the expectations of current offshore or inshore fisheries. However, if suggested modifications derived from this study are used, pots may be found to outcompete open water longline fisheries in inshore areas of Nunavut, where gillnets are prohibited (i.e., Cumberland Sound). Additional video work with future pots should be conducted in coastal waters to determine the most suitable design before it is introduced to offshore waters or compared to baited gillnets.

Conclusion

In summary, further testing of baited pots as an alternative gear type in the Greenland halibut fixed gear fishery should be considered. Minor differences among our six pot treatments did show how varying design features can impact Greenland halibut catch rates, and video observations gave greater insight on obstacles (i.e., entanglement, entry alignment, and escapes), contributing to the assessment of the experimental pots. With the suggested modifications and further testing, it is possible that this research will eventually lead to pots competing with the offshore gillnet fishery. Baited pots could be a sustainable and efficient option for fishing Greenland halibut in these Arctic regions while avoiding the capture of non-targeted species, including the Greenland shark.

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Tables

Table 1. Summary of the percent of the total catch weight (%Total) for non-targeted species captured in six experimental pot treatments in NAFO Division 0A. The frequency of occurrence (%Occ) within the pot treatment is also shown.

	W_{3mm}		W_{50mm}		W_{19mm}		N_{3mm}		N_{50mm}		N_{19mm}	
Species	%Tot	%Occ	%Tot	%Occ	%Tot	%Occ	%Tot	%Occ	%Tot	%Occ	%Tot	%Occ
Threebeard rockling (*Gaidropsarus ensis*)	2.40	30.0	2.83	33.3	3.18	35.3	4.71	44.4	2.44	31.9	3.75	54.7
Silver rockling *(Gaidropsarus argentatus)*	0.98	14.0	2.23	28.1	1.09	27.5	1.41	31.5	0.77	23.4	1.63	41.5
Atlantic wolffish *(Anarhichas lupus)*	5.72	12.2	2.65	8.8	5.23	13.7	4.95	15.4	4.05	14.9	2.14	7.5
Spotted wolffish *(Anarhichas minor)*	2.33	4.1	0.86	3.5	0.27	2.0	0	0	0.29	2.1	0.95	5.7
Spinytail skate *(Bathyraja spinicauda)*	0.91	6.0	0.85	5.3	0.69	5.9	0.66	5.6	0.96	6.4	0.41	5.7
Polar eelpout *(Lycodes polaris)*	0.09	4.0	0.14	10.5	0.19	13.7	0.03	3.7	0.03	2.1	0.10	11.3
Roughhead grenadier *(Macrourus berglax)*	0	0	0.33	5.3	0.16	3.9	0	0	0.45	4.3	0.22	5.7
Polar sculpin *(Cottunculus microps)*	0.04	2.0	0.01	1.8	0	0	0.05	3.7	0.04	6.3	0	0
Total (all species)	12.47		9.89		10.81		11.81		9.03		9.19	

Table 2. Underwater video observation summary illustrating the total number of hours of video observed, total number of approaches, encounters, entry attempts, successful entries, escapes, parlour entries, and entanglements by teeth in different pot locations for two pot treatments.

	$N_{19\ mm}$	$N_{50\ mm}$	Total
Video duration (hrs)	55	83	138
Approaches	68	383	451
Encounters	28	138	166
Entry Attempt	25	114	139
Successful entry	14	34	48
Escapes	3	15	18
Enter parlour	11	12	23
Entangle by teeth			
Outer side panel of entrance chamber	2	3	5
Entrance funnel	8	60	68
Inner side panel of entrance chamber	7	25	32
Parlour entrance	16	53	69
Inner side panels of parlour	13	33	46
Total	45	174	219

Table 3. Greenland halibut approach direction relative to the bottom current.

