REDUCING BOTTOM TRAWL SEABED IMPACTS AND BYCATCH IN THE EASTERN CANADA OFFSHORE NORTHERN SHRIMP (*Pandalus borealis*) FISHERY

by

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ABSTRACT

The offshore Northern shrimp (*Pandalus borealis*) fishery in Eastern Canada is currently harvested by factory freezer vessels using bottom trawls. This fishery is a major contributor to the regions' economy. However bottom trawling typically is associated with negative benthic impacts and bycatch. To address seabed impact, this thesis evaluated the at-sea performance of a traditional roller footgear using underwater cameras. Results showed that footgear sections were rotating at extremely low rates and offered essential information to further develop an innovative footgear with reduced seabed impact. Secondly, an innovative aligned-rolling footgear was designed and evaluated for use in the fishery. I compared traditional and experimental footgears using engineering models and simulated seabeds in a flume tank. Results revealed that the aligned-rolling footgear bottom trawl produced significantly lower warp loads and reduced seabed contact up to 71.5% depending upon seabed penetration depth modelled. Next, I addressed the issue of a recent increase of juvenile redfish (*Sebastes spp.*) bycatch in the shrimp fishery. This study investigated the effectiveness of 17 and 15 mm bar spacing Nordmøre grids in a twin-trawl configuration against the traditional 22 mm bar spacing grid. Results showed that smaller bar spacing grids resulted in no significant reduction in shrimp catch across all length classes. Conversely, catch of juvenile redfish was significantly reduced with the smaller bar spacing grids. However, the overlap in body/carapace width between redfish and Northern shrimp limits the overall sorting efficiency of the grids, leaving some juvenile redfish still vulnerable to capture. Finally, I investigated the behaviour of juvenile redfish in response to Nordmøre grids. Behaviours were analyzed for 22 mm and 19 mm bar spacing grids. Reducing bar spacing to 19 mm slightly reduced the number of redfish retained (1.83% reduction) and behaviours exhibited by redfish were similar for both grids. The most common behaviours that led to escapement were redfish that approached upwards, had no contact with the grid, and swam upwards to finally escape through the grid opening.

This thesis provides important advancement toward the development of bottom trawls with reduced environmental impacts and contributes to the sustainable development of the fishery.

GENERAL SUMMARY

The offshore Northern shrimp (*Pandalus borealis*) bottom trawl fishery in Eastern Canada is a major contributor to the regions' economy. However bottom trawling can produce impacts on the seabed and incidentally capture non-target species (i.e., bycatch). The traditional shrimp trawl footgear is in contact with the seabed, protects the trawl netting from damage, and is designed to roll over the seabed. Firstly, it was determined (Chapter 2) that the footgear rotated at extremely low rates, which can increase seabed impact compared to rotating footgears. Secondly, I developed and tested an aligned-rolling footgear (i.e., wheels aligned with the towing direction capable of rolling) in a flume tank using simulated seabeds and scaled engineering models. The new aligned-rolling footgear had significantly lower drag and seabed contact was greatly reduced (up to 71.5%). Thirdly, I addressed the issue of a recent bycatch increase of juvenile redfish (*Sebastes spp.*) in the same fishery. Currently, a bycatch reduction device (BRD) known as the Nordmøre grid is mandatory for the Northern shrimp fishery. This grid has vertical bars with 22 mm spacings between them to sort the catch by size; larger bycatch species are excluded through the outlet located on top of the gird and shrimps pass between the bars and are retained in the trawl codend. However, juvenile redfish are as small as shrimp and can pass through the grid bar spacings. I investigated the effectiveness of 17 and 15 mm bar spacing grids at reducing juvenile redfish bycatch. Findings suggest that the smaller bar spacing grids significantly reduced redfish bycatch with no reductions on shrimp catches. However, shrimp and redfish are similar in size leaving some redfish still vulnerable to capture, even when using reduced bar spacing grids. In my fourth and final study, I investigated the behaviour of juvenile redfish in response to 22 and 19 mm bar spacing Nordmøre grids using underwater cameras. The

19 mm grid slightly reduced the number of redfish caught (1.83% reduction). Redfish that were more likely to escape approached upwards, had no contact with the grid, and continued to swim upwards towards the bycatch outlet.

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The following section presents the co-authorship statement using the CRediT Authorship Contribution Statement format.

Chapter 1 and 6

Tomas Araya-Schmidt: Writing - original draft, Writing - review & editing, Visualization. **Paul Winger:** Writing – review & editing, Supervision. **Shannon Bayse:** Writing - review & editing, Supervision. **Truong Nguyen**: Writing - review & editing, Supervision.

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AIC	Akaike information criterion
BW	Body width
BRD	Bycatch reduction device
CI	Confidence interval
CL	Carapace length
CW	Carapace width
df	degrees of freedom
GLM	Generalized linear model
GLMM	Generalized linear mixed model
HDPE	High-density polyethylene
NGO	Non-governmental organization
SD	Standard deviation
SEM	Standard error of the mean
SFA	Shrimp fishing area
TL	Total length
TRC	Time to complete a rotation

CHAPTER 1. Introduction and Overview

1.1. Background

Bottom trawls are widely used to target fish and shellfish species that live on or near the ocean seabed (Gabriel et al., 2005; He, 2007). This fishing method has been broadly used since the 1950s and continues today as an efficient and economically viable fishing practice (Valdemarsen, 2001; Watson et al., 2006; Valdemarsen et al., 2007). Bottom trawling greatly contributes to global food security, accounting for almost one-quarter of the total wild marine landings annually (Amoroso et al., 2018). There are environmental impacts associated with bottom trawling, demonstrated and evidenced by a growing body of literature (see Duplisea et al., 2002; Olsgard et al., 2008; Althaus et al., 2009; Hiddink et al., 2019), including physical and biological impacts on benthic habitats (Hiddink et al., 2017; Sciberras et al., 2018), as well as incidental catch, known as bycatch, of environmentally or commercially important species (Kelleher, 2005; Bayse and He, 2017). Bottom trawls targeting Northern shrimp are in direct contact with the seabed and employ small mesh codends to capture and retain small shrimp. As a result, these fisheries by their design are known for both seabed impacts and incidental bycatch of non-targeted species. There have been many efforts to reduce seabed impacts (Ball et al., 2003; Murphy, 2014; He and Balzano, 2009; Munden, 2013; Brewer et al., 1996, Sheppard et al., 2004; Nguyen et al., 2015a) and to increase exclusion of bycatch species by modifying bottom trawls (Broadhurst, 2000; Eayrs, 2007). However, the issues persist in many bottom trawl fisheries worldwide.

The following introductory chapter describes shrimp bottom trawls and their main components, the environmental impacts produced by bottom trawls, with special emphasis on seabed impact and bycatch, as well as recent research on bottom trawl development in relation to the reduction of these environmental impacts. It will describe the Eastern Canada offshore Northern shrimp (*Pandalus borealis*) fishery, the process behind fishing gear development, and provide an outline of the research presented in this thesis.

1.1.1. What is a bottom trawl?

Generally speaking, bottom trawls are cone-shaped nets that can be made from two, four or more panels (Figure *1.1*). The catch is collected in the bag or codend, located at the end of the cone-shaped body of the trawl. They are towed by one or two fishing vessels and as the name indicates they are towed across the ocean bottom. However, there are also midwater, pelagic, and semi-pelagic trawls (FAO, 2022). The vertical opening of the trawl is achieved with floats or other hydrodynamic devices (e.g., kites) attached to the headline, and weights attached to the footrope or fishing line (i.e., footgear). The horizontal opening can be accomplished by using a beam, trawl doors, or by using two vessels to tow the trawl at a certain distance from each other. In the Eastern Canada offshore Northern shrimp (*Pandalus borealis*) fishery, vessels tow one (single-trawling) or two (twin-trawling) bottom trawls using trawl doors and a center clump for twin-trawling (Figure *1.1* and Figure *1.2*, respectively).

1.1.2. Bottom trawl components

From the fishing vessel winches, there are warps connected to each trawl door for single trawling (Figure *1.1*) or three warps in the case of twin trawling, of which two are connected to the trawl doors and the third one connected to the central clump (Figure *1.2*). The central weight can be as simple as a clump of chain (Montgomerie, 2015). However, a roller clump is more commonly used in the Eastern Canada offshore Northern shrimp fishery (Figure *1.3*), which are designed to roll over the seabed. The length of the warp deployed relative to the bottom depth of the water being fished (i.e., warp-to-depth or scope ratio) influences bottom contact, stability and spread of the trawl doors, bottom contact of the lower bridles, and hence overall trawl performance and geometry. Generally, small variations in scope ratio will have little effect on trawl performance and geometry. However, differences in warp lengths (i.e., warp offset) between port and starboard sides can change the symmetry of the trawl and bottom contact stability of the footgear.

Trawl doors are made of steel and are intentionally heavy to keep the trawl close to or on the seabed. They are towed at an angle of attack to the towing direction (i.e., trawl path), generating hydrodynamic and shearing forces for spreading the trawl doors and opening the net horizontally (Gabriel et al., 2005; Montgomerie, 2015). Trawl doors produce sand clouds as they are towed along the ocean floor, enhancing the herding of fish toward the path of the net (Winger et al., 2010).

Following the trawl doors or clump, sweeps and bridles are used to increase the swept area and herd targeted species into the net path (Winger et al., 2004). However, shrimp/prawn trawls typically have shorter sweeps and bridles as these species tend to be herderded poorly due to their limited swimming capacity (He, 2007). Bridles are connected to the lower and upper wing ends of the net; the upper bridle is connected to the headline, while the lower bridle is connected to the fishing line and footgear. Wings are designed to guide the target species into the mouth of the trawl. The rope on the upper edge of the net is known as the headline, while the rope on the lower edge is known as the footrope or fishing line. To spread the net vertically, floats are attached to the headline and a weighted groundgear or footgear is attached to the fishing line using toggle/bobbin chains (Montgomerie, 2015). The footgear helps to maintain the trawl in contact with the seabed and protects the trawl netting from damage. There are several types of footgear depending on the seabed types and target species (Gilkinson, 1999; Løkkeborg, 2005; He, 2007). They can be as simple as a chain wrapped around the fishing line and as complex as roller footgear (Figure 1.4), which is a footgear commonly used in the Eastern Canada offshore Northern shrimp fishery (Araya-Schmidt et al., 2021b) (Figure *1.5*).

The trawl net itself is constructed of multiple tapered netting panels, which are selvedged together to create a cone-shaped bag. Common parts of a trawl net include, wings, square, belly, codend extension, codend and chafer (i.e., codend cover). The Eastern Canada offshore Northern shrimp fishery commonly uses 4-panel bottom trawls (i.e. top, bottom and side panels) to increase vertical opening and two codends to reduce shrimp damage when hauling the trawl. Codends can contact the seabed when large catches occur (West, 1987; He, 2007), consequently, to protect the codend from damage and wear, they can be covered with larger mesh size netting (i.e., larger than the codend mesh size) and chafing gear, made of rope filaments or other materials, are added on the codend bottom panel (He, 2007).

1.2. Bottom trawl environmental impacts reduction

1.2.1. Seabed impacts

Bottom trawls move, herd, guide, and finally capture demersal species by using heavy components (e.g., trawl doors, rockhopper footgear) that are in contact with the seabed (Winger et al., 2010). Bottom trawls are customized according to the target species, depth, and seabed type, therefore, producing different levels of seabed impact depending on these factors (Sciberras et al., 2018; Depestele et al., 2019). Due to advancements in remote sensing and sampling technologies over recent decades, the scale of anthropogenic impacts of bottom trawling on the seabed is better understood (Oberle et al, 2018). Multiple studies have shown that bottom trawling can impact benthic habitats and species, which can be classified into several categories, including, 1) direct effects, 2) short term impacts and 3) long term impacts and chronic trawling:

1) Direct effects include (see Mayer et al., 1991; Collie et al., 2005; O'Neill and Ivanović 2016; Sciberras et al., 2016):
    a. Mortality of benthic organisms.
    b. Alteration to seabed composition and bathymetry.
    c. Reduction of seabed topographic complexity and
    d. Changes to sediment biogeochemistry.
2) Short term effects (see Kaiser and Spencer, 1994; Collie et al., 2017):
    a. The attraction of scavengers due to direct mortality and bycatch discards.
3) Long term impacts and chronic trawling (see Kaiser et al., 2000; Duplisea et al., 2001; Jennings et al., 2001; Hiddink et al., 2006; Queirós et al., 2006; Tillin et al., 2006; Johnson et al., 2015; Van Denderen et al., 2015):

a. Benthic biomass reduction.
b. Diversity reduction.
c. Reduction in the number of individuals.
d. Productivity decrease.
e. Changes in trophic structure and function of the benthic community.
f. Body size changes.
g. Age structure changes.
h. Change to communities dominated by organisms with shorter life histories.

All the previously mentioned impacts on benthic species and habitats are concerning (Kaiser et al., 2016), and have led to the development of bottom trawls that reduce environmental impacts. Specifically, trawls that minimize bycatch of benthic species and seabed impacts by reducing contact area, penetration depth, and weight of bottom trawl components in contact with the seabed (He, 2007; He and Winger, 2010). Some of the technologies developed include, rolling footgears (Ball et al., 2003; He and Balzano, 2010; Murphy, 2014, Araya-Schmidt et al., 2021a), aligned footgears (Winger et al., 2018; Munden, 2013) or bottom trawl components (i.e., footgears, sweeps, bridles and doors) that have reduced penetration depth, weight or area of contact with the seabed (Brewer et al., 1996; Sheppard et al., 2004; Sterling 2008; Broadhurst et al., 2015; Nguyen et al., 2015a; Sistiaga et al., 2015; Brinkhof et al., 2017; McHugh et al., 2017; Larsen et al., 2018a; Lomeli et al., 2019). Furthermore, there has been some development in the use of pelagic and semi-pelagic trawls to target demersal species (DeLouche and Legge, 2004; He et al., 2006; Sala et al., 2010; Rivierre et al., 2013; Bayse et al., 2021).

