BAIT EXPERIMENTS TOWARD DEVELOPING A PROFITABLE, SUSTAINABLE, AND EFFICIENT SNOW CRAB (*Chionoecetes opilio*) FISHERY IN THE BARENTS SEA

by

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ABSTRACT

The development of a new and modern snow crab fishery in the Barents Sea has necessitated significant research and development in sustainable fishing practices. Large offshore fishing vessels from Norway currently face a number of challenges related to baiting traps efficiently, the need to reduce labour requirements, minimizing health risks for fishermen, and the need to find affordable baits with good catching performance. This thesis documents two at-sea field experiments designed to address some of these challenges. The first experiment was a comparative fishing study aboard the *R/V Helmer Hanssen* in February 2016 to investigate the performance of plastic jar and mesh bag bait protection devices. Results revealed that mesh bags decreased CPUE by 73% when compared to plastic jars. The second experiment was a comparative fishing study aboard the *M/S Northeastern* in May/June 2016 to investigate the catching performance of alternative baits from harp seal and minke whale fishery by-products in comparison to traditional bait (i.e., squid). Results revealed that baits consisting of seal fat and seal fat with skin produced catch rates comparable to squid, while all of the other experimental baits decreased mean CPUE considerably (up to 97%).

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LIST OF ABREVIATIONS AND SYMBOLS

CMB	Commercial mesh trap and bag of bait
CMJ	Commercial mesh trap and jar of bait
CPUE	Capture per unit effort (number of crabs per trap haul)
CW	Carapace width (mm)
SF	Seal fat bait
SFS	Seal fat and skin bait
SMB	Small mesh trap and bag of bait
SMJ	Small mesh trap and jar of bait
SM	Seal meat bait
WFS	Whale fat and skin bait
WMF	Whale meat and fat bait

CO-AUTHORSHIP STATEMENT

The research presented in this thesis was completed by myself with supervision from Dr. Paul Winger, Director of the Centre for Sustainable Aquatic Resources, located at the Fisheries and Marine Institute of Memorial University. Dr. Scott Grant and Dr. Roger Larsen were members of my supervisory committee. Research ideas and hypotheses were proposed in collaboration with SINTEF, Norway. Myself and Leonore Olsen were responsible for the collection of the field data. I led the analysis, interpretation, and write-up of all material presented in this thesis.

Lasse Rindahl, Roger B. Larsen, and Paul D. Winger are second, third and fourth authors for Chapter 2, respectively.

Leonore Olsen, Lasse Rindahl, Roger B. Larsen, and Paul D. Winger are second, third, fourth and fifth authors for Chapter 3, respectively.

It is expected that Chapter 3 will be submitted as a separate manuscript to a scientific journal.

INTRODUCTION AND OVERVIEW

1.1. Snow Crab Habitat and Distribution

Snow crab (*Chionoecetes opilio*, O. Fabricius, 1788) (Figure 1.1) is an Arctic and subarctic species (Armstrong, 2010) that has the widest distribution among the crabs of the *Chionoecetes* genus (Jadamec *et al.*, 1999). It is found in the cold waters of the Northwest Atlantic, the Northern Pacific, and the Sea of Japan (Yusty *et al.*, 2011; Armstrong, 2010; Bailey and Elner, 1989). More specifically, it inhabits the east of the Korean Peninsula in the Sea of Japan, the Sea of Okhotsk, the Beaufort Sea as far east as Cape Parry, north of the Alaska Peninsula in the Bering Sea and from Greenland south to Casco Bay in the Northwest Atlantic (Figure 1.2) (Jadamec *et al.*, 1999). Abiotic factors such as bottom substrate and temperature are related to its bathymetric distribution (Lovrich *et al.*, 1995). Snow crab is usually found on mud and sand bottoms (Robichaud *et al*., 1989) at depths from 0 to 450 meters, and temperatures ranging from 0 to 5 ^{o}C (Lovrich *et al.*, 1995; Kon, 1996; Tremblay, 1997).

1.2. Diet

Snow crab provide a predatory and scavenging role in many ecosystems. Diet studies in different habitats suggest that snow crabs ingest a large diversity of benthic prey including bivalves, gastropods, polychaetes, ophiuroids, and crustaceans (e.g., Squires and Dawe, 2003; Divine *et al.*, 2015). In some regions, cannibalism on juveniles and predation on other crab species is a significant contribution to their diet (Lovrich and Sainte-Marie, 1997; Chuchukalo *et al*., 2011). Yet, the importance of cannibalism may vary by location and be related to the abundance of juveniles compared with the abundance of other available prey (Divine *et al.,* 2015). When snow crabs terminally molt and have larger chelae, they are able to feed from larger prey items, including molluscs and clams with harder shells (Squires and Dawe, 2003; Kolts *et al*., 2013).

1.3. Snow Crab Invasion in the Barents Sea

The Barents Sea is located north of the mainland of Norway and Russia, limited to the north by Franz Josef Land, to the west by Svalbard, and by the deep waters of the Greenland and Norwegian Seas (Figure 1.3). It is a large shelf area of approximately 1.4 million km^2 with an average depth of 230 m (Agnalt *et al.,* 2008). It is an important fishing area for Norway and Russia, with fisheries management conducted through bilateral agreements (Agnalt *et al.,* 2008). Introduced red king crab (*Paralithodes camtschaticus*) and native northern shrimp (*Pandalus borealis*) are crustacean fisheries that take place in the Barents Sea (Jørgensen and Nilssen, 2011).

Snow crab is considered an invasive species in the Northeast Atlantic. In 1996 five individuals were captured with trawl nets in the eastern Barents Sea during May – December of that year (Figure 1.2) (Kuzmin *et al.,* 1999) and ten more individuals were reported during 1998 and 1999 (Kuzmin, 2000; Kuzmin, 2001). Since then the abundance and distribution of snow crab has increased steadily every year (Agnalt *et al.,* 2008; Alvsvåg *et al.,* 2008; Pavlov and Sundet, 2011).

Snow crab colonized favorable conditions in the Barents Sea, including depths, substrates, and temperature ranges that match its biological preferences (Agnalt *et al.*, 2008). The abundance of snow crab increased significantly from 2004 to 2009. Starting in 2006, more crabs were found in the eastern part of the Barents Sea as well as an important number of crabs were captured in the central Barents Sea area (Figure 1.4) (Agnalt *et al.*, 2008). Establishment of a self-recruiting population of this new species is now undisputable. Small juvenile crabs, ovigerous females, and adult crabs have been captured during multi-species bottom trawl surveys beginning in 2004 (Agnalt *et al.*, 2008; Pavlov and Sundet, 2011). Beginning in 2014, commercial sized crabs have been harvested by Norwegian and Russian fishing vessels. Taken together, these indicators prove this new invasive species has settled in the Barents Sea (Sherstneva, 2013; Lorentzen *et al.*, 2016).

1.4. Invasion Theories

There are many theories about how snow crab invaded the Barents Sea. Snow crab is a poor migrant and is not able to crawl from the Northwest Atlantic (Kuzmin *et al.*, 1999). A more likely suggestion is that snow crab were transported during their early life stages. Embryos hatch from late winter through early summer. Three planktonic stages follow this process; the prezoeae exit the egg from the female's abdomen and migrates upward in the water column. Prezoeae molts to zoeae I stage in a matter of hours and to the zoeae II stage one month later (Jadamec *et al.*, 1999). During these stages, larval snow crab are able to travel with water masses. Kuzmin *et al.* (1999)

discuss the possibility of natural invasion of this species in the Barents Sea by means of larval drift. The authors concluded that larvae traveling in water masses are unlikely to survive a journey of eight months or more in unfavorable sea temperatures. Rather, it is more likely that snow crab larvae were introduced due to anthropogenic factors such as the transport in ballast water of ships from the Northwest Atlantic and discharged in the Barents Sea, where snow crab larvae finally settled (Kuzmin *et al.*, 1999; Agnalt *et al*, 2011). DNA analyses have shown that snow crab from the Barents Sea are related to Canadian populations (Sévigny and Sainte-Marie, 2009). Nevertheless, the origin of the snow crab population in the Barents Sea is unclear and needs to be further investigated (Agnalt *et al*., 2008).

1.5. Economic Importance

Approximately 1.5 million tonnes of various crab species are consumed globally each year, with snow crab representing about 10% of the total consumption (Lorentzen *et al.*, 2016). Snow crab fisheries are economically important, especially in Eastern Canada (producing 55-60% of the global demand), Western Greenland, and the Bering Sea (Burmeister 2002; Lorentzen *et al.*, 2016), with additional fisheries in Japan, South-Korea, Russia, and Norway (Lorentzen *et al.*, 2016). It is a popular product due to its fine white meat (Gardner, 2014) and is exported mainly to the USA and Japan, which constitute close to 96% of all historical demand. Lesser amounts are imported to Europe, Canada, and South-Korea (Gardner, 2014; Lorentzen *et al.*, 2016). Commercial landings of snow crab in Norway reached 4,000 tonnes in the year that the fishery was open

(2014), with an export value of 100 million NOK (16 million CAD) (Lorentzen *et al.*, 2016). It is projected that landings could reach a value of 2.5 to 7.5 billion NOK (400 million to 1.2 billion CAD) in the next 15 years (Hansen, 2016).

1.6. The Barents Sea Snow Crab Fishery

A total of nine Norwegian fishing vessels participated in the Barents Sea snow crab fishery in 2014. Additional vessels from Spain, Lithuania, and Latvia also landed Barents Sea snow crab in Norway that same year (Hansen, 2015), before current regulations were set. According to the Norwegian Fishing Vessel Owners Association (in Norwegian: Fiskebåt), 8 factory vessels operated during 2016 (Figure 1.5). Currently there are 56 licenses for snow crab and 11 vessels actively operating (Leonore Olsen, SINTEF, personal communication). Although not presently regulated, the fishery typically ceases during mid-June until the end of September when the snow crab molts (Atle Forland, Opilio AS, personal communication). The meat of the animal is less desirable during this period and high discard mortality may occur due to the discarding of soft shelled animals.

Vessels targeting snow crab are presently operating in a crowded area which is traditionally used by vessels targeting Northern shrimp and groundfish (Figure 1.6), creating a conflict between trawlers and crab vessels (Leonore Olsen, SINTEF, personal communication). Current fishery management practices include:

i) historical rights are necessary to be granted a license for snow crab

ii) only traps can be used to harvest snow crab

iii) minimum carapace width must be 100 mm

iv) only Norwegian and Russian vessels are allowed to participate in this fishery (Leonore Olsen, SINTEF, personal communication).

1.7. Fishing Method

Conical and rectangular baited traps are the primary fishing gears used to harvest snow crab (Lafleur *et al.*, 1983; Sainte-Marie and Turcotte, 2003). In Canada, fishing enterprises tend to use small conical traps set in fleets (Figure 1.7) or large conical traps set individually (Figure 1.8). Conical traps are selective, efficient, easy to handle and manipulate, and are stackable (e.g., Moriyasu *et al.*, 1989; Vienneau *et al*., 1993; Winger and Walsh, 2011). The traps are typically baited with squid or Atlantic herring (Sainte-Marie and Turcotte, 2003; Grant and Hiscock, 2009). Squid (*Illex spp.*) imported from South America is currently the most commonly used bait when targeting snow crab as it tends to perform better than other natural baits (e.g. Grant and Hiscock, 2009). The use of bait protection devices (hereafter called shields) is a common practice in many areas. Mesh bags and perforated plastic jars are the most common types of shields (Figure 1.9) (Grant and Hiscock, 2009). They are typically attached to the top of the trap in a manner that lets them hang in the centre of the trap (Figure 1.7). Chemical attractants are released from the bait and transported horizontally by the current, producing an odour plume, whose shape, orientation, and area strongly depends on the amount of bait, the current speed, direction, and turbulence (Okubo, 1980; Sainte-Marie and Hargrave, 1987; Chiasson *et al*., 1992; Moore *et al*., 1994; Winger and Walsh, 2011). Snow crab are attracted by the smell of the bait (McLeese, 1970; Mackie, 1973; Hancock, 1974) from down current, crawling towards the trap (Karnofsky and Price, 1989; Lapointe and Sainte-Marie, 1992; Chiasson *et al.*, 1992; Vienneau *et al*., 1993). Once they locate the trap, snow crab climb the exterior walls and enter through the top entrance (Stiansen *et al*., 2010; Winger and Walsh, 2011). A circular rigid funnel-shaped plastic skirt is normally used as an entrance to encourage ingress and discourage egress once captured (Lafleur *et al*., 1983). In 2016, some fishing enterprises in Newfoundland began using small low-powered LED lights to increase the CPUE of snow crab traps (Nguyen *et al.*, 2017). Functional explanations for why lights improve catch rates are still unknown and warrant further investigation.