Approach direction	Number of approaches	Percent
Against current	361	80.0%
With current	45	10.0%
Cross-current	45	10.0%
Total	451	

Figures

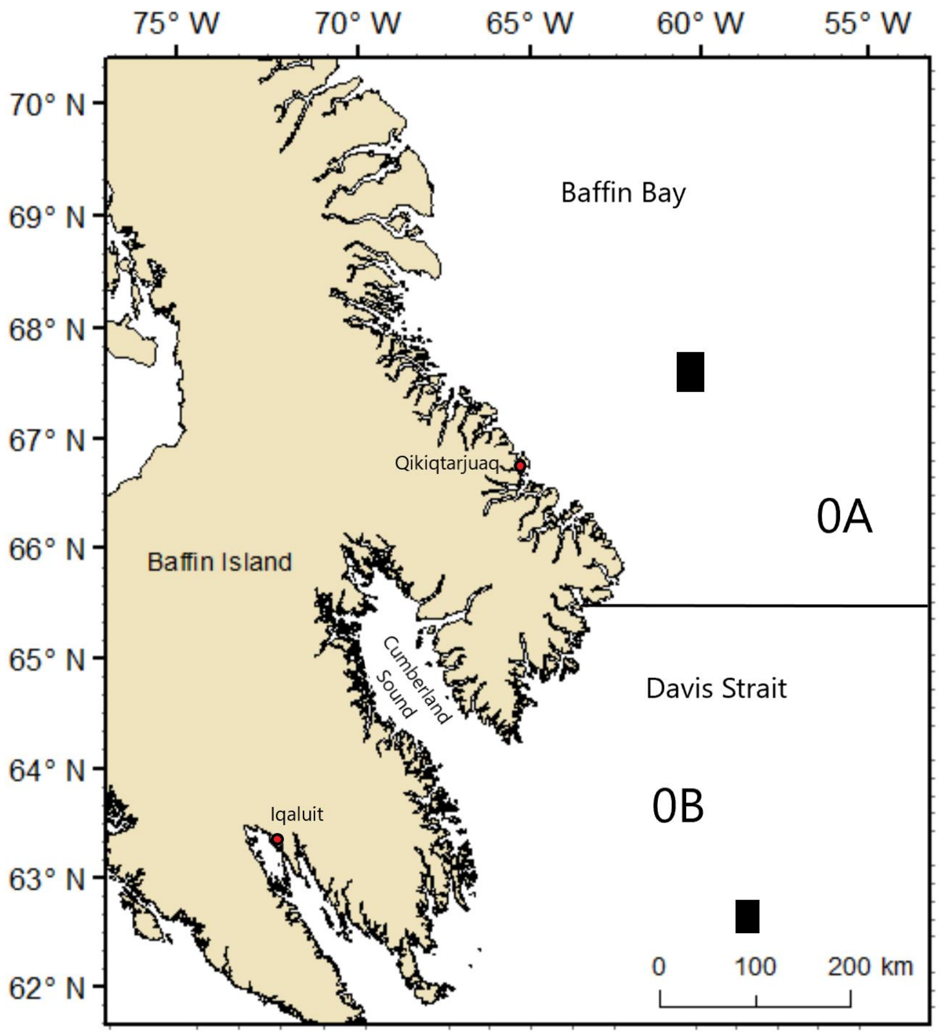

Figure 1. Map showing the area in NAFO Division 0A where the 12 fishing sets occurred and the area in NAFO Divsion 0B were additional video work was carried out. The two areas are indicated by black boxes.

Basemap was obtained from the Canadian Land Cover GeoBase series, containing information licensed under the Open Government License – Canada.