1.2.2. Bycatch and discards

Conventional shrimp trawls typically retain large quantities of non-targeted species, known as bycatch (Saila, 1983), due to their small mesh size (Broadhurst, 2000). Shrimp trawls employ small-mesh sizes in the codend or throughout the bottom trawl to retain the small-sized targeted shrimp species. As a result, larger-sized non-target species cannot exit the bottom trawl through the meshes and are commonly retained in the codend. Bycatch and subsequent discards are highly important issues in global fisheries. Estimations of worldwide, yearly discards in commercial fisheries range from 6.7 to 16.1 million tonnes (Pérez Roda et al., 2019) and bottom trawl fisheries, have the highest discards and account for nearly half (46%) of the total discards globally (Pérez Roda et al., 2019). There are many biological, ecological, economic, and socio-cultural impacts associated with this issue (De Groot, 1984; Jones, 1992; Dayton et al., 1995; Pérez Roda et al., 2019), specifically, bycatch, discard, and mortality of juveniles of important commercial and recreational species is of significant concern as it could reduce recruitment, biomass, and sustainability of those fisheries (Broadhurst, 2000).

Today shrimp trawls usually use some form of bycatch reduction device (BRD) that separates target from non-target species, so the latter ones can exit the bottom trawl. Behavioural BRDs are designed to separate shrimp from other non-target species by exploiting behavioural differences (Winger et al., 2010), while other BRDs separate shrimp and fish relying on the difference in the size between them (Broadhurst, 2000). Funnels, panels and windows are used in bottom trawls based on the principle that fish are more responsive to trawl components than shrimp, therefore fish behaviourally react to these devices and can exit the trawl (Watson and Taylor, 1986, 1996; Rulifson et al., 1992; Brewer et al., 1998; Robins et al., 1999; Crawford et al., 2011; Steele et al., 2001; Boopendranath et al., 2012; Brown et al., 2018). BRDs that separate species by size include oblique panels or grids that are usually installed in the funnel section before the codend (Kendall, 1990; Robins-Troeger, 1994; Andrew et al., 1993; Isaksen et al., 1992; Broadhurst and Kennelly, 1996). Even though fish may behaviourally respond to these BRDs and influence the outcome (i.e., excluded or retained), they are designed to mechanically sort animals by size, excluding individuals that do not fit through the panel or grid openings (Karlsen and Larsen, 1989; Broadhurst et al., 1996). There are also combinations of size and behavioural BRDs that are specifically useful when non-target species are of similar size as the targeted shrimp. Since, in this case, both shrimp and fish can pass through sorting panels or grids, a behavioural device can be used in combination with the size BRD to enhance escapement (Watson et al., 1986; Karlsen and Larsen, 1989; Kenney et al., 1990).

1.2.3. Summary

Even though seabed impacts, and bycatch can be considerable in bottom trawling and these challenges persist in many fisheries today, multiple developments, such as the gear modifications and innovations mentioned in the previous two sections (1.2.1 and 1.2.2), have led to incremental technological advancements in bottom trawl technology (Graham, 2006). Today, modern bottom trawls are designed with the highest engineering standards, materials, and quality workmanship. They hardly resemble the earlier designs and materials of the 1920s-60s. Nonetheless, they are not perfect and require continued improvement and refinement in each fishery where they are employed. This is especially important in an information age in which consumers demand sustainably caught seafood. This had led to the development of several third-party certifications which can affect market access, brand success, and social licence (Grieve et al., 2015; Kaiser et al., 2016). Consequently, bottom trawls designs are constantly evolving, improving, and innovating (see fishing gear development cycle, Winger et al., 2006).

1.3. Eastern Canada offshore Northern shrimp (*Pandalus borealis*) and striped shrimp (*Pandalus montagui*) fishery

1.3.1. Introduction

The fishery started in the early 1970s after exploratory fishing efforts confirmed the commercial abundance of Northern shrimp (*Pandalus borealis*) and striped shrimp (*Pandalus montagui*) in areas off of Baffin Island, down to the north and east coasts of Newfoundland and Flemish Cap (Figure *1.6*; DFO, 2018). This fishery largely evolved from a Scandinavian Northern shrimp fishery in the Northwest Atlantic (Foley et al., 2015). Initially, four companies began operating in 1977 to determine the commercial feasibility of the fishery. Landings significantly increased during the 1980s and 1990s, adding more fishing licenses to the fishery; in 1991 there were seventeen offshore licenses (vessels with length overall (LOA) greater than 100' or 30.48 m) and no more offshore licenses have been issued since this time (DFO, 2018). In 1997, fishing quotas were developed, access was given to the inshore fleet (vessels with LOA smaller than 65' or 19.81 m) and special allocations were granted to community groups and indigenous organizations (DFO, 2018). Landings of shrimp in Newfoundland and Labrador reached 35.5 thousand tonnes, with a total landed value of $143 million in 2020 (DFO, 2021), which represents an extremely important contribution to the region's economy.

Currently, the fishery takes place off the coast of eastern Canada from the Flemish Cap and the northern edge of the Grand Banks up to Baffin Bay (Figure *1.6*). Northern shrimp is the main species. However, striped shrimp can be found in lower abundances. Fishing depths usually range from 200 to 600 m. The fishing grounds are divided into Shrimp Fishing Areas 0, 1, 4 – 7 (SFAs). These areas are used for management purposes and to distribute the fishing effort. An Enterprise Allocation (EA) system is used to manage the fishery, where the Total Allowable Catch (TAC) is divided equally between the seventeen fishing licences, except for SFA 0 which is harvested on a competitive basis (DFO, 2018).

Vessels in this fishery are required to change fishing area by a minimum of 10 NM from the last tow if the bycatch of groundfish species exceeds 2.5% of the total catch weight, or 100 kg in total weight, according to the licence conditions (known commonly as the "move-away protocol"). This protocol has rarely been evoked during the past few decades. However, a recent increase in juvenile redfish (*Sebastes spp.*) abundance (DFO, 2020) has increased bycatch levels and the move-away protocol is now often triggered by onboard fisheries observers. This surge in redfish bycatch is of significant importance since it can affect the trophic structure of communities impacting other commercial fisheries (Dayton et al., 1995; Devine and Haedrich 2011). It is also concerning regarding the future of a redfish fishery; since these species are long-lived and have slow growth rates (Campana et al., 1990), its mortality could harm the stock's recruitment and biomass. Even further, redfish is considered threatened under the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) since 2010 (Government of Canada 2021). This bycatch issue is also of significant importance for the fishing companies. When the move-away protocol is triggered, fishing vessels are forced to leave the area, increasing time at sea and fuel consumption, which in turn increases operational costs and carbon dioxide emissions.

The offshore fleet is comprised of approximately 10 factory freezer trawlers > 30.48 m LOA and > 500 t in weight. The shrimps are size sorted, cooked, frozen and packaged at sea. The fleet operates from ports in Newfoundland and Nova Scotia, with fishing trips that range from 20 to 75 days, totaling 9 - 12 fishing trips per year (DFO, 2018).

1.3.2. Northern and striped shrimp

Northern shrimp is distributed in the Northwest Atlantic, from Baffin Bay south to the Gulf of Maine, while striped shrimp is distributed from Davis Strait south to the Bay of Fundy (DFO, 2017). Northern shrimp inhabits areas with soft and muddy seabed, between 150 and 600 m depth and in temperatures that range between 0 to 6 ˚C. Striped shrimp are typically found on harder seabeds, between 100 and 500 m deep, and in temperatures that range between -1 to 2 ˚C (DFO, 2017).

In both species, female shrimp carry the fertilized eggs for seven to eight months, hatching in spring. Hereafter, pelagic larvae spend three to four months in the water column, before they settle on the seabed. During the second or third year of life, shrimps reach male sexual maturity. Northern and striped shrimp are protandrous hermaphrodites; shrimp function as males for two to three years and then change to female for the remainder of their lives. They usually live between six to eight years and reach 15 to 16 cm in total length. At three years of age, with 17 mm carapace length (CL), they are considered harvestable, and they are mostly females at that age (DFO, 2017).

1.3.3. Fishing gear

Bottom trawls, either single or twin-trawling configurations, are used exclusively in this fishery. Most vessels are capable of both fishing techniques, switching between configurations depending on the production capacity of the vessel's onboard factory and environmental conditions (e.g., wind, sea state, substrate, and ice). Single trawling is generally preferred when environmental conditions are poor. If conditions are suitable and the factory can handle larger catches, then twin-trawling is preferred. A minimum mesh size of 40 mm is authorized throughout the bottom trawl to retain shrimp. However, there are cases where bottom trawls have larger size meshes on the anterior sections (up to ~ 200 mm mesh size). Bottom trawls in this fishery are usually made of four panels, use two bridles, and have between 60 - 70 m headlines and between 70 - 75 m fishing lines. Doors can reach 14 m^2 and the center clump, used for twin-trawling can weigh up to 10,000 kg on large vessels (~ 79 m LOA, ~ 16 m width, ~ 4,500 t gross tonnage).

Roller footgear

Roller footgears are prevalent in this fishery. They consist of several sections (bosom, quarter, and wing sections) of rubber discs, rubber spacers, lancasters, washers and weights that are threaded onto a steel chain. Sections are then connected using swivels, which permits some rotation of the sections (Araya-Schmidt et al., 2021b). Other footgear designs use bare chain and steel bobbins on the wing sections instead of rubber components. Bobbins and rubber discs are large and usually ~ 0.6 m in diameter, which provides protection of the fishing line and trawl netting in rough seabed conditions. Footgear weight in seawater is usually around ~ 2,000 kg, which ensures contact with the seabed. The footgear is attached to the fishing line with toggle chains. These chains have a minimum regulated length of 71.12 cm (DFO, 2018), which allows several non-target species to pass under the fishing line and escape under the bottom trawl. However, there are no other restrictions associated with the footgear and it has not changed drastically throughout the years when compared to other bottom trawls components, which have evolved considerably (i.e., doors, netting materials, Nordmøre grid, ropes, floats, among others). The footgear is one of the main bottom trawl components in direct contact with the seabed. It is designed in a way that follows the curvature of the fishing line, hence most of the rubber discs are not aligned with the towing direction (Araya-Schmidt et al., 2021b), increasing contact area and likely digging forces (Fridman, 1986), which translates into increased damage to benthic communities, as well as increased sediment remobilization (O'Neill and Summerbell, 2016; Hiddink et al., 2017; Depestele et al., 2019).

As mentioned before, several footgear technologies have been developed and evaluated with the goal of reducing seabed impacts. However, to my knowledge there has not been an adoption of these technologies in commercial fisheries and footgears have not changed much in recent decades.

Nordmøre grid

Concerns regarding bycatch levels led to the introduction of the Nordmøre grid (Isaksen et al., 1992) in 1993 and its use was made mandatory in 1997 (DFO, 2018). Nordmøre grid greatly reduced bycatch in Canada's east coast shrimp fisheries, reducing finfish bycatch from 15% to 2% (> 85% reduction by weight) of the total landings of shrimp (ICES, 1998). The Nordmøre grid is a BRD that separates animals by size. However, some animals behaviourally react when approaching the Nordmøre gird. In these cases, the grid functions as both a size and behavioural BRD (Figure 1.7). The Nordmøre grid was first developed in 1990 in Norway and consisted of a rectangular aluminum grid with longitudinal bars, angled at 48˚. It is designed to be installed in the extension, before the codend (Isaksen et al., 1992). In front of the grid, a guiding funnel or panel is used to guide the animals to the bottom of the grid, once they reach the grid, smaller animals such as shrimp will pass through the bar spacings and transit to the codend, while larger sized animals cannot pass through the bars and will exit the trawl through the outlet on the top of the grid (Figure *1.7*). Isaksen et al. (1992) recommended a bar spacing of 19 mm, which only reduced shrimp catches by 5% and allowed various fish species to exit the bottom trawl by reacting to the grid and swimming out of the trawl, or by sliding along the bars towards the outlet, including, cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), redfish (*Sebastes* sp.), long rough dab (*Hippoglossoides platessoides*), polar cod (*Boreogadus saida*) and Greenland halibut (*Reinhardtius hippoglossoides*) (Isaksen et al., 1992).

In the Eastern Canada offshore Northern shrimp fishery, 22 and 28 mm maximum bar spacing Nordmøre grids are permitted, depending on the fishing area (DFO, 2018). However, most, if not all of the fishing fleet uses 22 mm bar spacing. The grids are typically constructed of high-density polyethylene (HDPE) and can reach sizes up to 5m^2 (Araya-Schmidt et al., 2022a). When used properly, they not only sort groundfish and skates (Rajidae), but also Greenland sharks (*Somniosus microcephalus*), marine mammals, and even turtles on some occasions (DFO, 2018). As a result of this innovation, bycatch in this shrimp fishery has consistently remained low over the last several decades, giving rise to a well-regarded and sustainable fishery, certified by the Marine Stewardship Council in 2011 (Marine Stewardship Council, 2022).

Several research initiatives have focused on the design and performance of Nordmøre grids in an effort to overcome ecological and operational challenges, including bar spacing experiments (Araya-Schmidt et al., 2022a, Hickey et al., 1993; CAFID 1997; Orr 2018; He and Balzano 2012; Silva et al., 2012), new grid designs (Grimaldo and Larsen, 2005; Grimaldo, 2006; He and Balzano 2007, 2011, 2013; Veiga-Malta et al., 2020) and sorting grid configurations (Riedel and DeAlteris, 1995; Larsen et al., 2018b). However, the bycatch of juvenile fish remains an important issue that many shrimp fisheries are facing. The similarity in size between juvenile fish and targeted shrimp, as well as the restricted swimming capability of juvenile fish limits the efficiency of size or behavioural BRDs to work efficiently. Therefore, more research needs to be conducted to find solutions to this significant problem.