1.8. Bait Configuration

Bait quantity

Several studies have shown that the catchability of decapod crustaceans in traps increases with increasing bait quantity (e.g., Thomas, 1954; Zimmer-Faust and Case, 1982; Zimmer-Faust and Case, 1983; Miller, 1983; Takeuchi, 1988; Cyr and Sainte-Marie, 1995). The amount of chemical attractants released from the bait is directly proportional to the bait quantity (Zimmer-Faust and Case, 1983), therefore increasing bait quantity will increase the field of attraction of the trap and the concentration of chemical attractants, resulting in attracting more animals (Sainte-Marie and Hargrave, 1987).

Bait position

Bait position is another important factor to consider when baiting traps. According to Vienneau *et al*. (1993), positioning the bait greater than 35 cm from the trap bottom may reduce its overall efficiency depending on the properties of the water current. Keeping the odour plume close to the seafloor is therefore necessary to attract crabs effectively towards the trap. Horizontal position is also important in order to optimize capture efficiency. It is recommended to position the bait in the centre of the trap (Vienneau *et al*., 1993). The authors found that when the bait was positioned near the side of the trap and the current directs the odour plume towards that same side and out of the trap, the number of crabs entering was considerably reduced, while the same bait positon with opposite current toward the interior of the trap did not decrease catchability of the trap compared to a centered position (Vienneau *et al*., 1993).

Bait shields

Several studies have reported that depending on the fishing location, exposed baits may be depleted by undesired species within a few hours of soak time, losing their attractant properties and decreasing catch rates considerably (Richards and Cobb, 1987; Robertson, 1989; Miller, 1990). Other studies have shown that catches increased significantly with unshielded baits (Miller, 1978; Pfister and Romaire, 1983; Cyr and Sainte-Marie, 1995), while others observed no significant differences between shielded and unshielded baits (Robertson, 1989). Some have speculated that using unshielded baits allows animals to feed from the bait, increasing the effluence of chemical attractants and creating visual stimulation for conspecifics outside the trap, therefore attracting more crabs toward the trap (Miller, 1978; Pfister and Romaire, 1983). Furthermore, exposed baits may keep crabs passive inside the trap since they are not starving, allowing newcomers to enter the trap and not be deterred by aggressive behaviour (Cyr and Sainte-Marie, 1995). On the other hand, given that small scavenging amphipod species cannot penetrate some types of shields, the bait is thus slowly depleted and the odour plume continues attracting crab, therefore efficiency is prolonged over a longer period of time (Robertson, 1989). Taken together, the above observations demonstrate significant variation in the benefits and costs of using bait shields.

1.9. Main Challenges in the Fishery

Occupational health and safety at work

Fishing is a high-risk occupation in Norway that exceeds land-based occupations in accidents and incidents per man-labor year (Lindøe, 2007; Bye and Lamvik 2007; Håvold, 2010; Lindøe *et al*., 2011). Working at sea operating heavy equipment on an unstable work platform with strong winds and large waves involves significant personal risk for fishermen (McGuinness *et al*., 2013a; McGuinness *et al*., 2013b; Antão *et al*., 2008; Windle *et al*., 2008). Added to this, many fishing vessels are now operating more frequently under rough weather conditions for financial reasons (Aasjord *et al.*, 2003).

Emptying and filling the bait shields and placing them in the traps is a repetitive task. This type of repetitive manual work may cause wrist and hand disorders, such as carpal tunnel syndrome, cramping of the hand and forearm, and tendon disorders (e.g., Viikari-Juntura and Silverstein, 1999; Muggleton *et al*., 1999; Hansson *et al*., 2000).

One way to reduce labour, increase efficiency, and provide a safer work environment for fishermen is to develop an automated trap baiting system. Mechanization of longline and gillnet vessels are examples found in Norway, where development of technology enables reduced manual labour, improves safety, and allows a better utilization of limited resources (Johnsen, 2005; Larsen and Rindahl, 2008). Development of a higher level of mechanization and more efficient operations in the Norwegian fisheries during the period 1995-2000 allowed total landings to increase, with lower man-labour year, lower working hours, and fewer days at sea (Johnsen, 2005).

Bait intensive fishery

The snow crab fishery in the Barents Sea is a bait intensive activity that, similar to most decapod crustacean fisheries, relies on large amounts of bait to effectively harvest the target species. This bait represents a significant operational cost and an emerging conservation issue (Vazquez and Kawamura, 2011). To lure snow crabs into the traps imported squid is the most preferred bait used in Atlantic Canada (Grant and Hiscock, 2009), as well as in Norway. Not only is this type of bait expensive and variable in cost, it is also food grade (used for human consumption) and imported from South America, which contributes to increased emissions and carbon footprint due to shipping and cold storage. With an increasing human population and decreasing fish stocks (Vazquez and Kawamura, 2011), common sense dictates that some marine resources should only be used for human consumption (FAO 1997). Hence, there is a significant need for accessible and sustainable alternative baits that are not based on resources used for human consumption (Vazquez and Kawamura, 2011; Løkkeborg *et al*., 2014). Many efforts have been undertaken to find artificial or restructured baits to replace the use of fish (e.g., Mackie *et al*., 1980; Carr, 1986; Daniel and Bayer, 1987; Miller, 1990; Mohan-Rajan and ShahuI, 1995).

One potential solution is the use of natural by-products (i.e., offal) from existing fisheries. Large amounts of these by-products are produced from both the fishing and aquaculture industries in Norway. These by-products have little or no alternative usage and in some cases there are even costs associated with their destruction (Dale *et al.*, 2007). The harp seal (*Pagophilus groenlandicus*) and minke whale (*Balaenoptera acutorostrata*) catch in Norway are without exception and some parts of the animals have little or no use and are routinely returned as offal to the sea. Although these fisheries are sustainable and well managed (Leonore Olsen, SINTEF, personal communication), it would be advantageous if greater utilization of the entire animal could be accomplished so as to reduce apparent waste and increase social license. It is speculated that some of the offal from these fisheries might make suitable bait for snow crab. However, a review of the literature revealed no known studies using marine mammal by-products as bait for crab fisheries, although anecdotal evidence suggests it has been tried in Newfoundland and Labrador with some success (Brian Johnson, CCFI, personal communication).

1.10. Complexity of Bait Studies

Since bait performance studies for snow crab are commonly conducted at sea, managing all the sources of uncertainty can be a challenge (Grant and Hiscock, 2009). Not only does the type, quantity, and shield of bait influence capture per unit effort (CPUE), but there are also several factors that are known to affect catchability of traps, for example, target species behaviour may vary due to sensory limitations, temperature, metabolism, shell stage, life cycle, availability of food, currents, light level, and turbidity (Vienneau *et al*., 1993; Grant and Hiscock, 2009). Abundance of snow crab can also vary greatly from area to area depending on bottom substrate, temperature, depth, prey availability and fishing pressure (Grant and Hiscock, 2009).

1.11. Objective of my Research

The present thesis aims to contribute in the development of a profitable, sustainable, and efficient snow crab fishery in the Barents Sea. Two main challenges were identified; first, the need for improve occupational health, and safety aboard fishing vessels, and second, the need to reduce the excessive use of food-grade bait from distant foreign countries. Research was planned and undertaken to find partial solutions to these challenges. Chapter 2 documents an experiment to study the possibility of an automated trap baiting system with jars by comparing the performance of this type of bait shield with mesh bag shields in terms of number of crabs per trap haul (CPUE). Chapter 3 documents a separate experiment focused on finding an accessible and sustainable alternative bait by performing a comparative bait study against the traditional bait used by the fleet.

Chapter 2 documents an at-sea experiment in which snow crab traps were baited using two types of bait shields; perforated jars and mesh bags. The experiment was conducted aboard the *R/V Helmer Hanssen* in February 2016. The main objective was to compare trap catchability between the previous mentioned bait shields as a stepping stone to future (potential) implementation of an automated baiting system. Due to their nature, mesh bags are flexible which makes them a potentially poor candidate for robotic manipulation in an automated baiting system. Bait jars by comparison are rigid and predictable in shape, reducing entanglement and making them a better candidate for an automated baiting system. The following hypotheses were evaluated:

Ho: CPUE of snow crab traps is independent of the type of bait shield used.

Ha: CPUE of snow crab traps is dependent on the type of bait shield used.

Results revealed that using mesh bags decreased CPUE by 73% when compared to plastic jars. The research presented in this chapter is expected to inform engineers on the best potential pathway for the development of an automated baiting system.

Chapter 3 documents an at-sea experiment in which I studied the catchability of five new alternative baits manufactured from harp seal and minke whale by-products in comparison to traditional squid bait. The objective was to determine an accessible and sustainable alternative bait by performing a comparative bait study against the traditional bait used by the fleet. The experiment was conducted aboard the *M/S Northeastern* in May/June 2016. The following hypotheses were evaluated:

Ho: CPUE of snow crab traps is independent of bait type.

Ha: CPUE of snow crab traps is dependent on bait type.

Results revealed that seal fat and seal fat with skin baits produced catch rates comparable to squid, while all of the other experimental baits decreased mean CPUE considerably (up to 97%).

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1.13. Figures

Figure 1.1 .Snow crabs (*Chionoecetes opilio*) captured in the Barents Sea during research aboard R/V Helmer Hanssen in February 2016.

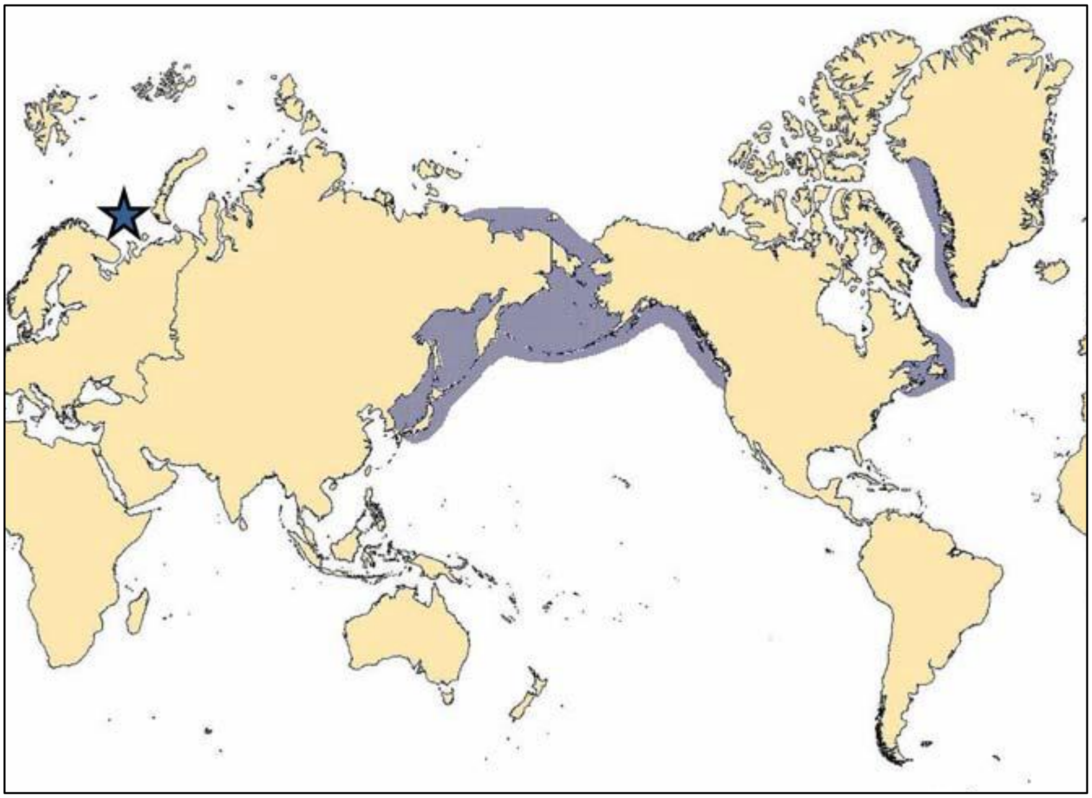

Figure 1.2. Natural distribution of snow crab (grey area) and observation of the new population in the Barents Sea (★) (Agnalt *et al*., 2008).