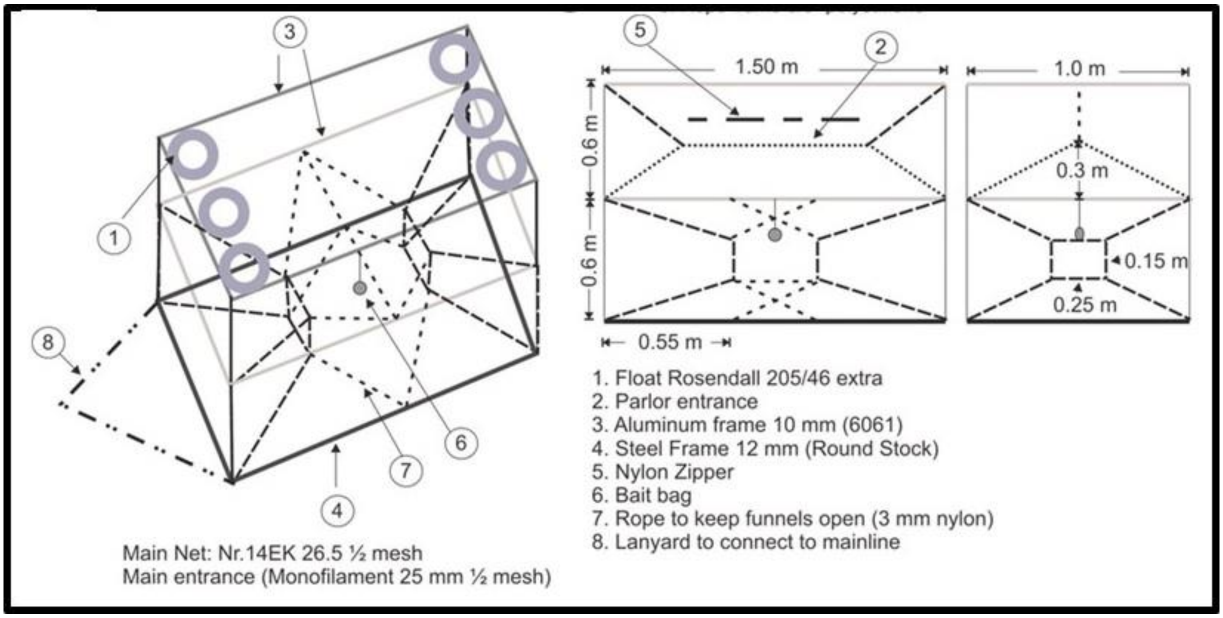

Figure 2. Schematic of the two entrance Norwegian-style pot (Meintzer et al.,2018).

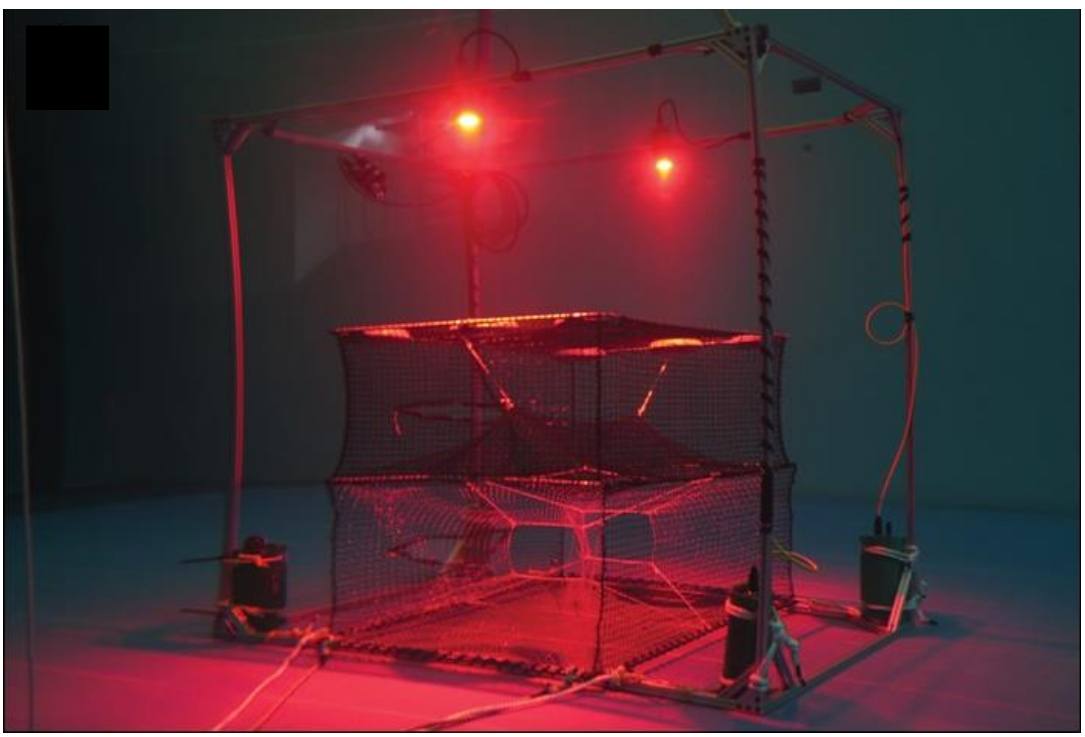

Figure 3. Photograph of potting video camera observation frame containing a Norwegian-style pot. Photograph was taken in Marine Institute flume tank (Walsh et al., 2015).