1.4. Designing and testing fishing gear

The development of modern fishing gears to meet high sustainability standards, including, bottom trawls with reduced seabed impact, minimal bycatch, and acceptable fuel consumption, among others, requires advanced design and testing techniques (Winger et al., 2006). On many occasions, designing or modifying a bottom trawl involves numerical simulation, physical modelling in a flume tank, and finally full-scale at-sea comparative fishing experiments, following the fishing gear development cycle (Figure *1.8*). The use of numerical simulation and flume tank testing in the early stages of development can assist trawl designers in the refinement process, before at-sea trials, at considerably lower costs (Winger et al., 2006). Once at sea, full-scale bottom trawl experiments usually aim to measure trawl performance, geometry, and selectivity of the new technology or invention (Wileman et al., 1996). In addition to documenting catch composition on the deck of the vessel, researchers can use direct observation techniques to assess fishing gear performance, such as underwater video, trawl mounted sensors and acoustics that can be used alone or in combination with the size selectivity experiment (see reviews by Urquhart and Stewart, 1993; Graham et al., 2004). For example, trawl-mounted sensors can be used to assess bottom trawl geometry in a catch comparison study experiment or underwater video can be used to directly observe the performance of BRDs. Each of these are discussed in greater detail in the following sections.

1.4.1. Numerical simulation

During the last two decades, numerical simulation of trawls using desktop computers has become a powerful tool to assess the dynamics of fishing gear systems before proceeding to engineering models in flume tanks or full-scale prototypes at sea (Nguyen and Winger, 2016). Using mathematics with known hydrodynamic principles, trawls can be modelled to predict their performance under various forces commonly found in the fishing environment, including, buoyancy, sinking, drag and shearing forces. In recent years, with the advancement in desktop computers and mathematical theory, numerical modelling of fishing gear has improved considerably (Lee et al., 2005). There are different software options for bottom trawl numerical simulation, even though they all have limitations, they are extremely useful to explore the feasibility of fishing gear concepts in their early developmental stages, investigate the effect of design modifications, towing speed or rigging in the bottom trawl, and estimate forces acting on the bottom trawl and seabed (Nguyen and Winger, 2016).

Results from numerical simulation need to be interpreted with caution as software predictions depend on multiple variables. The use of these software is recommended for preliminary designs of fishing gears for validating purposes and the following stages of flume tank testing and full-scale sea trials are strongly recommended (Winger et al., 2006; Nguyen and Winger, 2016). Even though this thesis does not include numerical simulation results, it represented an important component in the validation of the bottom trawl before model scaling and flume tank testing performed in chapter 3.

1.4.2. Model scaling and flume tank testing

Since flume tanks are limited in size (i.e., they are not infinitely large), the fishing gear under investigation needs to be scaled down. However, there are times where full-scale bottom trawl sections or components can fit in flume tanks for testing, such as BRDs (for example a Nordmøre grid system) or codends, for instance. Working engineering models of bottom trawls are constructed using Froude scaling laws (Tauti, 1934; Fridman, 1973; Hu et al., 2001). To better approximate the model bottom trawl characteristics to the full-scale fishing gear, force, geometric, kinematic, and dynamic modelling laws are used (Fiorentini et al., 2004; Queirolo et al., 2009; Sala et al., 2009; Nguyen et al., 2015b; Thierry et al., 2020). If scaled and constructed correctly, a model trawl will behave realistically in response to changes in towing speed and rigging configurations, giving accurate predictions of full-scale performance (Winger et al., 2006).

The scaling of bottom trawls is a meticulous process, starting with gathering detailed information on every component of the trawl, including dimensions, material, buoyancy, weight in seawater, etc. This information is used to source materials, and where necessary, custom-made parts are constructed by hand or 3D printer. Fishing gear technologists use science, engineering, and their artistic capabilities to successfully achieve the results (Winger et al., 2006).

Once built, working engineering models can be tested in a flume tank. Worldwide, there have been sixteen flume tanks built and constructed for the purpose of testing of model trawls, with fourteen currently in operation (Winger, 2021). Bottom trawl performance information is obtained by using a variety of optical and data acquisition systems (Winger et al., 2006); load cells can record tensions, current meters assess flow at different positions in the trawl, laser pointer or images are used to calculate distances, angles and trawl geometry, and video recordings are usually used as evidence to qualitatively validate the performance of the fishing gear (e.g., Araya-Schmidt et al., 2021b). These measurements are usually obtained for a variety of towing speeds, riggings configurations, or even simulated seabed types, which is the case for chapter 3 of this thesis. Full-scale predictions are then calculated from the model results. Flume tank testing can last for several days or weeks until results are satisfactory to continue with full-scale sea trials, otherwise, further modifications or a new design could be needed, which is why the fishing gear development cycle is started all over again on many occasions (Figure *1.8*) (Winger et al., 2006).

1.4.3. Comparative fishing experiments at-sea

Full-scale experiments at sea are commonly oriented toward measuring the selectivity of fishing gears and trawl geometry performance. The selection of marine species by a trawl is defined as the process which causes the catch to be different in composition to that of the population of marine species present in the towed area (Wileman et al., 1996). Scientists are interested in the relative probability that different species and sizes of animals would have of being retained by the trawl (Wileman et al., 1996). There are multiple methods to measure selectivity of trawls, however for selective devices (i.e., BRDs), a twin trawl or trouser trawl, alternate or parallel haul methods are used to measure the overall selectivity of the device and codend together (for a detailed explanation of the methods see Wileman et al., 1996). The twin-trawling method, which is used in Chapter 4, is recommended for whole trawl selectivity, and catch comparison as it best simulates the commercial fishing conditions by reducing effects that may be caused using covers (Wileman et al., 1996). The benefit of twin trawling is that many of the factors affecting size selection, such as seabed, fish population, towing speed, trawl geometry, water temperature, and many others are thought to be similar between the trawls as they are towed side-by-side. Therefore, under ideal conditions, observed differences in size selection can be directly attributed to the differences between the trawls being tested, in the case of Chapter 4, or to other trawl modifications under investigation.

With the collected catch data, including total catch weight, animal lengths (i.e., size), an observed or estimated number of individuals per species per trawl, fisheries scientists can use powerful statistical approaches to model the proportion of animals retained at each size class by the gears under study (Brooks et al., In Press; Wileman et al., 1996).

1.4.4. Underwater video observations

In recent years the availability of low-cost, high-quality, and small-size underwater cameras has increased drastically (Madsen et al., 2021). Not surprisingly, fishing gear technologists are using underwater video as a tool to qualitatively assess the behaviour of fish to understand the selectivity process (e.g., Queirolo et al., 2010; Grimaldo et al., 2018; Larsen et al., 2018c). Data can be extracted from the video using various software to quantitatively assess the behaviour of different species under study, the performance of fishing gear or assess selectivity of a device (e.g., Bayse et al., 2014, 2016; Underwood et al., 2015; Queirolo et al., 2019; Santos et al., 2020; Ahumada et al., 2021; Chladek et al., 2021ab).

Usually, individual fish are tracked from the first detection to the final stage of the selection process (i.e., excluded or retained). Studies have traditionally used regression models (Underwood et al., 2015; Bayse et al., 2016), but more recently behavioural trees have been implemented (Santos et al., 2020; Chladek et al., 2021ab). Regression models analyze the behaviours outcome according to the relationship between several explanatory variables, while in the behavioural trees if an animal is retained or excluded by the gear will be related to the sequences of behaviours throughout the selection process, accounting for the stage-wise nature of the behavioural data (Santos et al., 2020).

1.5. Chapter outlines and research objectives

This thesis is structured in 6 Chapters. Chapter 1 provides an introduction, Chapters 2, 3, 4 and 5 are the research chapters, which include data collected during sea trials, and Chapter 6 provides the final conclusions.

In Chapter 2, I investigated the performance of traditional roller footgear used in the offshore Northern shrimp bottom trawl fishery in Eastern Canada. As a first step toward designing a footgear with reduced seabed impact, this research focused on using direct underwater observation to assess the performance of the current footgear used by the fleet. Roller footgear is designed to roll. However, the orientation of most of the rubber discs does not align with the towing direction, reducing rotation, increasing contact area and likely digging forces

(Fridman, 1986), which in turn can increase seabed impact (O'Neill and Summerbell, 2016; Hiddink et al., 2017; Depestele et al., 2019). I investigated these hypotheses by quantitatively assessing footgear performance using underwater video and recording footgear rotation on different seabed types. I discussed the roller footgear performance concerning seabed impact and potential footgears that could ease some of the benthic impacts.

In Chapter 3, I examined the performance of a novel aligned-rolling footgear using working engineering models in a flume tank. I evaluated the performance of this innovative footgear by comparing it against the traditional roller footgear using three different simulated seabed roughness (smooth, semi-rough and rough) and measuring warp tensions. I estimated the predicted contact areas of the footgears at different penetration depths and qualitatively assessed the performance of the new footgear when in contact with rocks for prototype validation purposes. Finally, I discussed the benefits of the new aligned-rolling footgear in relation to seabed impact and fuel consumption.

In Chapter 4, I conducted a comparative fishing experiment using Nordmøre grids with reduced bar spacing as a means to reduce the bycatch of juvenile redfish (*Sebastes spp.*) in the same fishery described above. A recent increase in juvenile redfish abundance (DFO, 2020) has increased bycatch levels considerably. I compared the size selectivity of shrimp and redfish of a traditional 22 mm bar spacing Nordmøre against a 17 mm and a 15 mm bar spacing Nordmøre grids using a twin-trawling configuration aboard a commercial factory freezer vessel. I also performed morphometric analysis of shrimp and redfish to understand which size animals of these species fit through the different grids' bar spacings. I studied the relationship between redfish size and fishing depth. I collected underwater videos of the grid under operation to qualitatively assess their performance and gain insights into the size selectivity results. I finally discussed the benefits of using smaller bar spacing grids and provide directions for additional research to further reduce juvenile redfish bycatch in the fishery.

In Chapter 5, I investigated the behaviour of juvenile redfish in response to 22 mm and 19 mm Nordmøre grid systems using underwater video collected during commercial fishing operations. I recorded the behaviours exhibited by redfish at different stages in the grid systems to better understand which behaviours lead to retention or escape and gain insights into how the bycatch of juvenile redfish can be reduced. I used linear models and behavioural trees to analyze the data, as well as compared both methods. I discussed the feasibility of reducing redfish bycatch with BRDs, as well as the pros and cons of linear models and behavioural trees for analyzing behavioural data.

In Chapter 6, I summarized results and provided conclusions for Chapters 2, 3, 4 and 5. I discussed the ecological impact of bottom trawling and the use of fishing gear technology as a tool to reduce seabed impact, bycatch, and fuel consumption in the offshore Northern shrimp fishery of Eastern Canada. I described the limitations of my approaches and recommend directions for future research.

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1.7. Tables and figures

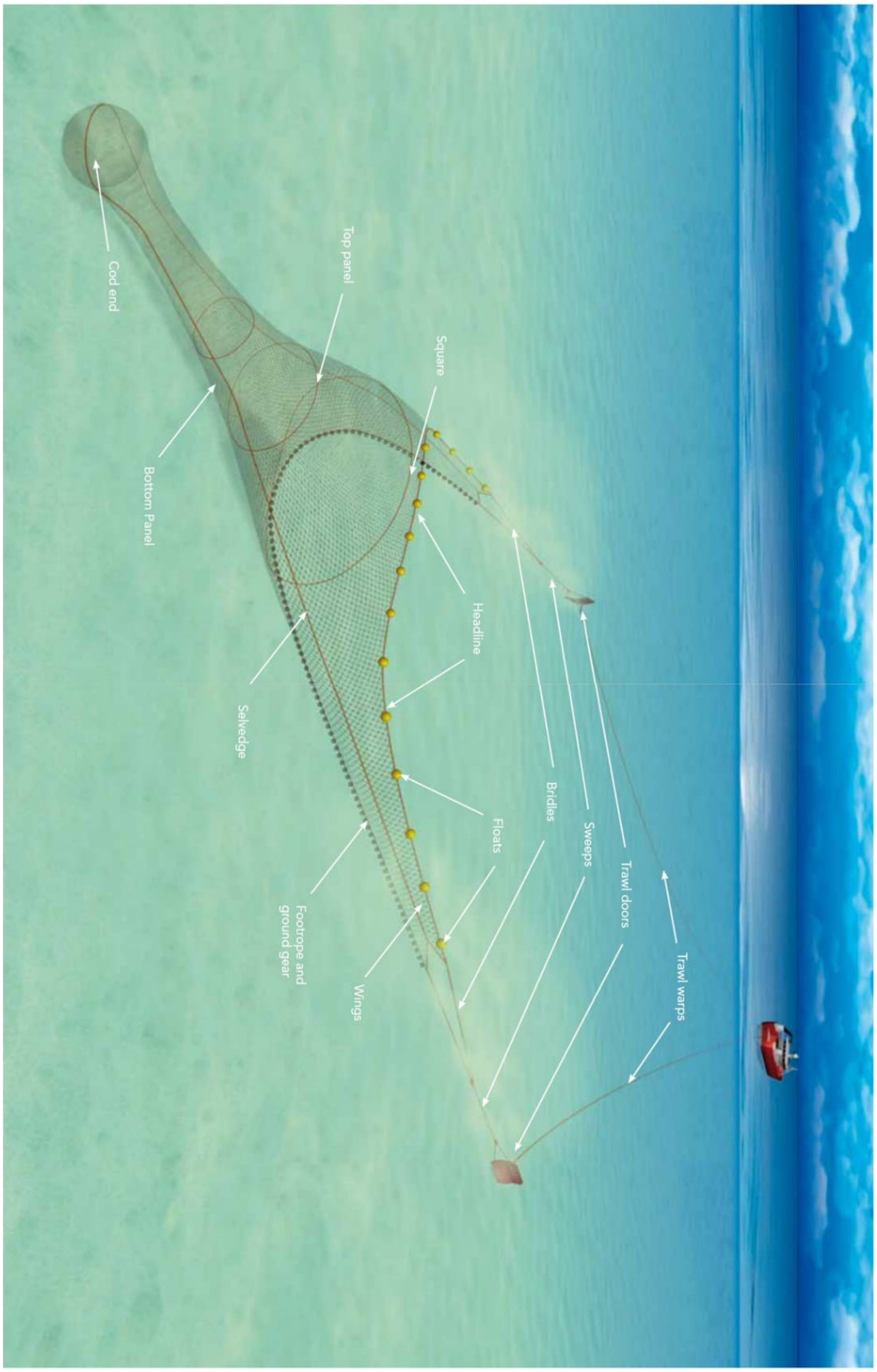

Figure 1.1. Bottom trawl with main components (Montgomerie, 2015).