Figure 1.3. Location of the Barents Sea in the northeast Atlantic Ocean, with surrounding seas and islands (Agnalt *et al*., 2008)

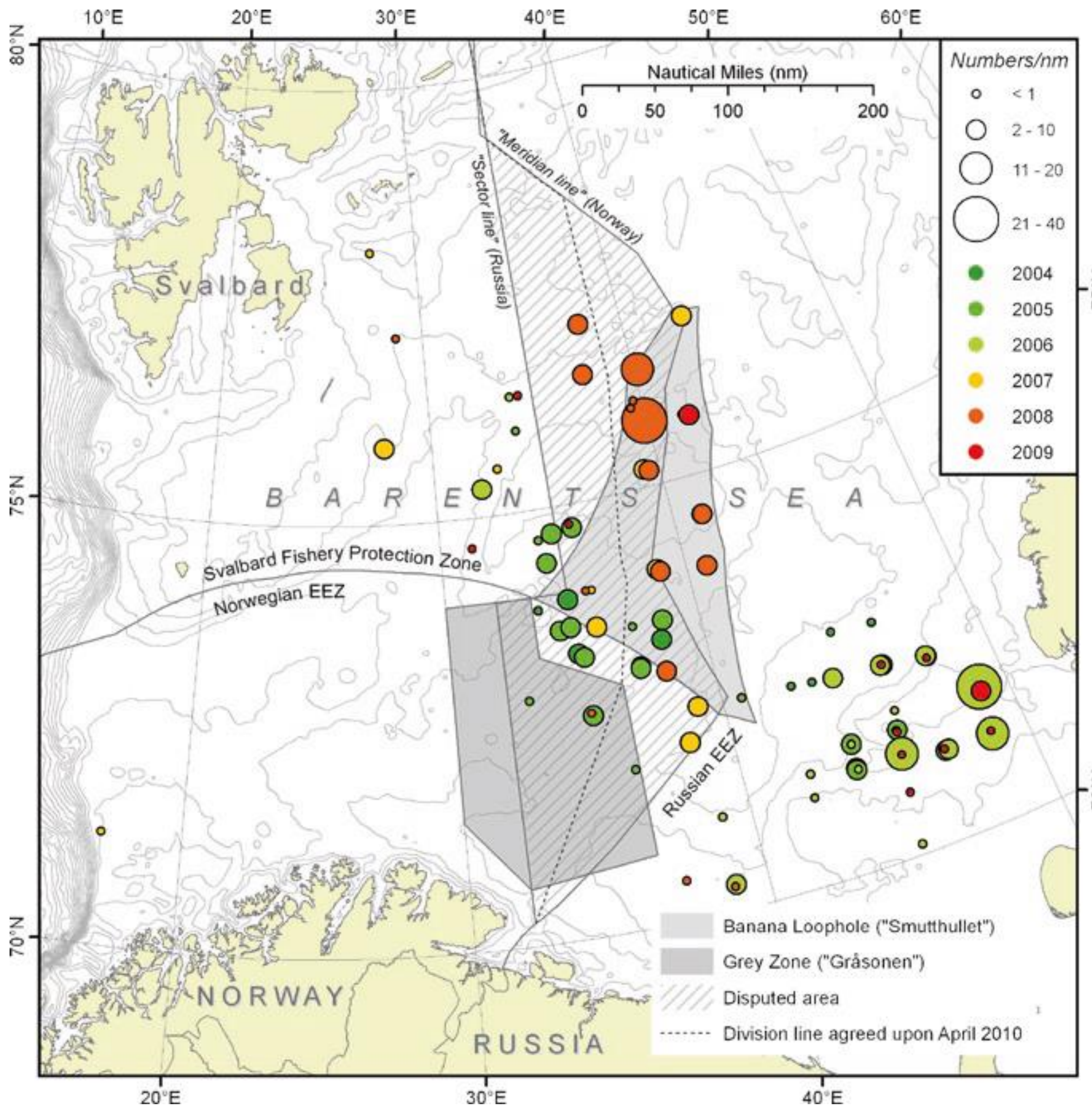

Figure 1.4. Abundance of snow crab (*Chionoecetes opilio*) in the Barents Sea estimated during the Norwegian bottom-trawl surveys 2004–2009. Abundance is number of crabs per mile trawled (Agnalt *et al*., 2008).

Figure 1.5. Snow crab factory vessels that operated during 2016 in the Barents Sea (Fiskebåt).

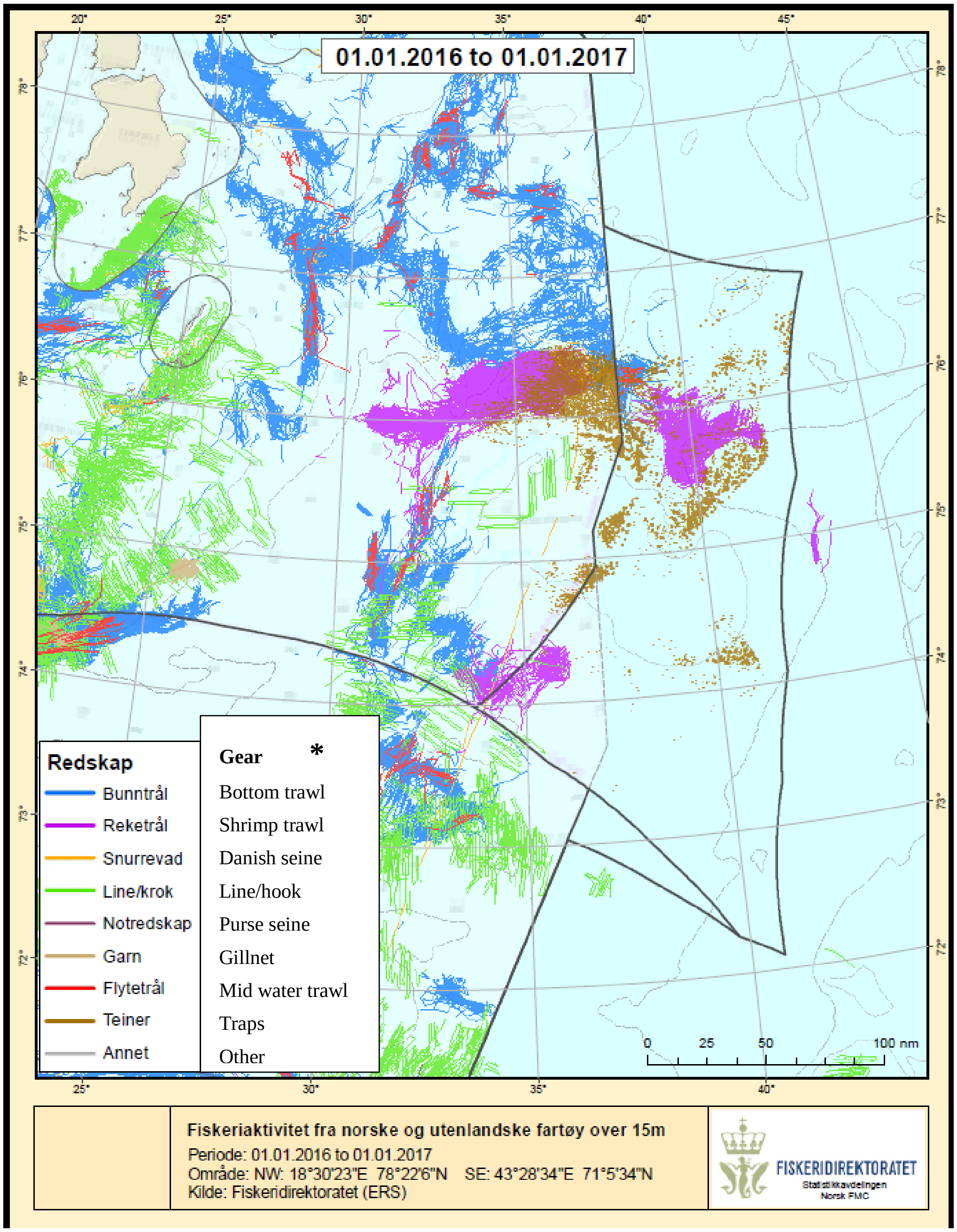

Figure 1.6. Overlap of fisheries in the Barents Sea area during 2016 (Directorate of Fisheries, Norway/Fiskeridirektoratet).* indicates the translation from Norwegian to English of the different fishing gears used.

Figure 1.7. Small conical snow crab trap - typical of fisheries in Newfoundland and Labrador, Canada. Also shown are the jar and mesh bag bait shields.

Figure 1.8. Large conical snow crab trap – typical of fisheries in the Gulf of St. Lawrence, Canada.

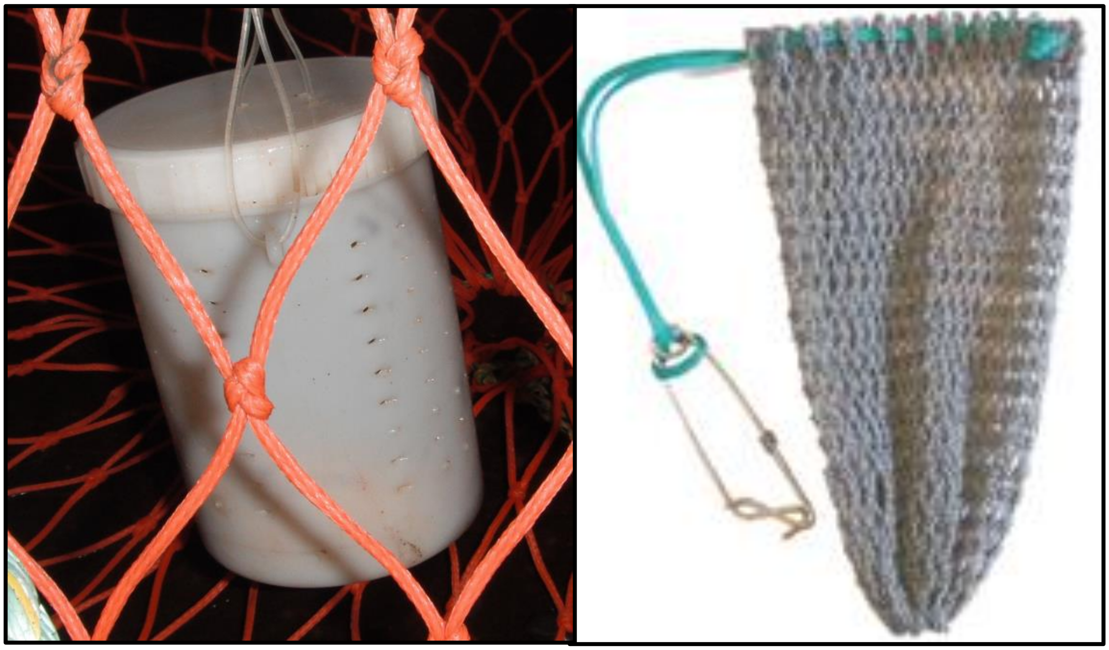

Figure 1.9. Bait shields commonly used in the snow crab fishery. Left: plastic jar, right: mesh bag.

PRELIMINARY OBSERVATIONS OF BAIT SHIELDS IN SNOW CRAB TRAPS - COMPARING JAR AND BAG EFFECTIVENESS IN ORDER TO IMPLEMENT AN AUTOMATED GEAR BAITING SYSTEM

2.1. Abstract

The snow crab fishery in the Barents Sea is carried out by large offshore fishing vessels with the capacity to haul traps at a rate of approximately 1,000 traps per day. Emptying and filling the bait shields used in this fishery, and installing them in the trap requires significant manual labour. The development of an automated baiting system is viewed by industry as an opportunity to increase safety and efficiency. This study aimed to compare the effectiveness of mesh bag and plastic jar bait shields commonly used by the fleet in order to assess the viability of implementing an automated baiting system based on plastic jars. A comparative fishing experiment was conducted aboard a research vessel in the Barents Sea (February, 2016) to evaluate the performance of traps equipped with the two different bait shields (CPUE). Results showed that the catch rate of snow crab varied with the experimental treatments. Higher bait depletion was observed in mesh bags, decreasing CPUE by 73% compared to plastic jars, while snow crab carapace width (CW) did not differ between shield types. Interpretation of the findings in this study should be made with caution as limitations of the experimental design are recognized. Nevertheless, this study demonstrated the importance of highly shielded baits (i.e. plastic jars) in the Barents Sea snow crab fishery, where more exposed baits in mesh bags were completely depleted after 3 and 4 days in the ocean. Furthermore, plastic jars performed

significantly better compared to mesh bag shields in terms of CPUE and no significant difference was observed in snow crab size between treatments, indicating that an automated baiting system with plastic jars may be feasible.

2.2. Introduction

Like many parts of the world, fishing in Norway is a high-risk occupation that results in more accidents annually than any other land-based occupation (McGuinness *et al*., 2013a; McGuinness *et al*., 2013b; Bye and Lamvik 2007; Lindøe, 2007; Håvold, 2010; Lindøe *et al*., 2011). Working at sea operating heavy equipment on an unstable work platform with strong winds and large waves involves elevated risks for fishermen (Windle *et al*., 2008; Antão *et al*., 2008). Moreover, fishing enterprises are operating more frequently under rough weather conditions because of financial conditions (Aasjord *et al.*, 2003).

Emptying and filling bait protection devices (hereafter called shields) and installing them in traps is a repetitive task. Large offshore fishing vessels operating in the Barents Sea snow crab fishery (e.g., *M/S Northeastern*) are hauling traps at a rate of approximately 1,000 traps per day with normally two fishermen dedicated to the fulltime task of emptying and filling bait shields and installing them in traps. Repetitive manual work of this nature can cause wrist and hand disorders, such as carpal tunnel syndrome, cramping of the hand and forearm, and tendon disorders (e.g., Viikari-Juntura and Silverstein, 1999; Muggleton *et al*., 1999; Hansson *et al*., 2000). Efforts to create an automated baiting system for snow crab traps are needed to develop a safer and more efficient snow crab fishery in the Barents Sea. Mechanization in Norwegian fisheries allowed an increase in total landings, with lower man-labour year, fewer working hours, and fewer days at sea (Johnsen, 2005). Highly mechanized longline and gillnet vessels are examples found in Norway in which the development of technology allows a better utilization of limited resources, enable reduced manual labour, and improves safety (Johnsen, 2005; Larsen and Rindahl, 2008).