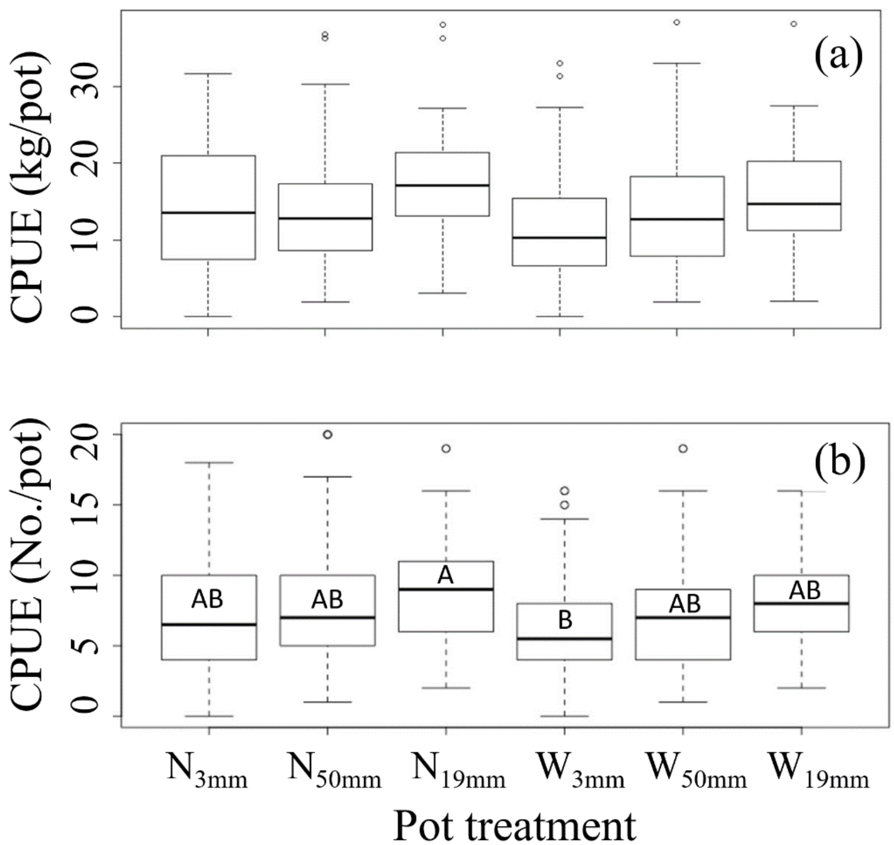

Figure 4. Catch per unit effort (CPUE) of Greenland halibut captured in each pot treatment. Panel (a) is kg/pot and panel (b) is number/pot.

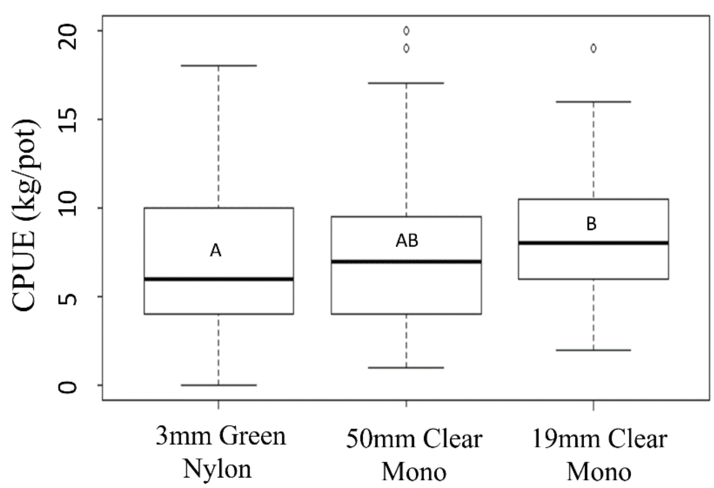

Figure 5. Catch per unit effort (CPUE; kg/pot) of Greenland halibut captured in pots with different entrance mesh type.

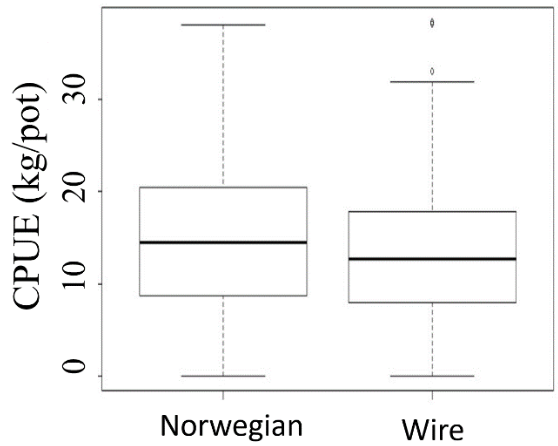

Figure 6. Catch per unit effort (CPUE; kg/pot) of Greenland halibut captured in the Norwegian pots and wire pots.