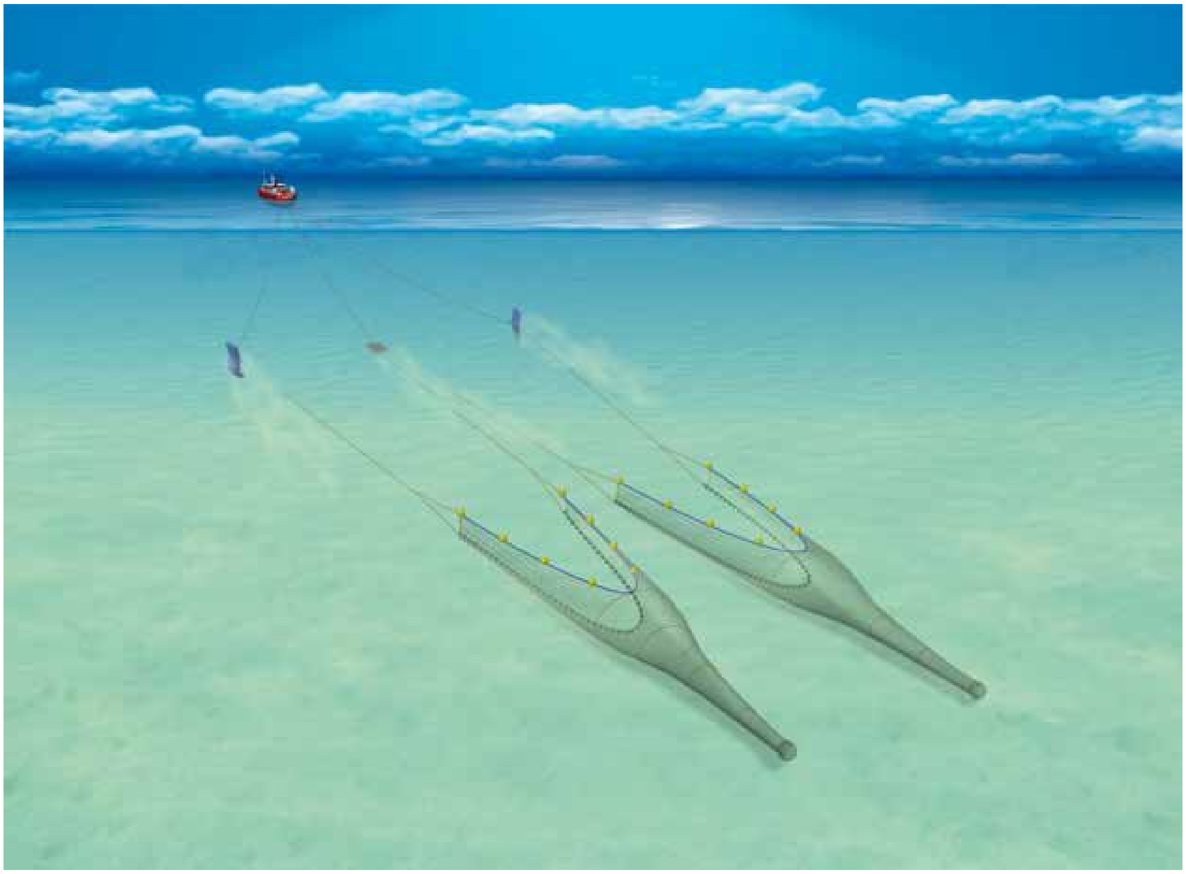

Figure 1.2. Twin-trawling configuration (Montgomerie, 2015).

Figure 1.3. Roller clump in Eastern Canada offshore Northern shrimp (*Pandalus borealis*) fishery used for twin-trawling.

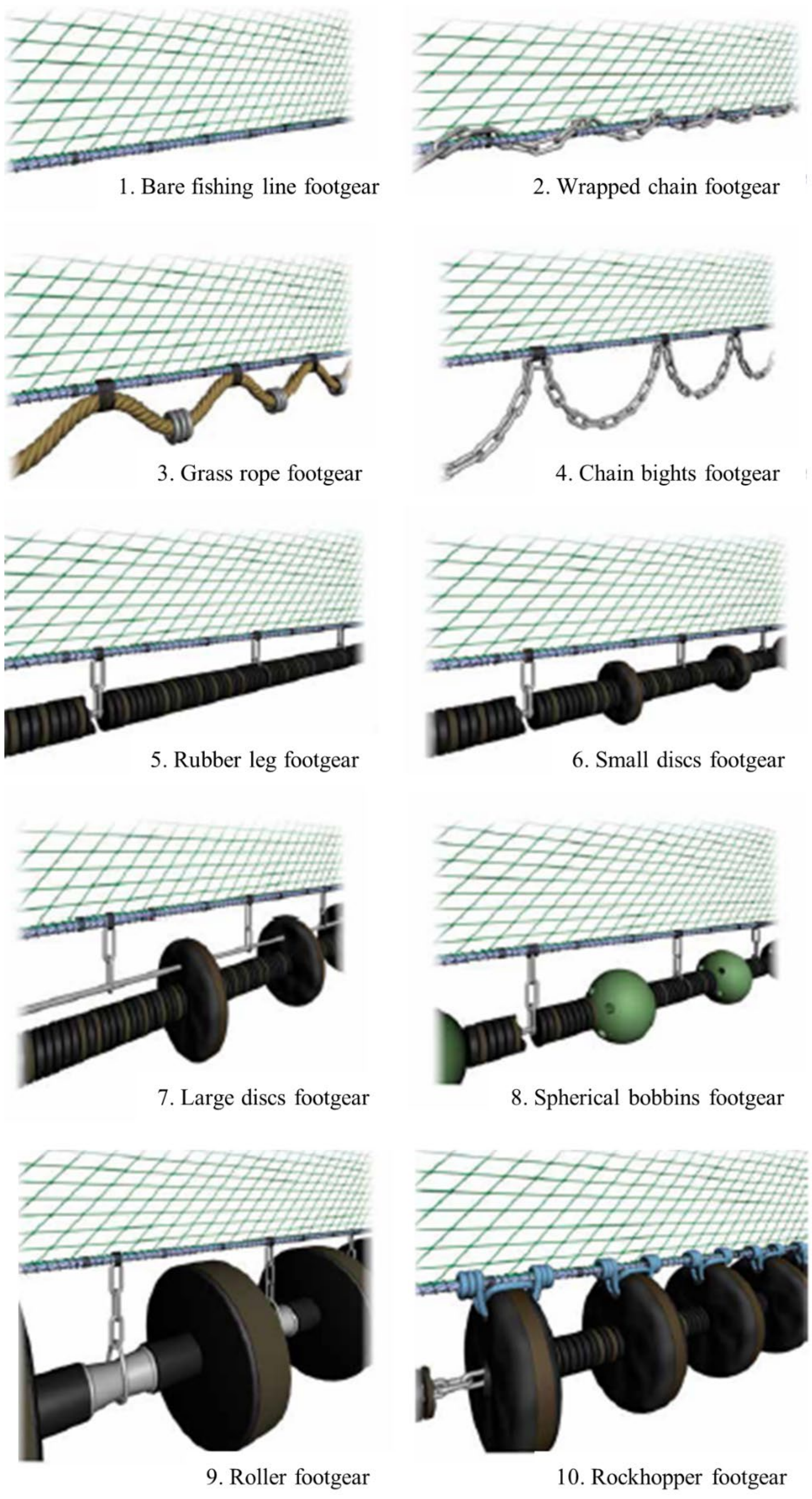

Figure 1.4. Types of footgear used in bottom trawling. Modified from Montgomerie (2015).

Figure 1.5. A typical roller footgear used in Eastern Canada offshore Northern shrimp (*Pandalus borealis*) fishery.

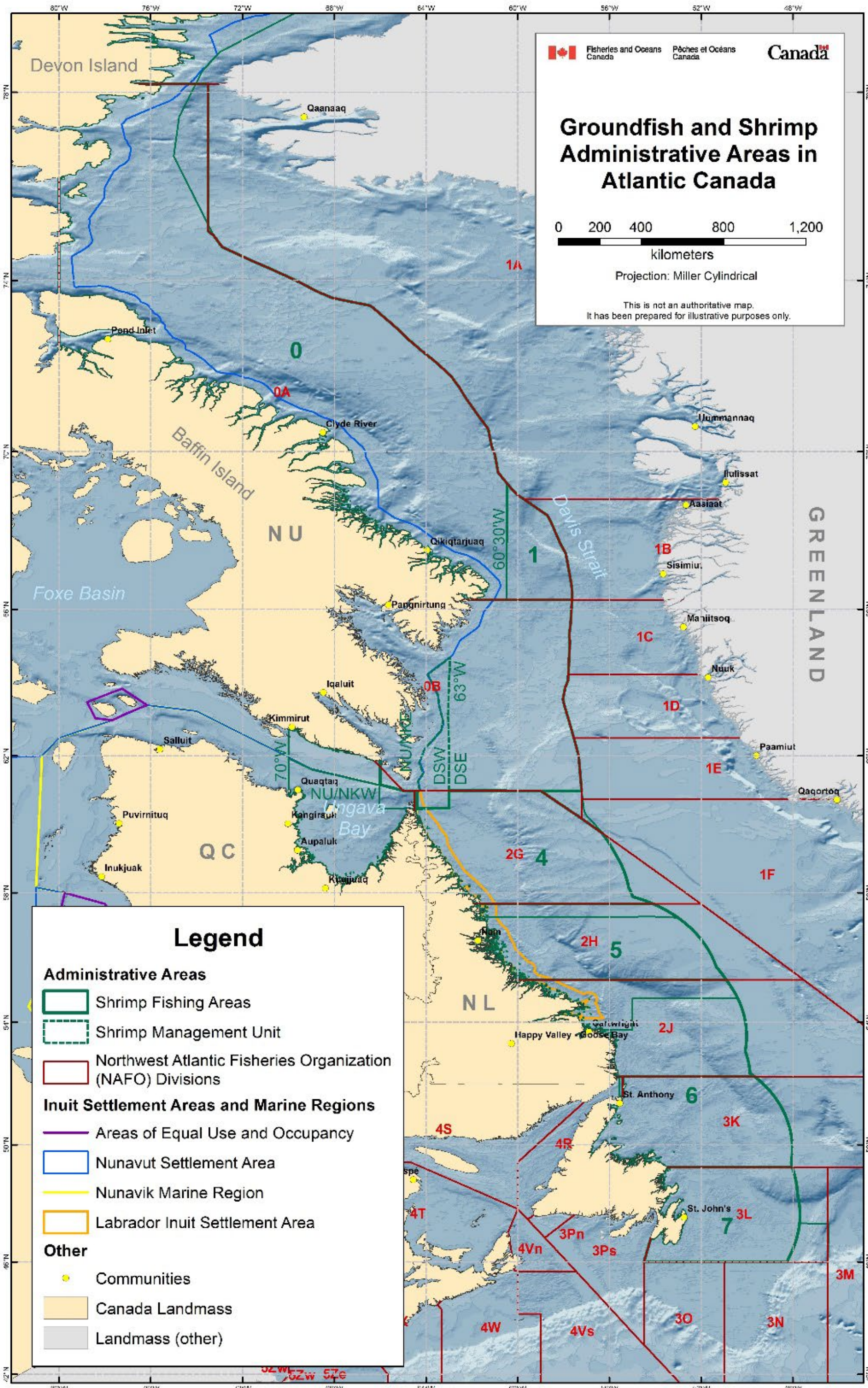

Figure 1.6. Map of shrimp fishing areas (SFAs) of the offshore Eastern Canada Northern shrimp (*Pandalus borealis*) and striped shrimp (*Pandalus montagui*) fishery (DFO, 2018).

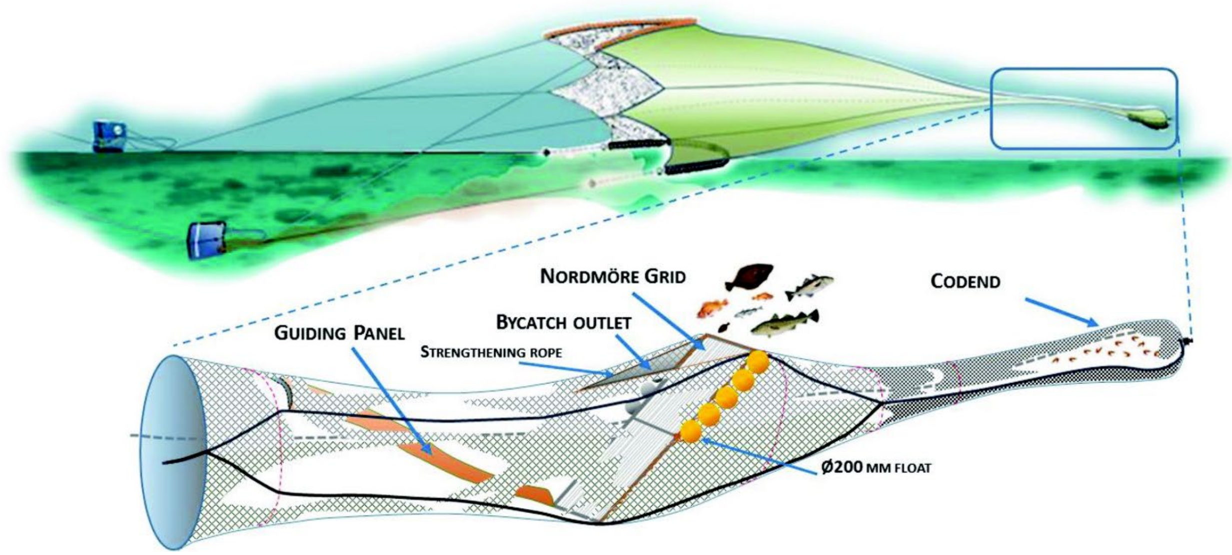

Figure 1.7. Working principle of the Nordmøre grid in a shrimp bottom trawl (Larsen et al., 2018).