Depending on the time of year and fishing location, exposed baits may be depleted rapidly by scavenging amphipods, losing their attractant properties and decreasing catch rates (Robertson, 1989; Miller 1990; Richards and Cobb, 1987). Fishermen have solved this issue by placing bait in perforated devices such as jars or bags, thus allowing diffusion of bait odor but preventing undesired bait depletion and increasing trap fishing time (Cyr and Sainte-Marie, 1995). The use of bait shields is a common practice in Canada’s east coast snow crab fishery. Baits are placed in jars or bags (Grant and Hiscock, 2009) depending on the grade of protection that fishermen want to achieve. Several studies have reported that catches increased significantly with unshielded baits (Miller, 1979; Cyr and Sainte-Marie, 1995; Pfister and Romaire, 1983), while in Robertson’s (1989) study catches did not differ significantly between shielded and unshielded baits. Evidence also suggests that exposed baits (i.e., no shields) allow crabs the opportunity to feed from the bait, thus attracting more conspecifics by increasing the effluence of chemical attractants or visual stimulation (Miller, 1979; Pfister and Romaire, 1983), which is particularly effective for short soak times (Robertson, 1989). On the other hand, baits placed in shields are more protected, decreasing depletion from scavengers, and increasing catch rates for longer soak times (Robertson, 1989).

Looking to the future, it is highly anticipated that mechanization will replace the tedious task of emptying and filling bait shields on Norwegian fishing vessels. Engineers at SINTEF are already exploring various methods for how this might be achieved (Leonore Olsen, SINTEF, personal communication). The utilization of jars as bait shields is expected to be more compatible with an automated baiting system. Key advantages include predictable shape, size, and bait quantity. Bait bags by comparison are flexible in shape and size and can hold variable quantities of bait, making them more complex to work with from an engineering perspective. Ultimately, the engineering solution might involve a robotic arm that unscrews a depleted bait jar from the side of a trap, empties it, refills it with fresh bait, and screws it back into position in a trap.

This study compares the performance of the jar and the mesh bag bait shields in the Barents Sea snow crab fishery. It documents an at-sea comparative fishing experiment aboard the *R/V Helmer Hanssen* in partnership with SINTEF and the University of the Arctic, Norway. Application of the results is intended to inform future design options for automated baiting systems that would eventually use jars as bait shields.

2.3. Materials and methods

Study area

This at-sea fishing experiment was conducted aboard the *R/V Helmer Hanssen* during February 2016. The vessel is a stern trawler of 63.8 m length with an engine power of 3000 kW/4080 Bhp at 750 rpm. It is a multipurpose vessel, designed for fishery and marine biological, geological and oceanographic surveys in open and ice covered waters. Experimental fleets of traps were deployed in the Sentralbanken area of the Barents Sea at a depth of 270 m (Figure 2.1).

Fishing experiment

In order to compare the effectiveness of different types of bait shields, 2 fleets of 30 small conical traps were deployed (see Figure 1.7). Each fleet contained 20 traps with commercial mesh (i.e. 140 mm stretched mesh) as well as 10 traps with small mesh (60 mm diamond) (Figure 2.2) in order to capture a wide size range of snow crabs. All traps were small Japanese-style conical traps similar to those used in eastern Canada (see Winger and Walsh, 2011) with top plastic entrance cone, a bottom ring diameter of 133 cm and a volume of 2.1 m^3. Fleet No. 1 contained 10 traps with commercial mesh size and baits bags (CMB), 10 traps with commercial mesh size and bait jars (CMJ), 5 traps with small mesh size and bait bags (SMB), and 5 traps with small mesh size and bait jars (SMJ) (Table 2.1). Fleet No. 2 contained 9 traps with CMB, 11 traps with CMJ, 6 traps with SMB, and 4 traps with SMJ. All four treatments were arranged randomly within the fleet of traps with 20 m of distance between each trap. Two whole fresh squids (0.4 kg) were used as bait to fill the jar or mesh bag in each trap. Bait jars were cylindrical in shape: 15.6 cm high, 9.5 cm diameter, and contained small holes of less than 3 mm diameter throughout. Bait bags were constructed of machine-made polyethylene netting with a stretched mesh size of 27 mm.

Fleet No. 1 was deployed and soaked for 4 days, while Fleet No. 2 was deployed and soaked for 3 days (Table 2.1). Variation in soak time was unavoidable due to rough weather conditions. Counts of legal-sized male snow crabs with CW $\geq$ 95 mm per trap were recorded. All individuals captured in the traps were measured and sex was determined.

Statistical analysis

According to O'Hara and Kotze (2010), count data should not be transformed to fit parametric tests. Consequently, a Generalized Linear Model (GLM) was used, assuming that the error follows a negative binomial distribution with log link due to the over-dispersed count of crabs per trap haul. Furthermore, the true mean count of crabs is equal to the exponential of a linear combination of bait shield, trap mesh, and soak time effects. Good fit of the model was assessed with Pearson Chi-Square value (p-value > 0.05) and omnibus test (p-value < 0.05). Deviations of the residuals were evaluated by graphing standardized deviance residual vs predicted value of mean response (values between 2 and -2). Presence of outliers was assessed with the frequency distribution of the standardized Pearson residual (no values > 2). Incident rate ratios were obtained from model parameter estimates and interpreted in the study results.

Frequency distribution of snow crab carapace width (CW) for the four different treatments were statistically compared using a Kruskal-Wallis test. A two-way ANOVA was used to statistically compare mean CW values for the different treatments as well as evaluate any interaction among the variables (i.e., bait shield*mesh type). Data treatment and manipulation was carried out using Microsoft Excel software and statistical analyses were carried-out using IBM SPSS Statistics Software Ver 22.

2.4. Results

Two fleets of 30 traps each were set and hauled successfully. Visual observations of the bait shields upon return to the surface revealed a difference in performance. Squid placed in jars returned to the surface fully intact, whereas squid placed in mesh bags was completely depleted (Figure 2.3). This pattern was consistent for all replicates. Close examination of the jars revealed the presence of amphipods inside the jars, while no detectable evidence of amphipods was seen in the mesh bags.

A total 164 legal-sized male snow crabs with CW $\geq$ 95 mm were captured in the traps. Higher catch rates were observed in the commercial mesh traps with bait jars (CMJ), with a minimum of 1.0, maximum of 16.0, and mean of 5.2 crabs per trap haul (Table 2.2). Small mesh traps with bait jars (SMJ) exhibited a minimum of 0.0, maximum of 8.0, and a mean of 2.2 crabs per trap haul. CMB and SMB traps captured snow crab at lower rates, with a mean CPUE of 1.0 and 1.5 respectively (Figure 2.4). Standard deviations ranged from 1.1 to 3.5 crabs per trap haul (Table 2.2). Overall, mesh bags decreased mean CPUE by 73% when compared to plastics jars. According to the negative binomial model, significant differences were observed in the count of crabs per trap haul depending on the type of bait shield (p-value < 0.001), while no significant differences were found regarding mesh size (p-value = 0.414) and soak time (p-value = 0.483) (Table 2.3). Incident rate ratios (IRR) from the generalized linear model estimated that incident rate of traps with bags is 0.3 times the incident rate for traps with jars. In other words, traps with jars captured crabs at rates 70% higher than traps with bags. Although mesh size and soak time were not significant predictors, IRR indicated that traps with commercial mesh captured crabs at rates 1.3 times higher than small mesh traps and for every unit increase in soak time (days), the number of crabs per trap haul increased by 25% (Table 2.4). When accounting for soak time as a covariate with a fixed value of 3.5 days, the model estimated a mean value of 1.1 and 3.8 crabs per trap haul for bags and jars, respectively. Under the same scenario (soak time fixed at 3.5 days) commercial mesh traps and small mesh traps exhibited a mean CPUE of 2.4 and 1.8 crabs per trap haul, respectively.

Mean carapace widths of 116, 114, 109, and 111 mm were observed for the CMJ, CMB, SMB, and SMJ treatments respectively (Table 2.5). A total of 11 male crabs under 95 mm CW were observed (equivalent to 6.3%); 2 were found in CMB treatment, 3 in CMJ treatment, 4 in SMB treatment, and 2 in SMJ treatment. A total of 7 female snow crab were also captured, and all of them were observed in three SMB traps (Table 2.5). The Independent-Samples Kruskal-Wallis test showed that the distribution of CW was the same across the four different treatments ($X^2_{(3)} = 4.908$, p-value = 0.179) (Figure 2.5), with a mean rank CW score of 87.43 for CMB, 68.93 for SMB, 93.40 for CMJ, and

78.39 for SMJ. The two-way ANOVA showed no significant differences in mean CW between commercial and small mesh traps ($F_{1,174}$ = 3.548, p-value = 0.061), no significant difference in mean CW between traps with bags and traps with jars ($F_{1,174}$ = 0.518, p-value = 0.473), and a non-significant mesh*shield interaction term ($F_{1,174}$ = 0.004, p-value = 0.952) (Figure 2.6). Finally, the one-way ANOVA indicated that there were no significant differences in mean CW between the four treatments (CMB, CMJ, SMB and SMJ) ($F_{3,174}$ = 2.036, p-value = 0.111) (Figure 2.6).

2.5. Discussion

Bait shields used in this study performed notably different from one another. Traps with mesh bags exhibited 73% lower CPUE than traps with plastic jars. After 3 and 4 days of soak time, squid placed in the mesh bags were completely depleted, while squid placed in jars remained fully intact. The presence of amphipods in the bait jars indicates conclusively the presence of this scavenging species on the fishing grounds during this experiment. The fact that no amphipods were found in the bait bags is not surprising given the large mesh size of the mesh bags (i.e., 27 mm). Interestingly, even traps with no catch of any species showed complete depletion of the baits in the mesh bags, suggesting that scavenging species other than snow crab, must have fed intensively on the bait. These scavengers must have been small enough to enter and exit without detection and/or fall through the meshes during haul-back. In the absence of any other data, these observations suggest that amphipods were the likely culprit, and given the large mesh size of the bait bag relative to the jars, were more effective at depleting the bait in this type of shield. Miller (1990) stated that amphipods, crabs, sea urchins, sea stars, finfish and seals can all eat bait, thus reducing the effectiveness of a trap. It is speculated that the smaller holes in the bait jars effectively protected the bait, allowing the trap to continue attracting crab, explaining the higher catch rates observed in the traps equipped with bait jars.

Traps are normally soaked between 5 and 14 days (i.e. *M/S Northeastern*), and fishing vessels in Norway currently use a combination of both bait jars and bait bags in every trap (i.e., one jar and one bag). It is speculated that this achieves multiple goals; a) long-term odor plume production via the jar, and b) ability for crab to access the bait through the meshes of the bait bag which increases the short-term concentration of chemical attractants, thus provoking a greater response and increasing catch rates until the bait is depleted (Miller, 1979; Pfister and Romaire, 1983). It is also possible that the mesh bags help to keep animals peaceful inside the trap because they are not hungry, allowing newcomers to enter the trap (Cyr and Sainte-Marie, 1995). Although this study does not investigate these aspects, it does open questions for further investigations.

The distribution of carapace width observed in this study showed no significant difference between the four treatments tested. Furthermore, mean carapace width was statistically the same between mesh types and bait shields, indicating that neither of these two variables had a significant effect on the size of snow crab captured. Although ANOVA can be sensitive to the unequal sample size presented in this study, thus, causing the lack of significant difference in CW, it is reasonable to assume that bait shield type does not affect snow crab size, while regarding mesh size, these findings are inconsistent with previous research which has shown that the size-selectivity of snow crab traps is related to the mesh size of the exterior walls of the trap (e.g., Miller, 1976, Coulombe and Beaulieu, 1987; Winger *et al.*, 2011). Given that the small mesh traps did capture more male crabs under 95 mm CW as well as the only 7 female crabs captured during the experiment, it is speculated that the low sample size of the experiment may have reduced the statistical power to detect a significant difference. Said another way, it is predicted that additional replicates would have increased the ability of the experiment to detect a significant effect of mesh size.

Interpretation of the findings in this study should be made with caution as limitations of the experimental design are recognized. Due to the limited number of traps and days at sea, only a limited number of replicates for the experimental treatments were achieved, resulting in a smaller than desired sample size. For this reason, these results should be interpreted as preliminary. Further studies on bait shields are recommended, including larger sample sizes as well as an additional experimental treatment that mimics the industry practice of using both jars and bags in a trap.

In conclusion, this study demonstrated the importance of highly shielded baits (i.e. plastic jars) in the Barents Sea snow crab fishery. Baits that were more exposed in mesh bags were completely depleted after 3 and 4 days in the ocean. Plastic jars also performed significantly better compared to mesh bag shields in terms of CPUE with no significant difference in snow crab size between treatments. Taken together, these results suggest that an automated baiting system with plastics jar may be a viable research pathway.