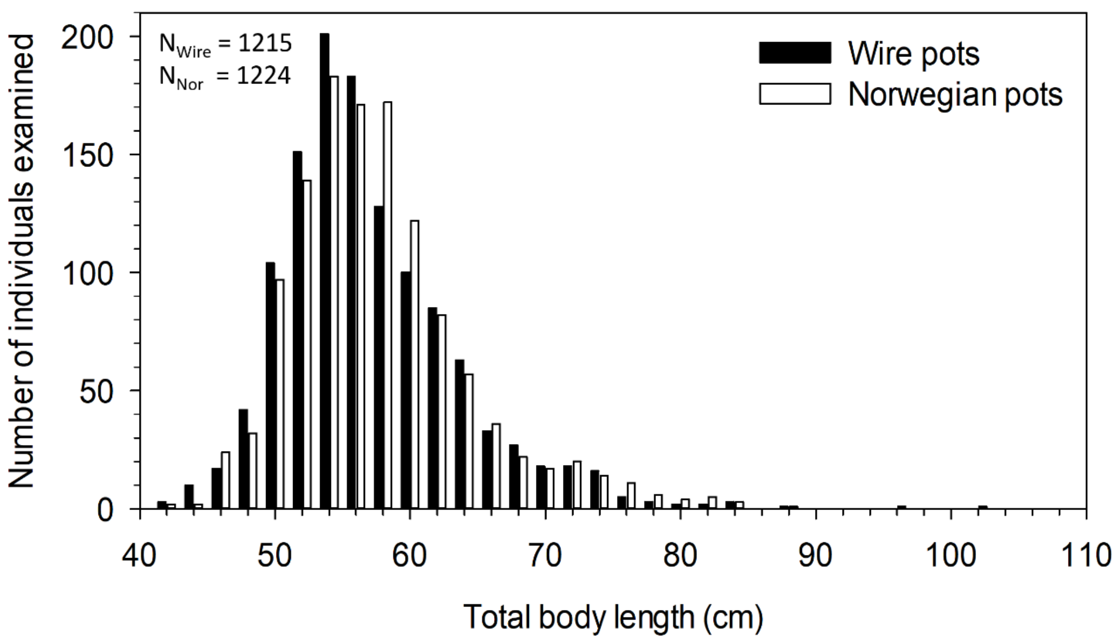

Figure 7. Length frequency distributions of Greenland halibut captured in wire and Norwegian pots in NAFO Division 0A. Total number of Greenland halibut examined for wire (N_{Wire}) and Norwegian (N_{Nor}) pots is also shown.

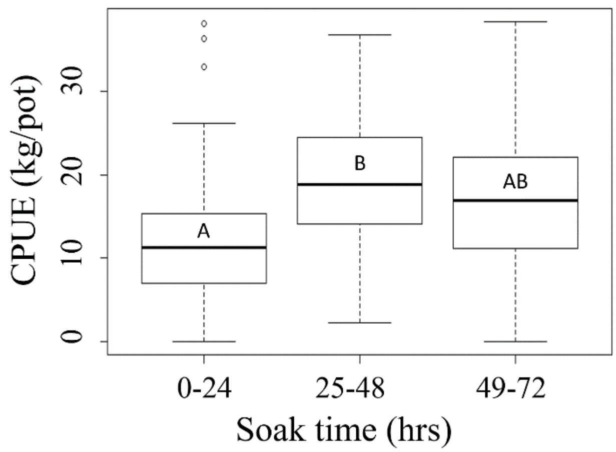

Figure 8. Catch per unit effort (CPUE; kg/pot) of Greenland halibut in all pot treatments combined at different soak times.