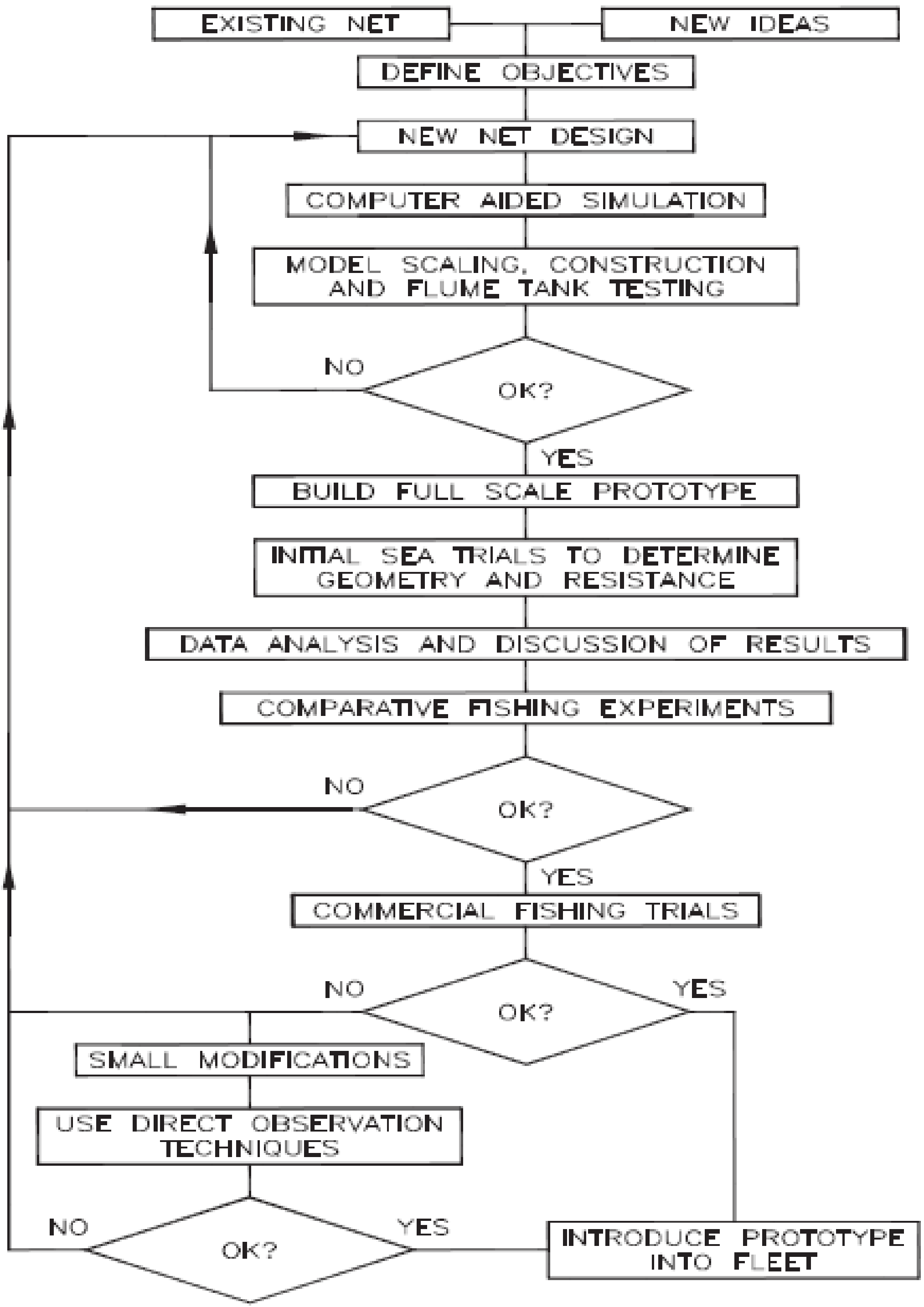

Figure 1.8. Fishing gear development cycle (Winger et al., 2006)

CHAPTER 2. Investigating the performance of a roller footgear in the offshore shrimp fishery of Eastern Canada using underwater video

2.1. Abstract

The offshore Northern shrimp (*Pandalus borealis*) fishery in Eastern Canada is currently harvested by factory freezer vessels using bottom trawls. This fishery is a major contributor to the regions' economy. However, bottom trawling typically is associated with negative benthic impacts. We evaluated the at-sea engineering performance of a roller footgear using underwater cameras. This footgear is designed to roll, limiting negative benthic impacts and reducing fuel usage, compared to non-rolling rockhopper footgear. We describe and document a new technique for measuring the time to complete a rotation in seconds (TCR) of bosom and quarter-wing footgear sections on hard, mixed, and soft seabed. Our results showed that footgear sections were rotating at extremely low rates. Results predicted a statistically significant 184% increase in TCR when comparing the bosom to the quarter-wing section ($p = 0.035$). TCR on hard seabed ranged from 23.6 s in the bosom to 43.4 s in the quarter-wing section, while mixed (from 169.0 to 311.1 s) and soft (from 862.6 to 1587.6 s) seabed types produced significantly longer TCR ($p < 0.001$). This study provides evidence that roller footgear is not rotating at the velocity expected by the industry and offers essential information to further develop innovative footgear with reduced seabed impact.

2.2. Introduction

Roller footgear is used by trawlers in the offshore shrimp fishery in Eastern Canada. Large rubber discs are threaded onto the footgear chain with rubber and steel spacers (i.e., lancasters) between them. The footgear is constructed in large sections, which are connected together using swivels. It is called “roller footgear” because these sections are free to roll in theory, allowing the footgear to roll over hard rocky seabed and protect the bottom trawl from damage (Montgomerie, 2015). The footgear is attached to the fishing line by chains threaded around the lancasters.

The geometry and shape of bottom trawls is largely determined by the hydrodynamic forces that are generated as the trawl is towed through water. However, given that many of the trawl components (e.g., trawl doors, footgear, bridles/sweep lines) are in contact with the seabed, friction and digging forces also play an important role, which together are known as the ground effect (Fridman, 1986). In the case of roller footgear, friction forces can be divided into two types; when the surface of the rubber discs slides over the seabed (sliding friction) and when the discs roll over the surface of the seabed while turning on their axis (rolling friction). A roller footgear is designed to reduce sliding friction as it rolls over the seabed. This reduction in friction varies with the angle of incidence of the discs axis to the direction of tow. Components oriented with an axis of 90º to the direction of tow will experience minimal rolling resistance and generally roll freely, while components oriented with an axis of 0º to the direction of tow will produce maximum ground resistance (Fridman, 1986). As a result, footgear components or sections near the center of the trawl (i.e., bosom) roll more efficiently, while rotation is more difficult in the quarter or wing sections, where the towing direction is not perpendicular to the footgear axis (He and Winger, 2010; Grieve et al., 2015).

Footgear discs in the quarter and wing sections can experience greater contact area with the seabed due to their greater frontal projected area, depending on seabed penetration depth, displacing larger amounts of sand, mud, and experiencing higher sliding, digging and drag forces

(Fridman, 1986; Esmaeili and Ivanović, 2014; Winger et al., 2018). Footgear components with greater frontal projected area and limited rotation can cause increased damage to benthic structures, higher mortality and exposure of benthic species, as well as increased sediment remobilization (Hiddink et al., 2017; Depestele et al., 2019). Recent studies have shown that the degree of sediment remobilization (i.e., sand/mud clouds) is largely determined by the hydrodynamic drag of the footgear components (O'Neill and Summerbell, 2016), suggesting that the remobilization of sediment is primarily a hydrodynamic phenomenon. The authors speculate that the amount of sediment remobilized by towed fishing gears can be reduced by reducing the hydrodynamic drag of footgear components in contact with the seabed.

This study provides a baseline investigation into the performance of a commonly used roller footgear system in the offshore Northern shrimp fishery in Eastern Canada. Using a video system, we developed and described a novel technique for measuring the performance of roller footgears, in particular their time to complete a rotation (TCR). We compared TCR values for different parts of the footgear on different seabed types during commercial fishing operations. The results are discussed in relation to potential future innovations that could reduce contact area, penetration depth, hydrodynamic drag, and sediment remobilization.

2.3. Materials and Methods

2.3.1. Study Area and Fishing Gear

This fishing experiment was conducted between 26 April and 12 May 2019, onboard the offshore factory freezer vessel *Sivulliq* (LOA: 64 m, GT: 2598, 6700 hp) during commercial fishing operations in Shrimp Fishing Area 5 (SFA5) off the coast of Newfoundland and Labrador, Canada (Figure *2.1*).

The bottom trawl used in this study was a 4-panel, 2-bridle, high opening AngCos 3325 small mesh shrimp trawl net manufactured by Isfell EHF in Iceland. The headline length was 60.4 m, and the fishing line length was 71.4 m. The roller footgear was 31.4 m long and made of bosom, quarter and wing sections. The rest of the footgear (i.e., from the end of the roller footgear wing section to the end of the lower wingtip) was constructed of bare chain and 0.61 m diameter spherical steel bobbins. Large swivels (6 t safe working load) were used in front of each roller footgear wing sections, and between quarter and bosom roller footgear sections (Figure *2.2*). The quarter and wing sections had no swivels between them, they must roll together, and therefore they were treated as one footgear section, hereafter named quarter-wing section. Disks in these sections cannot roll independently. The bosom footgear section was 7.4 m long and weighted 261.9 kg in seawater, while quarter-wing sections were 12.0 m long and weighted 546.5 kg in seawater. It was constructed of twelve rubber disks (0.61 m diameter and 0.12 m width), which are in contact with the seabed, while the quarter-wing section was constructed of sixteen rubber disks and two spherical steel bobbins (0.61 m diameter). Additionally, roller footgear sections had rubber spacers, lancasters, washers and weights distributed along the sections; bosom section had two 24 kg steel rings and four 11 kg steel rings, and the quarter-wing sections had six 11 kg steel rings (Figure *2.2*). This large footgear, meant for rough seabed conditions, is commonly used by the vessel and no modifications were made in order to assess its performance under normal commercial fishing operations. The roller footgear section was used for one fishing trip (~21 days) before this study. Towing speed was 2.9 knots, which is commonly used by the fishing vessel.

2.3.2. Video system

The video system used during the sea trials consisted of a Gopro hero 4 black action camera and a DIV08W diving light from Brinyte Technology Ltd. (white light, 1500 lumens and luminous intensity of 625cd) in underwater housings from Group B Distribution Inc. GoPro "Bacpac" battery and 4000 mAh external battery allowed to record continuously for 6 hours. Aluminum crash cages were designed and constructed to hold and protect the camera and light housings (Figure 2.3).

Video system was attached to the fishingline to observe the quarter-wing and bosom roller footgear sections. Additional flotation (12 kg lift) was added near the video system to counterbalance its weight in water. Footgear rubber discs were painted with a white stripe to observe rotation.

2.3.3. Statistical analysis

The Observer XT software from Noldus Information Technology was used to obtain the following data from the videos; Time to complete a rotation for the footgear section (TCR), footgear section being recorded (Quarter-wing or Bosom), and type of seabed (Seabed). During the videos, three types of seabed were observed: hard seabed, mixed seabed, and soft seabed. The hard seabed was characterized by a high occurrence of rocks and boulders. The mixed seabed was characterized by areas with sandy or muddy bottom with low occurrence of rocks and boulders. The soft bottom was characterized by smooth seafloor with sand or mud and small rocks.

Only underwater video in which the footgear was visible on the seabed was used to obtain data. Video where the footgear was off bottom and covered by sand clouds was discarded. Data obtained when the trawl net experienced door spreads outside the normal operational parameters of the gear (door spread <60 m), was not used for the statistical analysis but descriptively shown and explained in the results.

TCR was transformed into the natural log to meet the homogeneity of variance and normality assumptions. Linear models were fitted using Section and Seabed variables with the lm function of the nlem package (Pinheiro et al., 2019) in R statistical software (R Development Core Team, 2017). The optimal model with the best fit was found using AICctab function from the bbmle (Bolker et al., 2019) package in R. The model with the highest R^2, and lowest AIC value indicated the best fit (Burnham et al., 2011).

TCR was estimated with the following model,

$$\mathrm{Ln}(TCR) = \alpha + \beta_1 Section + \beta_2 Seabed + \varepsilon$$

where $\mathrm{Ln}(TCR)$ is natural log-transformed TCR (in seconds), α is the intercept, $\beta_1 Section$ is the section of the footgear (quarter-wing or bosom), $\beta_2 Seabed$ is the type of seabed (hard, mixed or soft), and ε is the error term.

The selected model was tested for outliers, independence, homogeneity, and normality according to the techniques described in Zuur et al. (2010) and Zuur and Ieno (2016). Residuals were compared against fitted values to assess model fit. Statistical significance was considered at a p-value ≤ 0.05.

Estimated marginal means and pairwise comparisons of the time to complete a rotation in the quarter-wing and bosom sections in the different seabed types were obtained using the emmeans function of the emmeans package (Lenth, 2019) in R.

Optimal revolutions per minute (rpm) of the footgear were calculated to set a maximum speed of rotation in an ideal scenario, full contact of the rubber disks with the seabed, no sliding across the seabed, and sections free to roll. The formula $rpm = \frac{S}{C}$ was used, where S is the speed in meters per minute, and C is the circumference of the rubber disk in meters; 2πR. Therefore, a 0.61 m diameter rubber disc towed at 2.9 knots (vessel speed over ground) should complete a rotation in 1.3 s (TCR).