2.6. References

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2.7. Tables

Table 2.1. Composition of the experimental fleets as well as the locations and depths deployed.

Fleet	CMB	Treatments CMJ	SMB	SMJ	Soak time (days)	Latitude	Longitude	Depth (m)
1	10	10	5	5	4	76º06'15"N	34º54'04"E	270
2	9	11	6	4	3	76º11'43"N	36º16'59"E	270

Table 2.2. Mean, minimum, maximum and standard deviation of CPUE in the different treatments.

Treatment	Mean CPUE	Min CPUE	Max CPUE
CMB	1.0 [1.1]	0.0	3.0
CMJ	5.2 [3.5]	1.0	16.0
SMB	1.5 [1.7]	0.0	5.0
SMJ	2.2 [3.4]	0.0	8.0

Table 2.3. Test of model effects from generalized linear model.

Source	Type III Wald Chi-Square	df	p-value
(Intercept)	0.001	1	0.970
mesh	0.668	1	0.414
shield	13.040	1	0.000
Soak time	0.493	1	0.483

Dependent Variable: CPUE

Model: (Intercept), mesh, shield, soak time

Table 2.4. Parameters estimates from generalized linear model.

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test			Exp(B) or IRR	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	p-value		Lower	Upper
(Intercept)	0.414	1.2287	-1.994	2.823	0.114	1	0.736	1.513	0.136	16.820
[mesh=Commercial]	0.294	0.3597	-0.411	0.999	0.668	1	0.414	1.342	0.663	2.716
[mesh=Small]	0[a]	.	.	.	.	.	.	1	.	.
[shield=Bag]	-1.209	0.3347	-1.864	-0.553	13.040	1	0.00	0.299	0.155	0.575
[shield=Jar]	0[a]	.	.	.	.	.	.	1	.	.
soak time	0.225	0.3201	-0.403	0.852	0.493	1	0.483	1.252	0.669	2.344
(Scale)	1[b]									
(Negative binomial)	1									

Dependent Variable: CPUE
Model: (Intercept), mesh, shield, soak time.
a. Set to zero because this parameter is redundant.
b. Fixed at the displayed value.

Table 2.5. Mean CW, sample size, number and percentage of males under 95 mm CW, and number of females captured by the different treatments.

Treatment	Mean CW (mm)	n	Males < 95 mm	Males < 95 mm (%)	Females
CMB	114	22	2	14%	0
CMJ	116	112	3	8%	0
SMB	109	19	4	26%	7
SMJ	111	22	2	14%	0

2.8. Figures

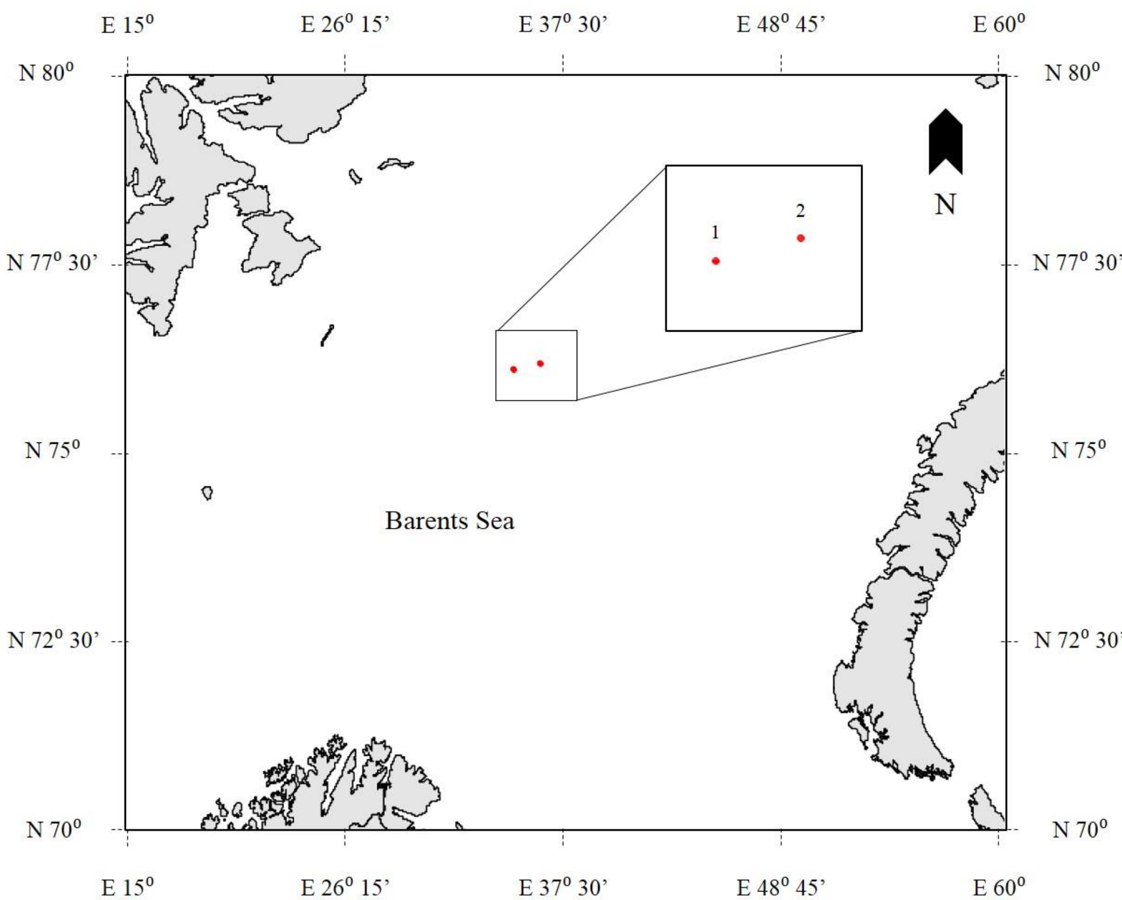

Figure 2.1. Map of the study area located in the Sentralbanken area of the Barents Sea with zoom in section. Numbers denote different fleets deployed.

Figure 2.2. Small mesh trap (60 mm working mesh), used to capture all sizes snow crabs.

Figure 2.3. Bait remaining in the jar (left) and in the mesh bag (right) after 4 days at sea.

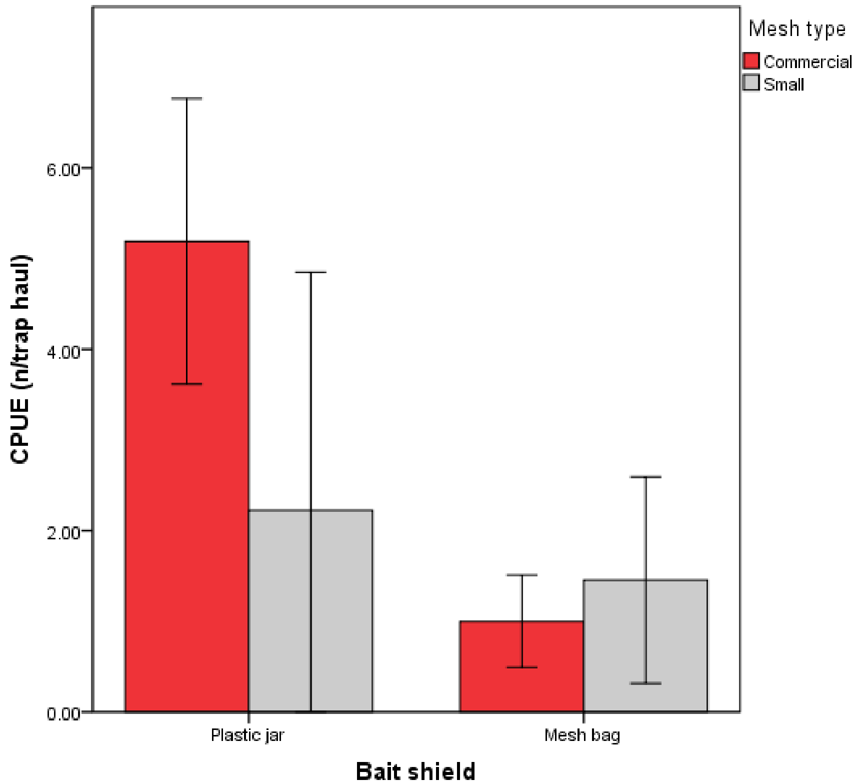

Figure 2.4. Mean CPUE of plastic jar and mesh bag bait shields in commercial and small mesh traps. Standard error of the different treatments is also shown.

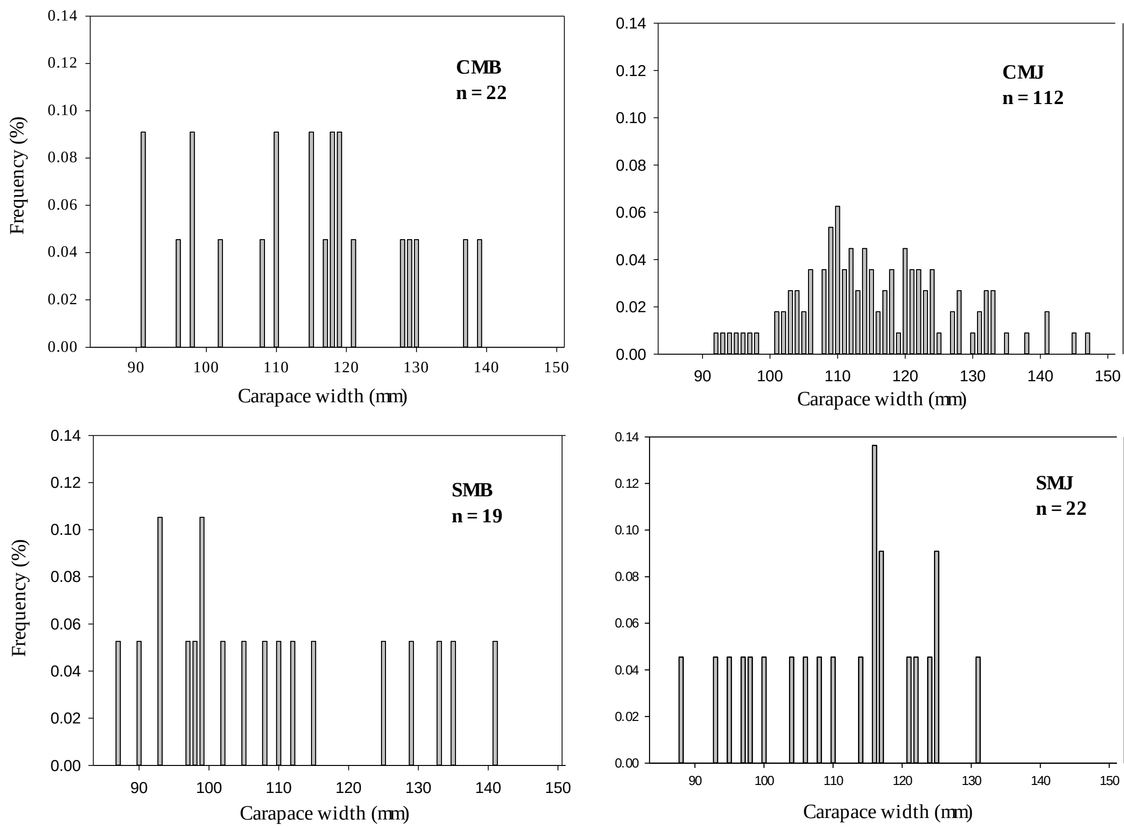

Figure 2.5. Bar graphs of carapace width distribution of snow crab captured. Each panel represents a different experimental treatment. n denotes the number of trap hauls.

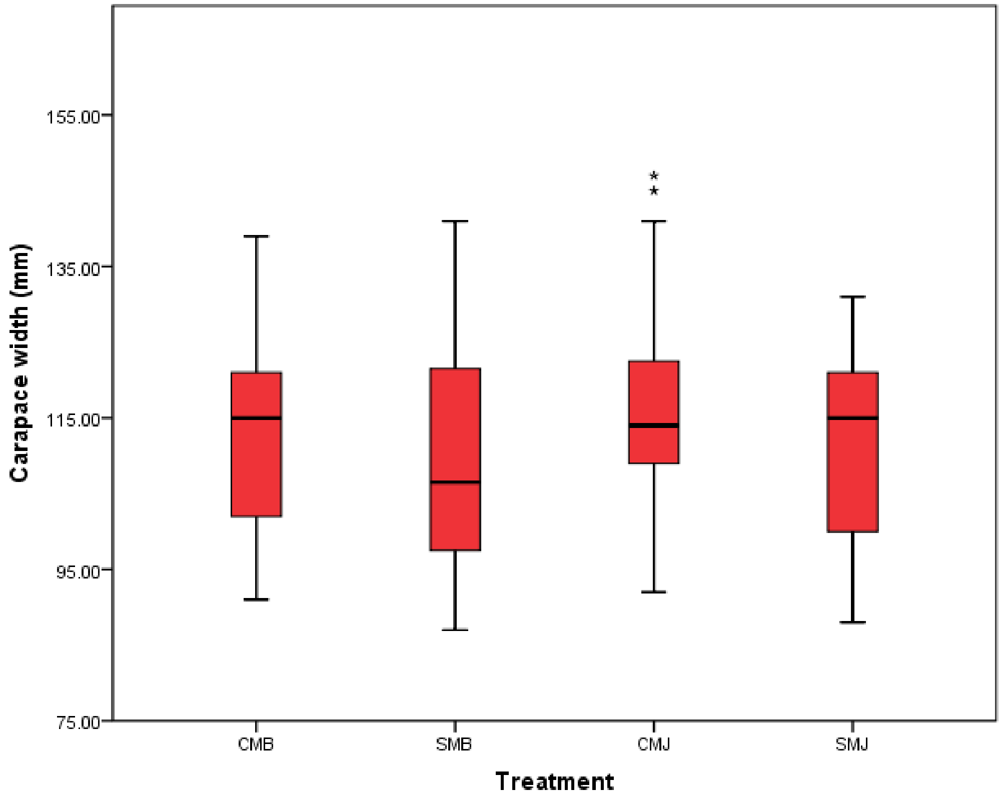

Figure 2.6. Boxplot of carapace width of snow crab captured by the different treatments.