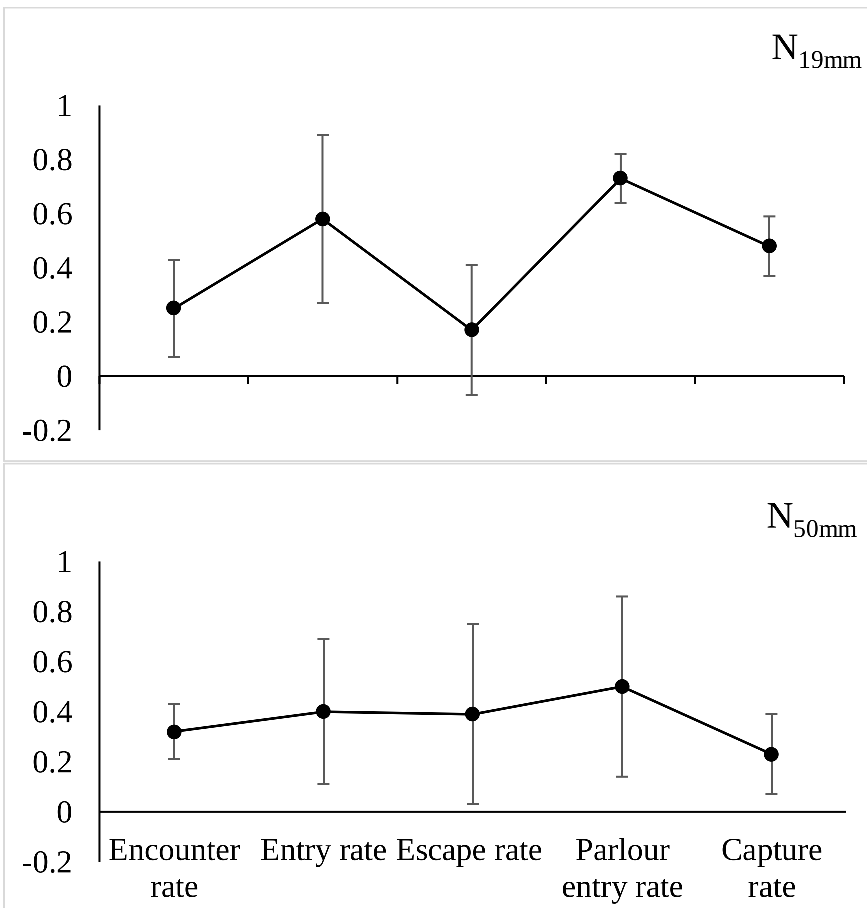

Figure 9. Mean (±1 S.E.) rates of encounter, entry, escape, parlour entry and capture for Greenland halibut in two pot treatments.

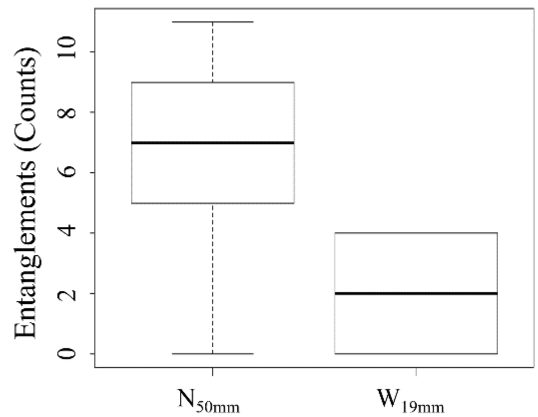

Figure 10. Number of entrance funnel entanglements by Greenland halibut observed in N_{50mm} and N_{19mm} pot treatments.

CHAPTER 3

General Conclusion

The objective of this study was to increase the baseline knowledge with regard to using potting technologies to capture Greenland halibut. My study was limited to one field season of fishing trials and video collection, however previous knowledge gained from initial studies carried-out by Murphy (2014) and Grant (2015) contributed to decisions on mesh size used in entrance funnels and materials used in the side and end panels of the six pot treatments. An additional field season within the time frame of this thesis was not able to occur; however, a second field season would have provided an opportunity to focus on video research to determine whether the modifications I recommended from year one do indeed increase capture rates of Greenland halibut, reduce catches of non-target species, and avoid gear depredation by Greenland sharks. The most suitable features of the pots tested should be addressed using underwater video before investments are made into several experimental pot treatments for at sea trials.

Working directly with commercial fishers allows fisheries researchers the opportunity to apply their ideas in a real life setting, while contributing to the fishery directly. It is critical for the sustainability of future resources that fish harvesters and fisheries scientists work together to answer fisheries related questions. With that being said, operational limitations on where and when data are collected is usually at the discretion of industry during these partnerships, unless the vessel is chartered by researchers. In this study it was suggested by industry that pots be fished in close proximity to baited gillnets for comparison, which in the end created uncertainty with the results. Future studies may aim to fish in less competitive areas, away from gillnet competition until a suitable pot design is properly established.