2.4. Results

Video observations were undertaken during four tows; two with the video system in the bosom section, where the video system field of view was centered with the fourth starboard disk from the center of the section, and two in the quarter-wing port and starboard sections, where the video system field of view was centered with the last fourth disk of the section, which yielded a total time of 24 hr, 29 min, 50 s of video. The total time of usable video recorded in the quarter-wing section was 2 hr 52 min 11 s, where 19 full rotations of the footgear occurred during that period. In the bosom section, 6 hr 55 min and 40 s were recorded, and 182 full rotations of the footgear were observed in total. The bosom section experienced hard seabed conditions for 74.5 min, mixed seabed conditions for 80.2 min and soft seabed conditions for 260.1 min. The quarter-wing section experienced hard seabed conditions for 2.8 min, mixed seabed conditions for 69.1 min and soft seabed conditions for 50.1 min. During the video observations the observed mean TCR (± SD) for the bosom section varied between 31.5 (± 21.7) and 1423.5 s (± 1023.5), and for the quarter-section section between 56.5 (± 30.0) and 1002.1 s (± 287.3) (Table *2.1*).

According to the *a priori* model selection guidelines, the model with the interaction term Section*Seabed had the best fit, but showed a negligibly higher R^2 and a non-significant ΔAIC (1.0) from the next-best model which contained both independent variables. Thus, since no other model had a competitive fit, the less complicated of the two models, which were not significantly different from each other, was selected.

Linear model output (Table 2.2) showed a predicted TCR of 23.6 s for the bosom footgear section on the hard seabed (Figure 2.4). From the bosom to the quarter-wing section, TCR was increased by 1.8 times (95% CI [1.2 – 2.8]), holding seabed constant ($p = 0.004$).

An increase by 7.2 times (95% CI [5.4 – 9.7]) was observed as we went from hard to mixed seabed ($p < 0.001$) and by 36.7 times (95% CI [24.2 – 55.6]) from hard to soft seabed ($p < 0.001$), holding footgear section constant (Table *2.2*). Pairwise comparisons indicated that for the quarter-wing and bosom footgear sections, the TCR is significantly different among seabed types ($p < 0.001$). For each seabed type, there was a significant difference in TCR between the bosom and quarter-wing footgear sections ($p = 0.004$).

Our model predicted that rotation of the footgear sections was extremely low; estimated marginal means indicated that the TCR on hard seabed was 23.6 s (95% CI [20.7 - 26.6]) in the bosom section, while in the quarter-wing section was 43.4 s (95% CI [28.5 - 66.0]). Mixed seabed produced estimated marginal means of TCR of 169.0 (95% CI [129.0 - 221.4]) and 311.1 s (95% CI [210.6 - 459.4]) for the bosom and quarter-wing sections, respectively. Soft seabed produced the highest TCR; 862.6 s (95% CI [578.6 - 1286.9]) for the bosom section and 1587.6 s (95% CI [1002.3 – 1451.0]) for the quarter-wing section.

It was calculated that in optimal conditions a discs of diameter 0.61 m in full contact with the seabed at a speed of 2.9 knots (1.49 m/s), with no sliding across the seabed and free to rotate, takes 1.3 s to complete a rotation (TCR).

2.5. Discussion

Our results indicated that roller footgear sections are rotating at extremely low rates. However bosom section showed a lower TCR when compared to quarter-wing section. This higher rotation in the bosom section is attributed to the section axis oriented ~ 90º relative to the direction of tow (He and Winger, 2010).

Harder seabed increased rolling and presumably reduced friction of the roller footgear sections (Fridman, 1986). Similar to this, Ivanović *et al.* (2011) observed higher drag for a roller clump on muddy sand when compared to stiffer sand seabed. The authors hypothesized that this was due to greater penetration of the clump in softer seabed. Our study suggests that this could also be attributable to a decrease in rolling over soft sediments, increasing friction and drag.

Model estimates were nowhere near the calculated optimal TCR. Factors, including: i) orientation of several footgear sections and disks axis are not perpendicular to the towing direction, ii) the footgear sections are generally large with a low number of swivels between them, iii) toggle chains not straight or wrapped around the footgear, and iv) friction between lancasters and toggle chain rings can prevent roller footgear rotation. Since footgear sections were not free to roll, a combination of sliding and rolling friction, as well as digging forces were observed (Fridman, 1986). Our findings suggest that the roller footgear rotated to some extent, reducing sliding friction and digging forces, but at very low levels. As a result, we speculate that the roller footgear observed in this study would therefore have a similar ground resistance to a non-rolling footgear (i.e., rockhopper) of the same characteristics (Fridman, 1986).

Despite the limited data obtained, this investigation provided valuable information on the performance of roller footgears for the offshore Northern shrimp fishery in Eastern Canada and documented a novel technique for analyzing the extent of actual rotation. We view this a baseline upon which other future innovative footgears can be quantitatively compared.

2.6. Acknowledgements

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2.8. Tables

Table 2.1. Summary of the observed mean time in seconds to complete a rotation, standard deviation (SD), and the number of rotations (n) in the bosom and quarter footgear sections in hard, mixed and soft seabed. Total values for the bosom and quarter sections are shown.

Footgear section	Hard seabed			Mixed seabed			Soft seabed			**Total**		
	Mean time (s)	SD	n	Mean time (s)	SD	n	Mean time (s)	SD	n	Mean time (s)	SD	n
Bosom	31.47	21.72	142	165.94	61.40	29	1423.48	1023.45	11	137.03	410.21	182
Quarter-wing	56.54	29.98	3	414.86	140.24	10	1002.13	287.34	6	543.74	389.49	19

Table 2.2. Parameter estimates of the linear model $Ln(Rotation\ time) = \alpha + \beta_1 Section + \beta_2 Seabed + \varepsilon$. Including, estimates and standard errors in natural log and back transformed, t-statistic and *p*-values, which are statistically significant based on an alpha of 0.05.

	Ln(Rotation time)		Exp(Ln(Rotation time)			
	Estimate	Std. Error	Estimate	Std. Error	t value	*p*-value
Intercept	3.16	0.06	23.57	1.07	48.57	< 0.0001
Quarter-wing section	0.61	0.21	1.84	1.23	2.95	0.0035
Mixed seabed	1.98	0.15	7.22	1.16	13.27	< 0.0001
Soft seabed	3.60	0.21	36.65	1.24	17.02	< 0.0001

2.9. Figures

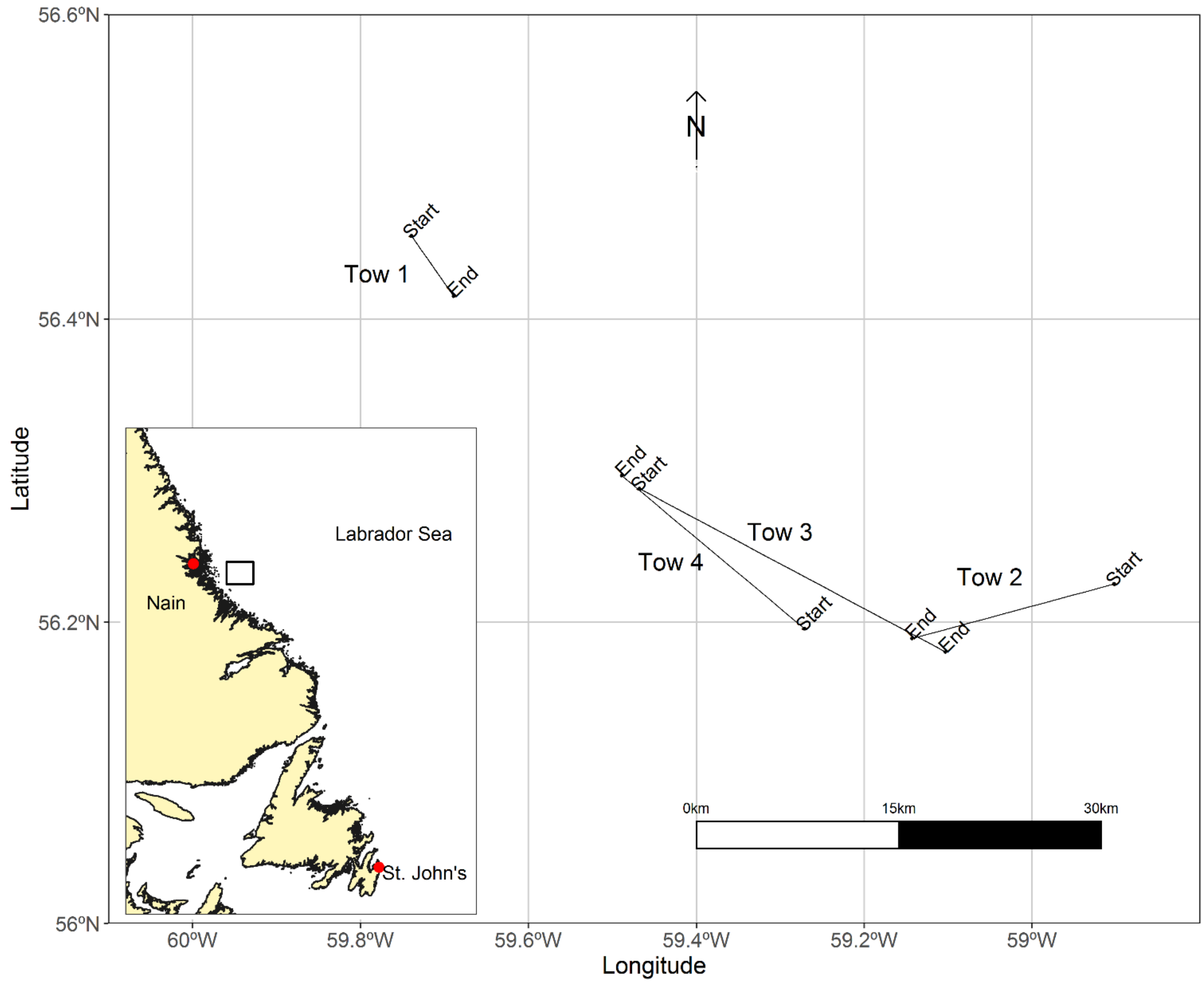

Figure 2.1. Map of the study area in Shrimp Fishing Area 5 (SFA5), located in the Labrador Sea off the coast of Nain, Newfoundland and Labrador, with inset map of the broader area. The black rectangle in the inset map indicates the study area. Lines indicate tows, where tow number and start/end position are shown. Map data from the GADM database of Global Administrative Areas (http://gadm.org/). Mercator projection WGS 84 was used.

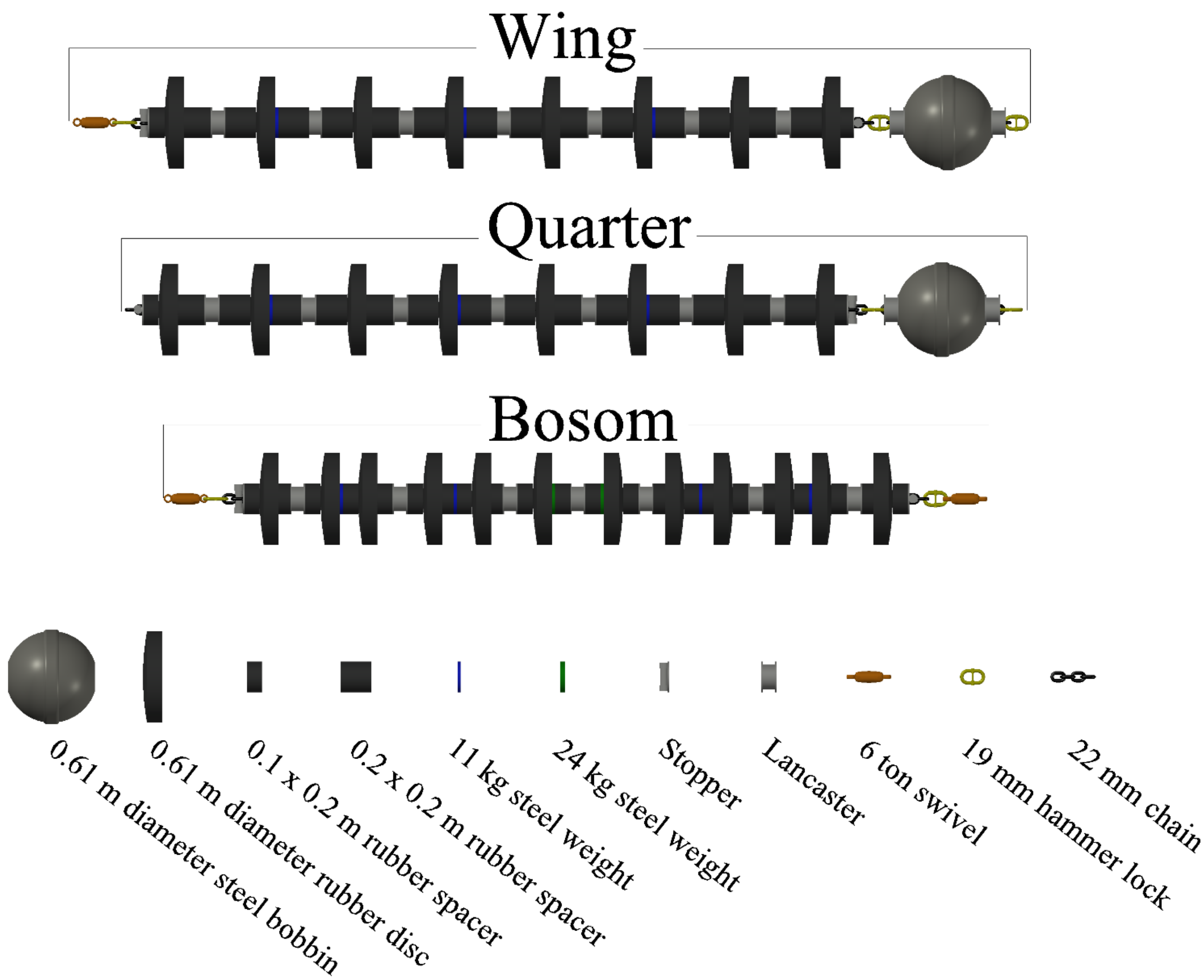

Figure 2.2. Schematic drawing of the roller footgear commonly used by the offshore shrimp fishery in Eastern Canada.

Figure 2.3. Video system attached to the fishingline above the port side quarter-wing footgear section.