ALTERNATIVE BAIT TRIALS IN THE BARENTS SEA SNOW CRAB FISHERY

3.1. Abstract

Commercial harvesting of snow crab (*Chionoecetes opilio*) in the Barents Sea started in 2014 by Russian and Norwegian fishing vessels. This new fishery has significant bait requirements, representing an emerging conservation challenge. In this study, the performance of alternative (natural) baits manufactured from harp seal (*Pagophilus groenlandicus*) and minke whale (*Balaenoptera acutorostrata*) by-products were evaluated. Five different types of new bait were evaluated, including whale fat with skin, whale meat with fat, seal fat, seal meat, and seal fat with skin. A comparative fishing experiment was conducted aboard a commercial fishing vessel in the Barents Sea (May-June, 2016) to evaluate the performance of traps with these different baits in terms of numbers of crabs per trap haul (CPUE). Control traps baited with squid captured a mean of 9.5 crabs per trap haul. The best performing experimental baits were seal fat and seal fat with skin, which captured a mean of 13.8 and 7.1 crabs per trap haul, respectively. All other baits produced lower mean CPUE, including seal meat and bone, whale fat and skin, and whale meat and fat, which were 2.1, 1.8 and 2.8, respectively. Results showed that there was no statistical difference in the mean CPUE between traps baited with squid, seal fat (p-value = 1.0) and seal fat with skin (p-value = 0.513), while all other bait treatments differed significantly in comparison to control traps (p-value < 0.001). High variability in CPUE was observed throughout the experiment and was

attributed to fishing location, soak time, and bait type. Mean carapace width (CW) and the frequency distribution of CW was not statistically different across the experimental treatments, indicating that the alternative baits tested had no effect on the size of snow crab captured. Overall this experiment suggests that fat and fat with skin from harp seal could be used to harvest snow crab in the Barents Sea, reducing bait costs and increasing sustainability since these new baits are produced from seal by-products locally obtained.

3.2. Introduction

Commercial harvesting of snow crab (*Chionoecetes opilio*) in the Barents Sea started in 2014 by Norwegian and Russian fishing vessels (Sherstneva, 2013; Lorentzen *et al.*, 2016). Commercial landings of snow crab in Norway reached 4000 tonnes that year, with an export value of 100 million NOK (Lorentzen *et al.*, 2016). This fishery is viewed as an important economic opportunity, with projections that landings could reach a value of 2.5 to 7.5 billion NOK in the next 15 years (Hansen, 2016). Due to the large amount of traps used by the vessels that operate in this fishery (~ 8000 traps per vessel) and the efficiency in which traps are deployed and hauled (~ 1000 traps per day), this new fishery relies on substantial amounts of natural bait to attract snow crabs into the traps, representing a substantial operational cost and an emerging conservation challenge.

Chemical attractants are released from the bait and transported by the current, producing an odour plume, whose shape, orientation and area strongly depends on the amount of bait, the current speed, direction, and turbulence (Okubo, 1980; Sainte-Marie and Hargrave, 1987; Chiasson *et al.*, 1992; Moore *et al.*, 1994; Winger and Walsh, 2011).

Snow crab are attracted by the smell of the bait (McLeese, 1970; Mackie, 1973; Hancock, 1974) from down current, crawling towards the trap (Karnofsky and Price, 1989; Lapointe and Sainte-Marie, 1992; Chiasson *et al.*, 1992; Vienneau *et al*., 1993), and eventually find the trap, climb the exterior walls, and enter through the top entrance (Stiansen *et al*., 2010; Winger and Walsh, 2011). Squid imported from South America is currently the most commonly used bait when targeting snow crab as it tends to perform better than other natural baits (e.g. Grant and Hiscock, 2009). Natural baits used in crab fisheries are expensive and suitable for human consumption (Dale *et al.*, 2007; Grant and Hiscock, 2009; Vazquez and Kawamura, 2011). With decreasing stocks of marine resources and increasing human population, there is a growing demand for bait resources. In the past decade, bait prices have increased significantly (Løkkeborg *et al*., 2014) creating additional drivers to find accessible and sustainable alternative baits that are not based on resources used for human consumption (Løkkeborg *et al*., 2014).

Since bait performance studies for snow crab are commonly conducted at sea, managing all of the sources of uncertainty can be a challenge (Grant and Hiscock, 2009). Not only does the type, quantity and shield of bait influence CPUE, there are also several factors known to affect catchability of traps. Evidence has shown that the target species behaviour may vary due to sensory limitations, temperature, metabolism, shell stage, life cycle, availability of food, water currents, light level, and turbidity (Grant and Hiscock, 2009). Abundance of snow crab can also vary greatly from area to area depending on bottom substrate, temperature, depth, prey availability, and fishing pressure (Grant and Hiscock, 2009).

This study evaluated the performance of alternative baits manufactured from harp seal (*Pagophilus groenlandicus*) and minke whale (*Balaenoptera acutorostrata*) by-products. Historically there is evidence that different types of marine mammals were used by fishermen to bait traps in commercial crab fisheries (Lescrauwaet and Gibbons, 1994). Several studies have attempted to use waste from fish processing industries to create alternative bait with some success (Mackie *et al*., 1980; Chanes-Miranda and Viana, 2000; Dale *et al*., 2007; Beecher and Romaire, 2010), but there are no bait comparison studies regarding the use of marine mammal by-products.

3.3. Materials and Methods

Study Area

This study took place in the Barents Sea, Norway aboard the commercial fishing vessel *M/S Northeastern* during May 24th - June 24th, 2016. The vessel was originally used for sealing; it is 57.91 m long and has a Gross Tonnage (GT) of 807. Fifteen commercial fleets containing experimental traps were deployed in the Sentralbanken area of the Barents Sea (Figure 3.1). The water depths ranged between 210 and 288 m for the fleets. Water temperature near the seabed was recorded using temperature loggers and was observed between 1.0 to 1.4˚C, during the experiment.

Fishing experiment

Five different types of new alternative baits were evaluated; harp seal fat (SF), harp seal fat with skin (SFS), harp seal meat (SM), minke whale fat with skin (WFS), and minke whale meat with fat (WMF) (Figure 3.2). Each treatment was separately and randomly distributed within commercial fleets of traps which were baited with whole squid. Trials were conducted under commercial fishing conditions with the gear deployed and retrieved in the manner typical for this fishery. Traps were deployed in fleets ranging from 130 up to 200 traps spaced at intervals of 30 m. All traps were small Japanese-style conical traps similar to those used in eastern Canada (see Winger and Walsh, 2011) with 140 mm stretched mesh, a top plastic entrance cone, a bottom ring diameter of 133 cm, and a volume of 2.1 m^3 (Figure 3.3).

Shielding of the bait from predation by amphipods was accomplished by placing the bait in perforated plastic jars and mesh bags. Each trap was baited using one jar and one mesh bag of bait, which were hung together in the centre of the trap attached to the top mesh of the trap. Control traps were baited with 1 kg of squid; 0.5 kg in the bag and 0.5 kg in the jar following the actual bait configuration used by *M/S Northeastern*. Experimental traps were baited with the same amount of alternative bait, which was cut in pieces approximately 0.17 kg each in order to mimic the number of pieces used in the control traps (e.g., 6 pieces of new bait: 6 whole squids: 1 kg of bait). Bait quantity remained constant throughout the experiment. Squid bait was thawed before baiting the traps, whereas the experimental baits did not require thawing as they were preserved in barrels with salt.

A total of 2,783 traps in 15 fleets were successfully deployed and hauled during the fishing trip (Table 3.1). Of these, 255 traps contained experimental bait and 387of the traps containing squid (i.e., control) were assessed. Due to the large numbers of traps in each fleet, only traps situated either side of the experimental traps, were declared control traps, the remainder of the traps were considered commercial gear and were excluded from the analysis. A total of 37 traps were baited with SF, 89 traps were baited with SFS, 19 traps were baited with SM, 61 traps were baited with WFS, and 36 traps were baited with WMF. Soak time, depth, and position (latitude and longitude) were recorded for all deployments. The number of male legal-sized hard-shell snow crab ($\geq$ 95 mm carapace width) per trap hauled was recorded. Carapace width (CW) was measured randomly for all size crabs, including sublegal individuals, sampling 1 to 3 individuals per trap depending on the available time before the next trap arrived. It was not possible to measure CW for all crabs due to the constant hauling of the fishing gear, processing of the crabs, and limited workspace onboard the vessel.

Statistical analysis

The numbers of crab per trap haul (CPUE) was treated as count data and was not transformed to fit parametric tests (O'Hara and Kotze, 2010). Generalized Linear Model (GLM) was used, assuming that the error follows a negative binomial distribution with log link due to the over-dispersed count of crabs per trap haul. The log of the expected catch was modeled as a function of the bait and soak time. Multiple comparisons between treatments were conducted based on the maximum likelihood ratio test with the

Bonferroni approach. Good fit of the model was assessed with Pearson Chi-Square value (p-value > 0.05) and omnibus test (p-value < 0.05). Deviations of the residuals were evaluated by graphing standardized deviance residual vs predicted value of mean response (values between 2 and -2). Presence of outliers was assessed with the frequency distribution of the standardized Pearson residual (no values > 2). Incident rate ratios were obtained from model parameter estimates and interpreted in the study results.

Frequency distribution of snow crab carapace width (CW) for the different treatments was statistically compared using the Kruskal-Wallis K sample Test. A one-way ANOVA was used to compare mean CW for the different treatments. If significant differences were detected, the post-hoc Tukey HSD multiple comparison test was used. Statistical analyses were made using IBM SPSS Statistics Ver. 22.

3.4. Results

Control traps baited with squid produced a mean CPUE of 9.5 (s.d. = 7.8) with an estimated mean soak time of 8.3 days, SF had a mean CPUE of 13.8 (s.d. = 12.9) with a mean soak time of 10.3 days, and SFS had a mean CPUE of 7.1 (s.d. = 7.1) with a mean soak time of 7.4 days, while the remaining treatments experienced noticeably lower catch rates (Table 3.2, Figure 3.4). A significant difference in CPUE among the treatments and soak time was detected (p-value < 0.001 for both variables) (Table 3.3). Incident Rate Ratio from the generalized linear model indicated that for every unit increase in soak time (days), the number of crabs per trap hauled increased by 19% (Table 3.4).Closer inspection by pairwise comparisons revealed no significant difference in the mean CPUE for traps baited with squid, SF (p-value = 1.0) and SFS (p-value = 0.513), however all other bait treatments were significantly lower when compared to control traps (p-value < 0.001) (Table 3.5).

According to model predictors, traps baited with squid captured a mean CPUE of 8.7 crabs per trap when accounting for soak time variable (soak time fixed at 8.2 days). In the same scenario, SF was 10.1, SFS was 6.8, SM was 1.7, WFS was 1.1, and WMF was 2.1 crabs per trap haul.

High variability in CPUE was observed throughout the experiment. Minimum values of 0 crabs per trap were observed in all bait types, regardless of the fact that maximum CPUE ranged from 7 to 38 crabs per trap. Standard deviation of the mean ranged from 2.0 (SM) to 12.9 (SF) (Table 3.2). Depths ranged from 210 to 288 m for the fleets, with an average depth of 243 m.

Mean carapace width (CW) ranged from 109 to 113 mm for the different experimental treatments (Table 3.6). Sample size of CW in experimental treatments was small compared to control traps. No females were observed while measuring crabs. Sublegal male crabs were observed while measuring CW. The percentage of sublegal crabs ranged from 2 to 27% (Table 3.6). No significant difference in the mean CW was detected between the different bait treatments ($F_{5,3122} = 1.012$, p-value = 0.409) (Figure 3.5). Independent-Samples Kruskal-Wallis test showed that the distribution of CW was the same across categories of bait ($X^2_{(5)} = 4.196$, p-value = 0.522) with a mean rank CW score of 1565.99 for Squid, 1657.71 for SF, 1610.42 for SFS, 1303.74 for SM, 1380.20 for WFS and 1430.74 for the WMF treatments.