Ultimately, it is not possible to unambiguously compare catch rates in a 1.7 km string of baited pots that soaked for 24-48 hours to catch rates in 4.6 km strings of heavily baited gillnets that soak for five or more days. Catch rates in baited pots must be judged on their own merits with the understanding that it is a combination of the mean catch rates in a baited pot and the number of pots a vessel can effectively haul over a 24 hour period. Also to be considered is the increased value of pot caught Greenland halibut over that of alternate fixed gears, and environmental impacts, including a reduction in discarding and unaccounted fishing mortality from dead and decomposed targeted and non-targeted species.

Potting fisheries targeting finfish struggle to compete with other fixed gears, however, they are occasionally turned to as a preferred fishing gear due to the environmental benefits such as a reduction in damage to seabed habitat and capture of non-targeted species. For example, gillnet and longlines are reported to have a higher impact rating on groundfish, corals, sponges and sharks than baited pots (Fuller et al., 2008). Throughout this experiment, I was able to show that potting gear can efficiently capture Greenland halibut with low incidental capture rates, and even lower mortality rates of other finfish species. Future studies should focus on reducing the bycatch of some of the small bodied fish captured in this study. However, my suggestion to use 100 mm polyethylene mesh in the side and end panels of pots in future testing is anticipated to reduce bycatch. Moreover, the limited interaction with gear observed and lack of visible damage to hauled gear, suggests a low direct impact on Greenland sharks, seabirds, and cetaceans by switching from gillnets and longlines to potting gear. These results indicate that pots could be an effective gear of choice in areas where bycatch is of high concern.

Through the information collected, this thesis has contributed to and improved the baseline knowledge on the capture rates and behaviour of Greenland halibut in and around potting technologies. With additional at sea trials in the Nunavut settlement area, and using the modifications suggested in the discussion of Chapter 2, an optimal potting design that would meet fishing industry expectations could be achieved.

Limitations of my approach

There were limitations to the approach of this experiment which should be taken into consideration when interpreting the results. This research was a continuation of earlier research on avoiding the incidental capture of Greenland shark in the Nunavut settlement area (NSA) (Grant et al., 2018; Grant et al., 2019). Due to the size class of the vessel we conducted our Greenland halibut potting research on (99 feet), data collection could not be done in inshore waters near Cumberland Sound where the incidental capture of Greenland shark was high in exploratory longline fisheries during the open water season (Young, 2010). Given the chance, it may be more applicable to test a small number of pots on board a smaller vessel that can operate in these areas where marine mammal and Greenland shark bycatch is of particular concern.

A second limitation to my approach relating to video observations was the inability to track all fish individually when many fish were observed in a pot at once. In future studies, if individual fish are able to be tracked it would provide clarity to which extent entanglements within the side panels or entrances of the pots are contributing to escapement. In the current study, the statistics were not based on individual fish, and therefore, autocorrelation between these variables could not be tested.

As previously mentioned, red light is suspected to be less visible to fish and is therefore commonly used for deep-water observations (Rooper et al., 2015). With that in mind, it is unclear if the presence of the red LED lights used in the video observations had an effect on the behaviour of Greenland halibut when interacting with baited pots. Future testing to investigate whether red light increases or decreases the amount of fish that interact with pots would be of value. One way of testing this could be to set up two strings of baited pots, one without red lights attached to each pot and one with red lights attached to each pot, and compare catch rates.

Deploying a large camera frame for deep sea video observations is a tricky and time consuming process. Nonetheless, the information gathered from this type of research is worth the effort involved. However, due to the difficulty of gathering this valuable source of information, we were unable to collect equal amounts of video for each pot type in this study. In the future, it would be of value to collect video on the pots with the 3 mm green twine entrances to properly investigate the effects of the smaller mesh used in the entrance funnels.

The pots tested in this study were designed to capture commercial numbers of Greenland halibut while reducing the negative ecological impacts such as bycatch of non-targeted species and damage to seabed associated with using other currently used fixed fishing gears. This thesis adds to the growing body of research investigating the value of underwater video observations in assessing the capture rates of fishing gear. It was successful in demonstrating the importance of visual information as well as showing there can be risks of drawing false conclusions when you base them on catch rate data alone.

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