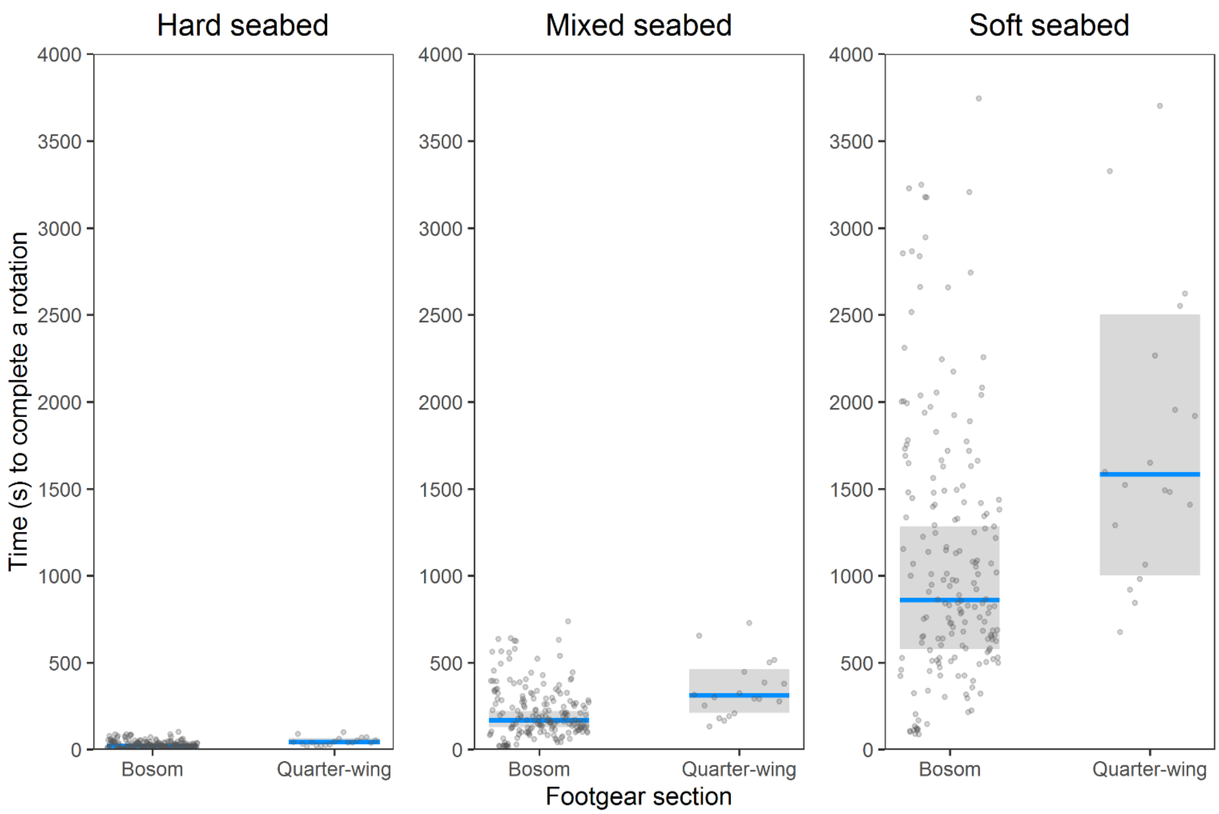

Figure 2.4. Back transformed linear model fit of the time in seconds to complete a rotation for the bosom and quarter-wing footgear section in the hard, mixed, and soft seabed. The blue line represents the linear model fit, 95% confidence intervals are represented by the grey shaded area, and dots show the partial residuals.

CHAPTER 3. Flume tank testing of an innovative footgear technology using simulated seabeds

3.1. Abstract

There have been many advancements in bottom trawls to reduce physical and biological impacts on benthic habitats. In this study, an innovative aligned-rolling footgear was designed and evaluated for use in the Northern shrimp (*Pandalus borealis*) fishery in Eastern Canada. We document a novel technique for comparing traditional and experimental footgears using engineering models and simulated seabed conditions in a flume tank. Footgears were compared using direct observation and by measuring warp load during simulated smooth, semi-rough, and rough seabed conditions in contact with bosom or wing footgear sections. Results revealed that the traditional footgear bottom trawl experienced significantly higher warp loads (converted to full scale values) for smooth (0.26 t higher), semi-rough (0.68 t higher), and rough seabed conditions (0.74 t higher) in the bosom section. In the wing section, traditional bottom trawl produced significantly higher warp loads for smooth (0.38 t higher) and rough seabed conditions (0.30 t higher). Bottom trawl with aligned-rolling footgear reduces seabed contact up to 71.5% depending upon depth of penetration modelled. To our knowledge, this study represents the first attempt at using simulated seabed conditions in a flume tank testing footgear technology.

3.2. Introduction

Since the 1950s, bottom trawls have been widely used to target demersal species in an efficient and economically viable manner (Valdemarsen, 2001; Watson et al., 2006; Valdemarsen et al., 2007). Bottom trawls accounts for almost one-quarter of the total wild marine landings annually (Amoroso et al., 2018), which represents a substantial contribution to global food security (Kaiser et al., 2016). However, these bottom-contacting fishing gears can result in physical and biological impacts on benthic habitats (Hiddink et al., 2017; Sciberras et al., 2018).

Bottom trawls typically employ heavy components to move, herd, guide, and finally capture demersal fish and shellfish in fishing gear (Montgomerie, 2015). The extent of contact and seafloor penetration varies with the trawling operation, which are customized for the target species, depth, and seabed type (Løkkeborg, 2005; He, 2007; Sciberras et al., 2018; Depestele et al., 2019). Bottom trawls can cause adverse effects on benthic species and habitat. Direct effects include mortality of benthic organisms (Collie et al., 2005), alteration to seafloor composition and bathymetry (Depestele et al., 2019), reduction of topographic complexity (O'Neill and Ivanović, 2016), and changes to sediment biogeochemistry (Mayer et al., 1991; Sciberras et al., 2016). In the first few days after trawling, direct mortality and bycatch discarded from fishing vessels can attract scavengers to the trawled area (Collie et al., 2017). In the long term, persistent trawling of an area can reduce benthic biomass, diversity, and numbers of individuals, which in turn can reduce productivity, change trophic structure and function of the benthic community, as well as generate changes to body size and age structure of benthic organisms (Jennings et al., 2001; Hiddink et al., 2006). Ultimately, chronic trawling can produce a change towards communities dominated by species with faster life histories (Tillin et al., 2006; Johnson et al., 2015; Van Denderen et al., 2015).

Growing concerns about seabed impacts (Kaiser et al., 2016) have led to the study of new technologies to reduce the area of contact, weight, or penetration depth of fishing gear components on the seabed, as well as the reduction of bycatch of benthic species (He, 2007; He and Winger, 2010). Much of this innovation has focused on improving the footgear of bottom trawls and has led to the development of footgears that roll over the seabed (Ball et al., 2003; He and Balzano, 2010), or that are aligned with the towing direction (Winger et al., 2018), or have reduced area/points of contact (Nguyen et al., 2015a; Brinkhof et al., 2017; Larsen et al., 2018).

Roller footgear is currently used by offshore trawlers targeting Northern shrimp (*Pandalus borealis*) in Eastern Canada. Large rubber discs are threaded onto the footgear chain with rubber and steel spacers (i.e., lancasters) between them. The footgear is constructed in large sections that are connected together using swivels. The footgear is called "roller footgear" because these large sections are free to roll, allowing the footgear to move over hard rocky seabed and protect the trawl from damage (Montgomerie, 2015). However, recent findings during fishing operations have shown that the footgear sections are rolling at extremely low rates (Araya-Schmidt et al., 2021), which may produce higher sliding, digging, and drag forces (Fridman, 1986; Esmaeili and Ivanović, 2014; Winger et al., 2018).

Footgear components with no, or limited, rotation and a larger contact area with the seabed likely cause increased damage to benthic structures, higher mortality, and exposure of benthic species, as well as increased sediment remobilization (O'Neill and Summerbell, 2016; Hiddink et al., 2017; Depestele et al., 2019). Aligned footgears reduce seabed contact by "aligning" footgear discs in the direction of the tow. In the 1940s, the first known aligned wheel footgear was designed in Germany. Presumably, footgears that can roll over the seabed were originally designed to reduce fuel consumption (He and Balzano, 2010). However, it has been shown that aligned footgear designs can reduce substrate material in the trawl net, bycatch, drag, area of contact, and presumably, seabed impacts (Ball et al., 2003; Zachariassen, 2004; He and Balzano, 2010; Winger et al., 2018).

A critical component of the fishing gear development cycle is flume tank testing of engineering models (Winger et al., 2006). This allows fishing gear technologists to identify design defects, measure changes to trawl geometry due to different riggings or towing speeds, measure forces, and document the dynamic motions of the fishing gear. Several footgear technologies have been tested in flume tanks (Ball et al., 2003; Grimaldo et al., 2014; Nguyen et al., 2015a; Winger et al., 2018). Laboratory experiments have been used to study the impacts of trawl doors on the seabed and infaunal bivalves (Gilkinson et al., 1998). Seabed penetration experiments for beam trawls have been performed in towing channels (Paschen et al., 2002). In recent years, numerical modelling of ground gear elements has been developed to estimate contact forces (Ivanović et al., 2008), penetration depth (Ivanović et al., 2011; Ivanović and O'Neill, 2015), soil displacement (O'Neill and Ivanović, 2016), and drag force (Ivanović et al., 2009). To our knowledge, testing model trawls with new footgear technologies is usually conducted in flume tanks with a flat moving seafloor. While a moving seafloor is better than no moving seafloor, the lack of texture does not allow fishing gear technologists to make inferences on the performance of the footgear over coarser seabeds.

Building on previous roller footgear concepts (Ball et al., 2003; Zachariassen, 2004; He and Balzano, 2010; Winger et al., 2018), this study designed and evaluated an innovative aligned-rolling footgear. We document a novel technique for comparing traditional and experimental footgears using engineering models and simulated seabed conditions in a flume tank. Footgears were qualitatively compared using direct observation and quantitatively assessed by measuring warp load for different seabed conditions (i.e., smooth, semi-rough, and rough seabeds) at different footgear sections (i.e., bosom and wing sections). The results are discussed in relation to expected seabed impact, prototype validation, and previous footgear innovations.

3.3. Materials and Methods

3.3.1. Modelling of bottom trawl

Numerical simulation of the bottom trawl with DynamiT software (IFREMER, France) was first performed to validate the dynamics of the fishing gear. A linear model scale of 1:10 was selected for the bottom trawl to fit in the flume tank and achieve the desired wingspread commonly used by the commercial fishing vessels (approximately 37 m). The model was constructed at the Fisheries and Marine Institute's Centre for Sustainable Aquatic Resources using Froude scaling laws (Tauti, 1934; Fridman, 1973; Hu et al., 2001). Force, geometric, kinematic, and dynamic modelling laws are commonly used in model scaling to approximate full-scale bottom trawl characteristics (Fiorentini et al., 2004; Queirolo et al., 2009; Sala et al., 2009; Nguyen et al., 2015b; Thierry et al., 2020). The fundamental modelling laws can be summarized as follows, where *f* and *m* in the subscripts represent the full-scale and model, respectively:

$$\lambda = L_f / L_m \tag{1}$$

$$A_m = A_f / \lambda^2 \tag{2}$$

$$F_m = (F_f / \lambda^3)(\rho_m / \rho_f) \tag{3}$$

$$\lambda^{1/2} = v_f / v_m \quad (4)$$

where λ, L, A, F, ρ, and v are the ratio of the length scale, length, area, force, water density, and towing speed, respectively.

3.3.2. Trawl design

The bottom trawl design used in this study was a 4-panel, 2-bridle, high opening AngCos 3325 small mesh shrimp trawl net manufactured by Isfell EHF in Iceland. The headline length was 60.4 m, and the fishing line length was 71.4 m. Floatation on the headline was provided by 232 trawl floats (200 Isfell titanium 200 mm Ø 2.90 kg of lift and 32 Atlantic floats 242 mm Ø 4.28 kg of lift). Additional floats were added along the selvedges (*n* = 25 titanium 200 mm Ø) and fishing line (*n* = 160 titanium 200 mm Ø). Mesh sizes ranged from 200 to 50 mm, and towing speed during fishing operations is 1.29 m s^{-1} (2.5 knots).

3.3.3. Traditional footgear

Two types of model footgears were scaled and constructed for flume tank testing. The traditional footgear was typical of that used by commercial fishing vessels in Eastern Canada. In full-scale terms, it consisted of five rolling footgear sections: a 4.4 m bosom section with 12 rubber discs, a port, and starboard 4.0 m first bunt wing section with seven rubber discs, and a second port and starboard bunt wing section with five rubber discs (Figure *3.1*). Each section contained rubbers, spacers, weights, and lancasters distributed along its length. Sections were connected by swivels, and 0.61 m diameter steel bobbins were placed in between sections. The remainder of the footgear, i.e., port and starboard wing sections, were 22 m long, made of bare chain, and five steel bobbins of 0.61 m diameter. Dan Leno assemblies with a 0.61 m diameter bobbin were used after the second bunt wing and wing sections. The bosom section had 22 mm chain, while the remainder of the footgear had 19 mm chain. Toggle chains were 72 cm, complying with local fishing regulations. Rubber discs were 0.61 m in diameter. In total, there were 36 rubber discs and 18 steel bobbins in contact with the seafloor. Full-scale weight in seawater was 2.11 t.

3.3.4. Aligned-rolling footgear

The aligned-rolling footgear consists of the same bosom section as the traditional footgear. However, the first and second bunt wing sections were replaced by a bare chain and four aligned-rolling rubber wheels (Figure *3.2*). Wing sections were replaced by a bare chain and five aligned-rolling rubber wheels (Figure *3.1*). The aligned-rolling rubber wheels were 0.61 m in diameter. Port and starboard wing Dan Leno assemblies with bobbin and first bobbin were also present in the aligned-rolling footgear configuration. The bosom section had 22 mm chain, while the remainder of the footgear had 19 mm chain. Toggle chains were 72 cm long to comply with fishing regulations. Rubber discs were 0.61 m in diameter. In total, the aligned-rolling footgear consisted of 12 rubber discs, 18 aligned wheels, and four steel bobbins in contact with the seafloor. Full-scale weight in seawater was 2.03 t.