During the fishing trip, 23,000 kg of whole squid were used to bait the commercial and experimental traps with an estimated price of 15 NOK/kg (2.37 CAD/kg) (Table 3.7). SF was purchased at 10 NOK/kg (1.58 CAD/kg) from a provider that sells this by-product for oil production, SFS at 15 - 25 NOK/kg (2.37 – 3.95 CAD/kg) depending on the provider, and SM can vary from 70 - 150 NOK/kg (11.07 – 23.73 CAD/kg) depending on the availability, while, WMF and WFS are by-products and have no commercial value.

3.5. Discussion

This study represents the first systematic attempt to investigate the performance of alternative baits derived from marine mammal by-products for the commercial capture of snow crab. Of the 5 experimental baits evaluated, SF and SFS produced catch rates comparable to squid, with no statistical difference in mean CPUE detected between the three bait types. All of the other experimental baits (SM, WFS, and WMF) decreased mean CPUE considerably (up to 97%) compared to squid. Functional explanations for why snow crab preferred SF and SFS are uncertain, however the common denominator appears to be the seal fat. Baits that did not contain seal fat did not perform as well, suggesting that the fat of the seal has attractive properties. Further investigation is warranted to determine what characteristics (e.g., amino acids, oiliness) determine its effectiveness.

In addition to catchability, the success of any new bait in a commercial fishery depends on its availability, storage logistics, and price (Dale *et al.*, 2007). A comparison of the purchase prices (Table 3.7) illustrates that SF bait is cheaper than squid by 57%, and SFS can vary between 35% cheaper and 8% more expensive compared to squid, and squid is the preferred bait type at the present time. For this study, the small amount of SF and SFS bait was sourced from a value chain that produces seal oil plus the possible value added of the skin present in the SFS bait. It is conceivable that an even better price could be negotiated if larger amounts were purchased, thereby lowering the price even further for both seal baits. The baits are also locally produced and do not need to be imported or shipped from great distances, lowering carbon footprint and greenhouse gas emissions. Finally, it also has the advantage that it is preserved in salt and does not require long-term freezer storage. All of these attributes offer significant opportunity to reduce the operational costs for fishing enterprises. Nonetheless, issues such as availability and bait cutting need to be further studied in order to implement these new baits in commercial fisheries.

Depending on the location and time of year, baits that are exposed in traps may be depleted by undesired species within a few hours of deployment, losing their attractant properties and decreasing catch rates (Richards and Cobb, 1987; Robertson, 1989; Miller, 1990). To avoid this unwanted depletion, fishing enterprises tend to use bait protection devices (i.e., shields). In this study, qualitative observations indicated that baits contained in mesh bags were, in all traps, more depleted than baits contained in jars. Depletion of bait was also observed in traps with no crabs, indicating the presence of species, other than snow crab, that feed from the bait (Dale *et al.*, 2007). Although not quantified, it was noted that all of the experimental baits experienced less depletion compared to squid. In fact in most of the cases there were high quantities of experimental bait remaining in the bait shields. This suggests that these baits may be reusable, which is another way to reduce operational costs. Further studies on bait reuse are recommended.

Several studies have shown that the catchability of decapod crabs increases with increasing bait quantity (Thomas, 1954; Zimmer-Faust and Case, 1982; Miller, 1983; Zimmer-Faust and Case, 1983; Takeuchi, 1988; Cyr and Sainte-Marie, 1995). This variable was not manipulated in this study, but could prove to be a valuable hypothesis for further evaluation. For example, it would be interesting to study the sensitivity of CPUE to varying amounts of the alternative baits presented here.

Limitations are recognized in the current study. Given the observations were conducted during commercial fishing activities, it was difficult to direct the fishing location, increase sample sizes, or standardize soak times. All of these items may have introduced error in the data and compromised the ability to draw more conclusions. Other co-variates may have included substrate type, temperature, fishing pressure, food availability, and current direction and velocity, all of which are suspected to affect the response thresholds of snow crab (Grant and Hiscock, 2009). Nonetheless, these results are encouraging and noteworthy. To our knowledge, this is the first systematic study on the use of seal and whale by-products as potential baits for snow crab fisheries.

In conclusion, this study evaluated the catching performance of several new alternative baits for catching snow crab in the Barents Sea. Each of the baits was based on a waste stream (i.e., by-product) from seal and whale fisheries. The results showed that seal fat and seal fat with skin from harp seals were the best performing baits, producing a mean CPUE comparable to squid which is the current preferred bait type by industry.

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3.7. Tables

Table 3.1. Fleets deployed during the experiment. Experimental bait tested, soak time, number of experimental traps and total traps, location and depth of the fleets.

Fleet	Experimental bait	Soak time (days)	Experimental traps	Total traps	Latitude	Longitude	Depth
45	Seal fat	6.5	19	173	75°55'56"N	037°03'15"E	218
8	Seal fat/skin	11.33	20	196	75°46'12"N	037°49'12"E	210
10	Seal fat	11.29	17	185	75°46'12"N	037°52'6"E	212
38	Whale meat/fat	11.4	9	197	76°12'6"N	037°59'24"E	262
12	Seal meat	11.5	10	190	75°19'18"N	037°59'48"E	220
35	Whale fat/skin	13.7	19	191	76°27'18"N	036°56'00"E	262
42	Seal fat	11.3	14	194	76°25'00"N	036°12'12"E	288
24	Whale meat/fat	11.0	10	190	76°27'06"N	036°19'00"E	220
45.1	Seal fat/skin	9.9	19	169	75°47'12"N	037°37'24"E	217
19	Seal fat	5.3	20	180	75°48'42"N	037°58'54"E	220
12.1	Whale meat/fat	4.9	16	189	76°19'18"N	037°59'48"E	262
18	Seal meat	4.7	9	195	76°22'24"N	037°02'00"E	270
1	Whale fat/skin	4.6	30	174	76°25'24"N	035°50'24"E	282
15	Seal fat/skin	4.7	30	189	76°32'24"N	036°28'30"E	230
2	Whale fat/skin	4.5	13	126	76°25'48"N	036°24'6"E	266

Table 3.2. Minimum, maximum and mean CPUE, percent change, and standard deviation for the different experimental bait treatments.

Bait	Min CPUE	Max CPUE	Mean CPUE [Std.Dev]	Precent change
Squid	0.0	32.0	9.5 [7.8]	0%
SF	0.0	38.0	13.8 [12.9]	45%
SFS	0.0	23.0	7.1 [7.1]	-25%
SM	0.0	7.0	2.1 [2.0]	-78%
WFS	0.0	17.0	1.8 [3.8]	-81%
WMF	0.0	16.0	2.8 [4.2]	-71%

Table 3.3. Test of model effects from generalized linear model.

	Type III		
Source	Wald Chi-Square	df	p-value
(Intercept)	0.840	1	0.359
Bait	184.620	5	0.000
Soak time	147.844	1	0.000

Dependent Variable: CPUE

Model: (Intercept), Bait, Soak time

Table 3.4. Parameter estimates from generalized linear model.

Parameter	B	Std. Error	95% Wald Confidence Interval Lower	95% Wald Confidence Interval Upper	Hypothesis Test Wald Chi-Square	Hypothesis Test df	Hypothesis Test p-value	Exp(B) or IRR	95% Wald Confidence Interval for Exp(B) Lower	95% Wald Confidence Interval for Exp(B) Upper
(Intercept)	-0.675	0.2418	-1.149	-0.201	7.802	1	0.005	0.509	0.317	0.818
[Bait=SF]	1.547	0.2626	1.032	2.061	34.697	1	0.000	4.696	2.807	7.856
[Bait=SFS]	1.146	0.2302	0.695	1.597	24.786	1	0.000	3.146	2.003	4.939
[Bait=SM]	-0.228	0.3517	-.917	0.461	0.420	1	0.517	0.796	0.400	1.586
[Bait=Squid]	1.395	0.2071	0.990	1.801	45.401	1	0.000	4.037	2.690	6.058
[Bait=WFS]	-.643	0.2626	-1.158	-0.128	5.997	1	0.014	0.526	0.314	0.880
[Bait=WMF]	0[a]	.	.	.	.	.	.	1	.	.
Soak time	0.175	0.0144	0.147	0.203	147.844	1	0.000	1.191	1.158	1.225
(Scale)	1[b]									
(Negative binomial)	1									

Dependent Variable: CPUE
Model: (Intercept), Bait, Soak time
a. Set to zero because this parameter is redundant.
b. Fixed at the displayed value.

Table 3.5. Pairwise comparison of the experimental treatments.

Bait		Mean Difference	Std. Error	df	Bonferroni Sig.	95% Wald Confidence Interval for Difference Lower	95% Wald Confidence Interval for Difference Upper
Squid	SF	-1.4188	1.80900	1	1.000	-6.7286	3.8910
	SFS	1.9179	.90558	1	.513	-.7402	4.5759
	SM	6.9751	.68547	1	.000	4.9631	8.9871
	WFS	7.5574	.51176	1	.000	6.0553	9.0595
	WMF	6.5365	.63855	1	.000	4.6622	8.4107

Table 3.6. Mean carapace width (mm), sample size, percentage of crabs under 95 mm CW, number of males, and number of soft shell crabs.

Bait	Mean CW	n	CW < 95 mm	Males	Soft shell
Squid	113	2891	10%	0	0
SF	113	53	8%	0	0
SFS	113	106	2%	0	0
SM	109	17	18%	0	0
WFS	110	30	27%	0	0
WMF	110	31	16%	0	0

Table 3.7. Bait price and total fishing trip bait cost in NOK and CAD (conversion rate July 31, 2017).

Bait	Price NOK/kg (CAD/kg)	Total cost per fishing trip NOK (CAD) 23,000 kg	Costs reduction % or increase %
Squid	23.25 (3.68)	534,750 (84,616)	-
SF	10 (1.58)	230,000 (36,394)	57%
SFS	15 – 25 (2.37 – 3.95)	345,000 - 575,000 (54,591– 90,985)	35% - 8%
SMB	70 – 150 (11.07 – 23.73)	1,610,000 - 3,450,000 (254,758 – 545,909)	201% - 545%
WFS	no commercial value		?
WMF	no commercial value		?

3.8. Figures

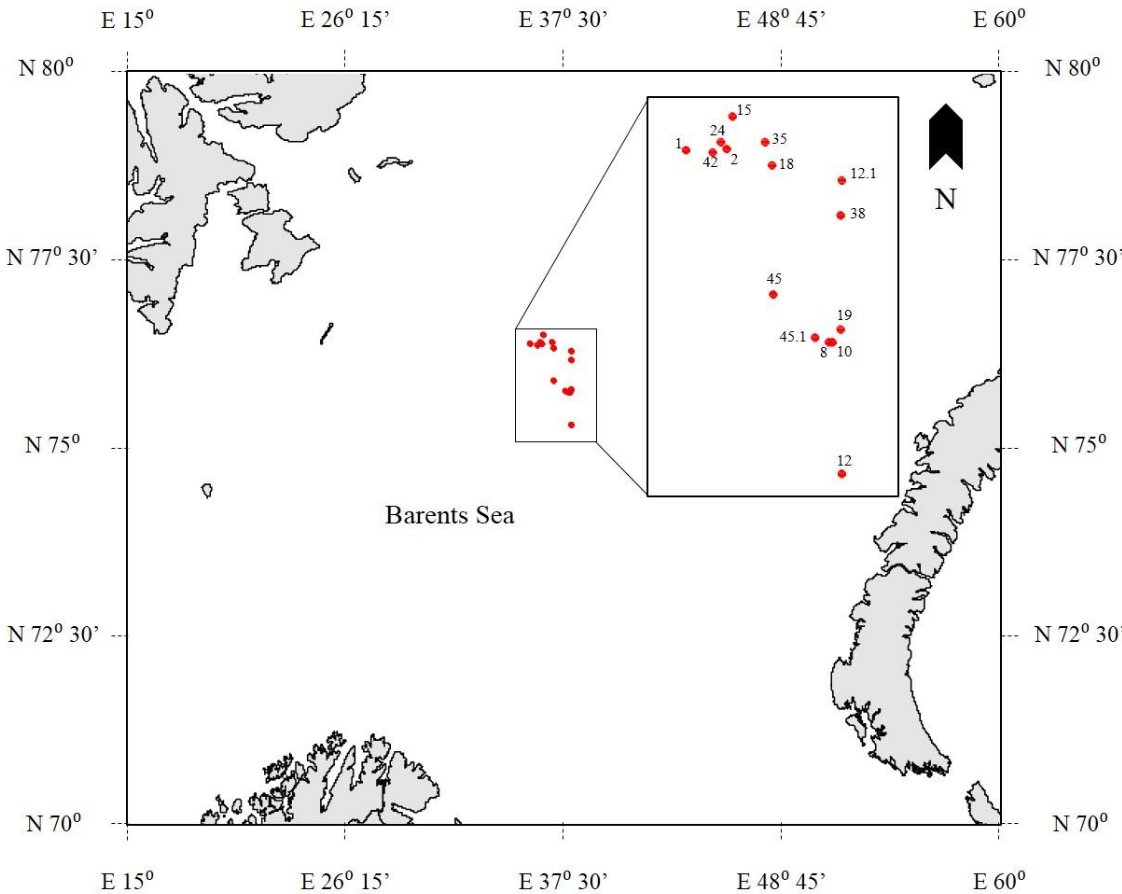

Figure 3.1. Map of the study area located in the Sentralbanken area of the Barents Sea with zoom in section. Numbers denote different fleets deployed.

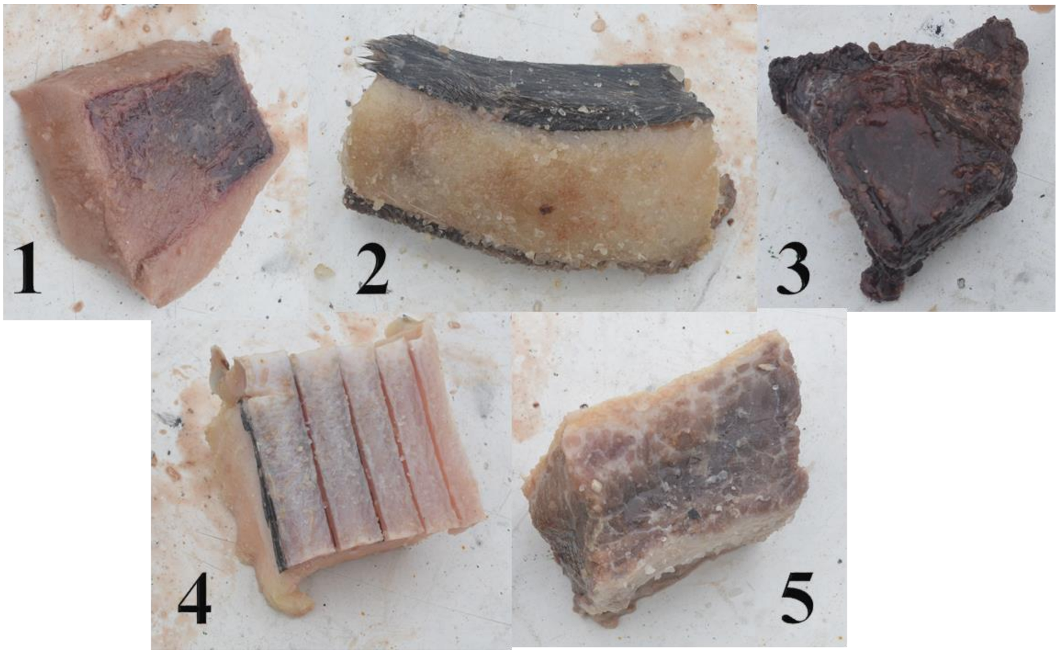

Figure 3.2. Alternative baits used in the experiment. 1: seal fat, 2: seal fat with skin, 3: seal meat, 4: whale fat, 5: whale meat with fat.

Figure 3.3. Small Japanese-style conical trap used in the Barents Sea fishery.

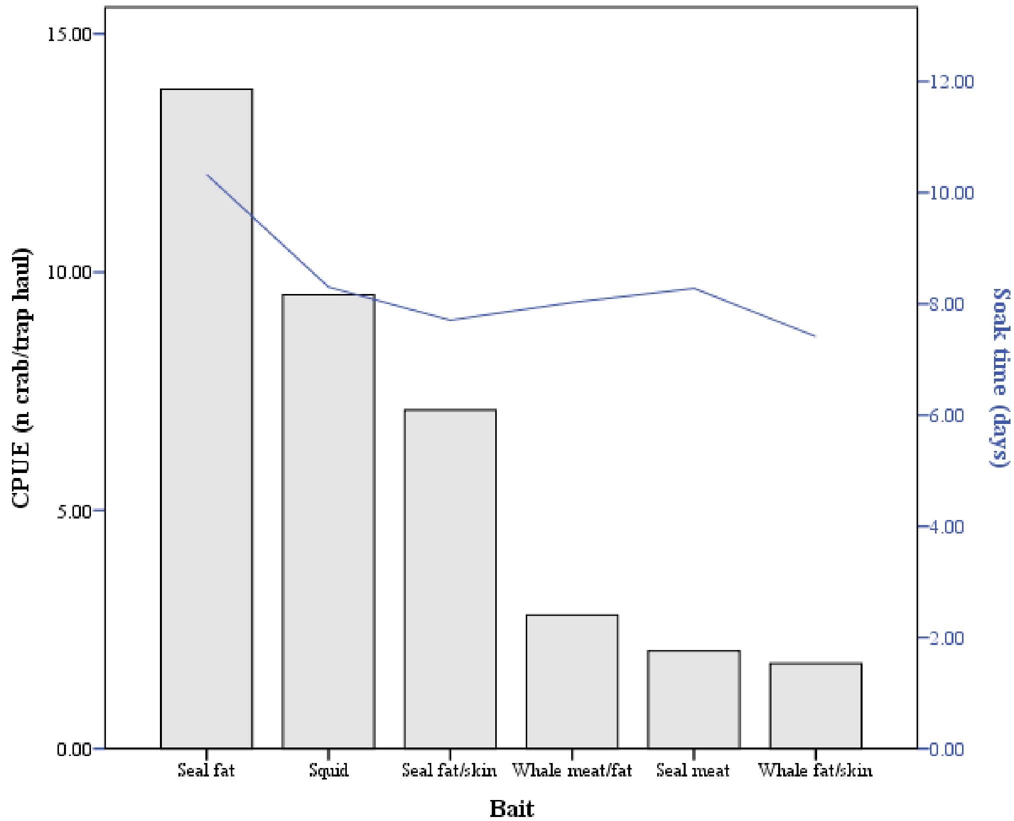

Figure 3.4. Mean count of crabs per trap haul and mean soak time per bait type. Blue line indicates mean soak time.

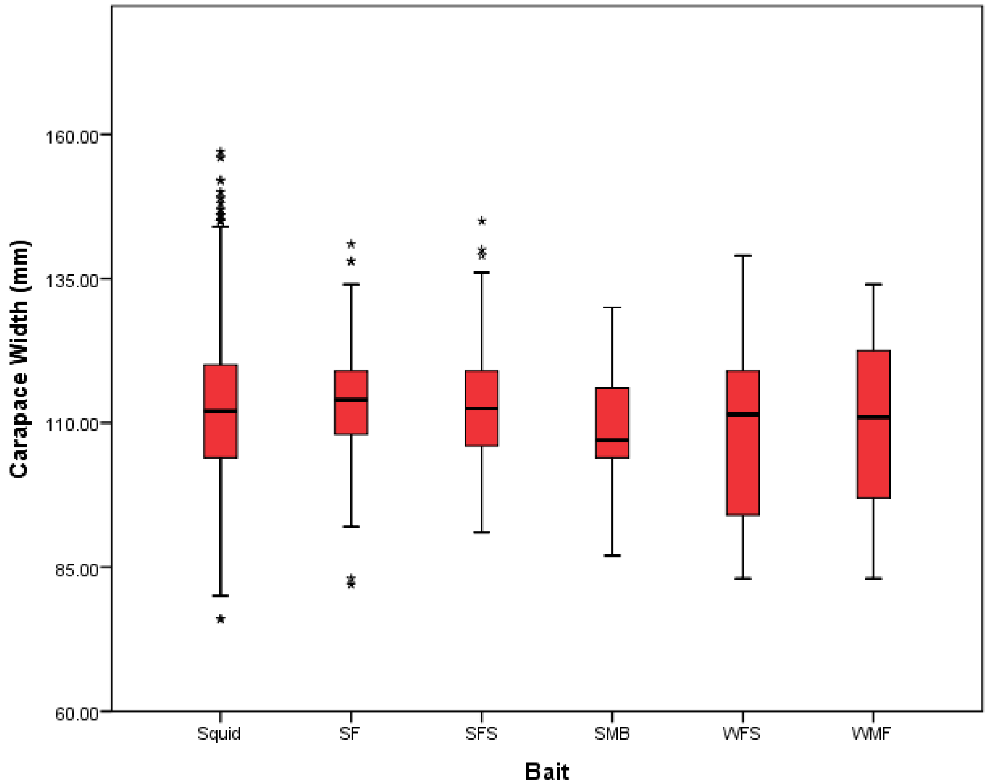

Figure 3.5. Boxplots of carapace width (mm) for each of the experimental treatments.

SUMMARY

4.1. Summary remarks

The research presented in this thesis is intended to contribute to the development of a more profitable, sustainable, and efficient snow crab fishery in the Barents Sea. Chapter 1 provides an introduction and overview of the species, fishery, and emerging challenges. Chapter 2 documents an experiment that evaluated the performance of plastic baited jars as a feasibility step toward the implementation of an automated baiting system. If developed, such a system will allow a more efficient trap baiting process, with reduced labour onboard, addressing some of the challenges related to environmental protection and occupational health and safety at work. The study indicated that traps with bait in jars performed significantly better, attracting more crabs inside the trap, compared to traps with baits in mesh bags. The likely explanation for this result is that bait placed inside the jars were more protected from scavenging amphipods, therefore experiencing less depletion and producing an odor plume for longer periods of time, while baits in mesh bags were rapidly depleted losing their attractant properties. It is recommended that additional experiments be undertaken to increase sample size, repeat at different times of year and/or locations where amphipod density varies, as well as mimic existing industry practice of using both bags and jars in each trap.

Chapter 3 documents an experiment that investigated the catching performance of alternative baits manufactured from whale and seal by-products produced in Norway. Results showed that certain bait types (harp seal fat and harp seal fat with skin) exhibited comparable catch rates per trap haul compared to traditional squid bait. This study documents the first known systematic investigation of the use of marine mammal offal as a bait type. Though these fisheries are sustainable and well managed in Norway, it would be advantageous if greater utilization of the entire animal could be accomplished so as to reduce apparent waste and increase social license. Using such a bait also has the advantage of reduced greenhouse gas emissions and carbon footprint associated with shipping and cold storage of squid from South America. It is recommended that further studies should be undertaken before implementing these alternative baits. Specific suggestions include increasing sample size, standardizing soak times and fishing areas, and evaluate bait availability, economics, and cutting/storage onboard. Taken together, these two experiments are intended to contribute in the development of a profitable, sustainable, and efficient snow crab fishery in the Barents Sea.

4.2. Limitations of Approach

Several limitations in experimental design were encountered in the studies. For this reason, the results should be considered preliminary in most cases and interpreted with caution.

The first experiment (Chapter 2) was performed on a research vessel in partnership with the University of the Arctic, Norway. Due to inclement weather, soak times for the two fleets were not standardized. As a consequence, Fleet No. 1 was soaked for 3 days and Fleet No. 2 was soaked for 4 days. In addition to differences in soak time, we also had limited numbers of traps (n=30) and only two weeks at sea in a research vessel that was performing concurrent experiments with trawl nets, therefore we were only able to set the fleet of 30 traps twice. This produced a smaller than desired sample size of the data. Furthermore, the lack of time and number of traps did not allow us to include a treatment that mimicked industry practice of including both bait shields in a trap (i.e., one jar and one mesh bag). If further studies are undertaken, it is recommended to include traps with a jar + mesh bag treatment, increase sample size, and standardize soak times. This will reduce variability, improve statistical inference, create better estimates, and create an understanding as to how traps with jars or mesh bags perform compared to traps with both bait shields together.

The second experiment (Chapter 3) was performed on a commercial fishing vessel during their regular fishing season. We were not able to standardize soak time due to skipper preferences and decisions. The number of experimental baits per fleet of traps was small in order to mitigate potential economic losses in the event the experimental baits did not catch snow crab. Under ideal circumstances a larger sample size of all treatments randomly distributed on each fleet should be included to obtain more robust data and thus improve statistical model. It is recommended that future investigations increase the number of experimental traps per fleet, standardize soak times, and limit the fishing area. Due to the rapid hauling speed and limited space on deck to store crabs, we were only able to randomly measure 2 to 3 crabs per trap haul. Ideally, all crabs from experimental traps should be measured in order to increase sample size of measured crabs and obtain more robust data regarding carapace width.

4.3. Conclusions

This thesis provides partial solutions to real challenges facing fishing vessels harvesting snow crab in Norway. Research presented in Chapter 2 and 3 investigated the feasibility of an automated baiting system with jars and the evaluation of alternative sustainable baits, respectively. Results indicate that jars perform significantly better than mesh bags, capturing considerably more crabs per trap haul, indicating that an automated baiting system with jars is a viable option. Results also indicate that baits produced from the fat of harp seals (i.e., harp seal fat and harp seal fat with skin) captured crabs at rates comparable to the traditional squid bait, demonstrating that this new bait may have potential application in the fishery. I recognize that the present studies have some limitations but results are promising, remarkable and contribute to development a profitable, sustainable, and efficient snow crab fishery in the Barents Sea.