Alignment of the wheels with the towing direction is critically important for an aligned footgear to work effectively (He and Balzano, 2010). This was achieved in the flume tank by measuring the distance between the bobbins along the traditional footgear at a simulated towing speed of 1.29 m s^{-1} (2.5 knots), and 65 m door spread. Angles of towing direction with respect to the footgear chain direction were then calculated for an effective design of the aligned wheel components in the bunt wing and wing sections.

3.3.5. Simulated seafloor experiment

Three aluminum plates of 1.22 m by 2.44 m (12.2 and 24.4 m full-scale) were used to simulate smooth, semi-rough, and rough seabed conditions for the flume tank testing of the traditional and experimental footgear (Figure 3.3). The smooth plate had a coat of paint for extra smoothness. The semi-rough plate had 139 rocks glued with PL Premium^{TM} construction adhesive, with a mean height of 0.010 m (0.10 m full-scale). The rough plate had 353 rocks glued, with a mean height of 0.014 m (0.14 m full-scale). Rocks were selected by size for each plate and randomly distributed on the surface (Figure 3.3).

The experiment began by deploying the model bottom trawl in the flume tank with gentle water flow (i.e., 0.5 m s^{-1} full-scale). The port and starboard warps were attached to a load cell and lowered to a height of 0.19 m off the seabed using the towing masts (see (Winger et al., 2006)). The width of the towing masts was set up to simulate a 65 m full-scale door spread, producing a lower wing-end spread of 37.13 m. Once the trawl was in place, the water flow was stopped, and an aluminum plate (smooth, semi-rough, or rough seabed condition) was lowered and placed on top of the fume tank belt, aligned with the centre of the bosom section or with the centre of the port wing section (Figure 3.3). Alignment of the plates with the specific footgear sections was achieved by marking the plates and using the flume tank belt lines as a reference. Once the plate was safely in place, the water flow was increased to a typical towing speed used by the fishing industry (1.29 m s^{-1} full-scale; 0.38 m s^{-1} model scale). The belt was then turned on, and the plate went under the bottom trawl. Once the plate was past the bottom trawl, the belt was stopped, the flow was reduced, the bottom trawl was lifted a few centimeters from the belt, and the belt was reversed back to the original position. The above process was repeated five times for each of the two footgears, in two footgear sections, using three seabed conditions, for a total of 12 trials of five replicates.

3.3.6. Seabed contact calculation

The traditional and aligned-rolling footgear were drawn in AutoCAD 2019 using measurement data collected during flume tank testing at 1.29 m s^{-1}, 65 m door spread, with a flat moving belt. This provided information on the discs' alignment with respect to the towing direction. Following the same procedure as Nguyen et al. (2015a) and Winger et al. (2018), based on a selected penetration pathway of the discs and bobbins, the total contact width of the footgear components was calculated and divided by total footgear width to obtain the percentage of total seabed contact by the traditional and aligned-rolling footgears. Previous experiments have documented seabed penetration depth of bottom trawl nets in sand, mud, and gravel during sea trials, ranging from 0.01 to 10 cm (Table 3.1). As such, a range of modelled penetration depths were selected ranging from 1 to 13 cm with 3 cm intervals.

3.3.7. Warp load measurement

Two 45.4 kg load cells (Model-No. 31, Honeywell, USA) were used to record port and starboard warp load (kgf). Data acquisition hardware logged the data at a frequency of 50 Hz. Before starting the experiment, load cell data inputs were calibrated through a series of weight measurements (4, 6, 8, 14, and 20 kg). Bosom, bunt wing, and wing footgear sections were video recorded with time stamps during testing to correlate load data to when the plate was in contact with the footgear section. Raw loads (kgf) were imported to MS Excel. Port and starboard load measurements during footgear contact with the plate were extracted, added to obtain the total load (total load = port + starboard), converted to full-scale values (t), and averaged for each replicate measurement of footgear:section:seabed combination, following a similar approach as Tsukrov et al. (2011).

Model warp load (kgf) was converted to full-scale values (t), following force modelling law:

$$F_m = (F_f / \lambda^3)(\rho_m / \rho_f) \tag{5}$$

where λ = 10, ρ_m = 999.6 $kg\ m^{-3}$ and ρ_f =1026.0 $kg\ m^{-3}$, a force scale of 1:1026.41 was obtained.

3.3.8. Statistical analysis

A three-way ANOVA was conducted to determine the effects of footgear section, seabed condition, and footgear type on the full-scale warp load using rstatix package (Kassambara, 2020) in statistical software R (R Core Team, 2020) with statistical significance considered at an alpha of 0.05. Pairwise comparisons of the mean warp loads were then conducted using a Tukey's honest significant difference test (Tukey HSD) using the stats package in statistical software R (R Core Team, 2020).

Three-way ANOVA assumptions were tested with residual analysis in R. Normality was assessed using Shapiro-Wilk's normality test, and Levene's test assessed homogeneity of variances. Residuals were normally distributed (p-value > 0.05) and there was homogeneity of variances (p-value > 0.05).

3.4. Results

A total of 60 mean warp load values were obtained from the experiment: five for each footgear, section, and seabed combination. Observed mean warp loads ranged between 12.55 t for the aligned-rolling footgear with smooth seabed in the wing section up to 13.57 t for the traditional footgear with the rough seabed in the bosom section (Table 3.2). Observed mean warp load reductions from traditional to aligned-rolling footgear ranged between 1.95% to 5.54% for semi-rough condition in wing section and rough condition in bosom section, respectively (Table 3.2). Video recordings provided qualitative evidence that the aligned-rolling footgear wheels were rotating and in an upright position. Furthermore, they were able to go over the rocks of the plates, and there was no entanglement or damage to the footgear or bottom trawl during testing.

Depending on the footgear type and section, the plates contacted different components when passing under the model trawl. For the traditional footgear, in bosom location (i.e., plate aligned with the centre of the trawl), the plates contacted 26 rubber discs and two bobbins, while in the port wing location (i.e., plate aligned with the centre of the port wing section), the plates contacted seven bobbins. For the aligned-rolling footgear, the bosom location of the plates produced contact with 12 rubber discs and six aligned-rolling wheels, while in the port wing location contacted two bobbins and five aligned-rolling wheels.

The seabed contact for the traditional footgear ranged between 24.6% and 53.5% of the total footgear width, depending on the depth penetration modelled (Figure 3.4, Table 3.3). In contrast, the seabed contact for the aligned-rolling footgear ranged between 9.4% and 15.3%. Thus, the reduction in seabed contact for the aligned-rolling footgear ranged between 61.8% and 71.5%, compared to the traditional footgear. AutoCAD drawings suggested that rubber disc angles with respect to the towing direction ranged between 3° to 25°, 32° to 51°, and 54° to 58° for the traditional footgear bosom, first bunt wing, and second bunt wing sections, respectively. The aligned-rolling footgear bosom section was identical to the traditional footgear bosom section; in consequence, the angles of the bosom rubber discs were the same (between 3° and 25°, with respect to the towing direction). The remainder of the rubber discs were aligned with the towing direction (0° angles).

Results from the ANOVA suggested a statistically significant three-way interaction between section, seabed condition, and footgear ($F_{(2, 48)} = 8.966$, p-value < 0.001) (Figure 3.5,

Table *3.4*). Tukey HSD post hoc test showed that the traditional footgear produced significantly higher mean warp loads for all seabed conditions in the bosom section, compared to the aligned-rolling footgear in that same section; warp load in traditional footgear was 0.26 t greater for the smooth plate ([0.003, 0.517] 95% C.I., p-value= 0.044), 0.68 t greater for the semi-rough plate ([0.42, 0.93] 95% C.I., p-value < 0.001), and 0.74 t greater for the rough plate ([0.48, 1.00] 95% C.I., p-value < 0.001) (Figure 3.5, Supplemental table 3.1). With the plates in wing section, the mean warp load was significantly higher for traditional footgear in smooth plate (difference = 0.38 t [0.12, 0.63] 95% C.I., p-value < 0.001) and rough seabed (difference = 0.30 t [0.05, 0.56] 95% C.I., p-value = 0.008). For the semi-rough seabed, the mean warp load indicated a difference; however, the p-value was slightly over the alpha of 0.5 (difference = 0.25 t [-0.003, 0.51] 95% C.I., p-value = 0.055) (Figure 3.5, Supplemental table 3.1)

The traditional footgear experienced significantly higher warp loads in the bosom section for semi-rough and rough seabed conditions, compared to the same conditions for the wing section, with a statistically significant difference of 0.35 t [0.09, 0.61] 95% C.I. (p-value = 0.001) and 0.52 t [0.26, 0.78] 95% C.I. (*p*-value < 0.001), respectively. By comparison, the aligned-rolling footgear showed no significant difference in warp loads between bosom and wing sections, for either the semi-rough seabed (difference = 0.07 t [-0.19, 0.33] 95% C.I., *p*-value = 0.998) or the rough seabed (difference = -0.08 t [-0.34, 0.18] 95% C.I., *p*-value = 0.995) (Figure 3.5, Supplemental table 3.1).

3.5. Discussion

This study documents a novel technique for comparing traditional and experimental footgears using engineering models and simulated seabed conditions in a flume tank. Footgears were qualitatively compared using direct observation and quantitatively assessed by measuring warp load during smooth, semi-rough, and rough seabed conditions. During qualitative observations, the dynamics of the traditional footgear model seemed to mimic very closely the dynamics of the full-scale traditional footgear observed at sea in Araya-Schmidt et al. (2021); the bouncing of the footgear sections over the simulated seabed was realistic compared to the video collected on full-scale trawls at sea. The approach proved helpful for initial prototype validation before proceeding to expensive sea trials, supporting the fishing gear development cycle (Winger et al., 2006). This same approach has been conducted for the development of novel trawl doors (e.g., (Sala et al., 2009)), netting (e.g., (Kebede and Winger, 2020)), and footgear (e.g., (Ball et al., 2003; Grimaldo et al., 2014)).

Results from our flume tank testing revealed that the aligned-rolling footgear substantially reduced the width of contact with the seabed compared to the traditional footgear. These results are encouraging, validating the simple concept that aligning footgear components with the towing direction can substantially reduce seabed contact width. Winger et al. (2018)

found similar results when flume tank testing an aligned (non-rolling) footgear, which reduced the predicted contact width with the seabed by 60% at a modelled penetration depth of 5.08 cm. Similarly, Nguyen et al. (2015a) found reductions in contact width, from traditional to experimental footgear, of 84% and 91% for 9-drop chain and 5-drop chain footgears, respectively (modelled penetration depth = 5.08 cm). While the previous example produced greater reductions in contact width than this study, it is important to note that there is a trade-off between the width of contact and the risk to damage the trawl; an exposed fishing line near a rough seabed with large rocks will likely lead to more trawl damage. Therefore, it is fundamental to consider the seabed type when developing a new footgear.

Our results also revealed a significant reduction in warp load associated with the aligned-rolling footgear compared to the traditional footgear. We attribute the increased drag of the traditional footgear to the larger number of rubber discs and bobbins producing greater sliding friction forces against the seabed, especially rubber discs in the bunt wing sections that are not aligned with the towing direction. By comparison, the aligned-rolling footgear exhibited less drag due to fewer rubber discs, fewer bobbins, and the aligned-rolling wheels. The rolling nature of the wheels meant they experienced mainly rolling friction rather than sliding forces (Fridman, 1986). The reduction in the cross-sectional area experienced by the aligned-rolling footgear presumably reduced hydrodynamic drag and could also have contributed to the overall reduction in warp tension (Fridman, 1986). These results are consistent with Ball et al. (2003), in which a rollerball net (i.e., with aligned wheeled components) reduced towing force by 12% at-sea trials when compared with a traditional design. Previous flume tank experiments with flat moving belts have shown that drag is directly related to towing speed (Fiorentini et al., 2004; Queirolo et al., 2009), which is not our case, where water flow remained constant, and seabed condition was changed during the experiment. However, it would be interesting to understand the effect on drag of several towing speeds using this simulated seabed approach.

Warp loads observed in this study may differ from full-scale warp loads at-sea due to many factors, such as seabed type, wind, current, and swell (Fiorentini et al., 2004; Sala et al., 2009; Nguyen et al., 2015b). However, with the addition of a simulated seabed in flume tank testing, model warp loads for the different seabed conditions provide an approximation of the expected differences in full-scale warp loads from smooth to rough conditions. Fiorentini et al. (2004) found less than 15% difference in warp load between model and full-scale trawl tests for the traditional trawl, but at the same time, large discrepancies for the experimental trawl were observed.

A key limitation of the reported study was the size of the plates. Ideally, the plates would have been large enough to cover the entire width of the trawl path, which would present a more realistic scenario and produce greater warp load differences between the footgears. Unfortunately, we needed to make trade-offs concerning safety, ease of deployment, and potential damage to the facility. We also recognize that the rocks in our study were permanently glued to the plates, whereas rocks on the seabed are commonly displaced by bottom trawls during full-scale fishing operations. For example, Freese et al. (1999) found that tire footgear, designed to bounce over the objects, displaced 19% of the boulders with a median size of 0.75 m in the trawl pathway. It would be of value to measure rock displacement by the aligned-rolling footgear. However, it is expected that traditional footgear would produce more rock and seabed material displacement when compared to aligned-rolling footgear. This was proven by Ball et al.

(2003), where rollerball footgear reduced seabed debris material in the trawl net by 66% during sea trials. Experimental bottom fishing studies have shown that fishing gears that penetrate deeper in the sediment will increase depletion in abundance and produce a slower recovery to control conditions of the benthic community (Sciberras et al., 2018). We hypothesize that full-scale aligned-rolling footgear, due to its aligned and rolling capacities, will reduce sliding forces and width of seabed contact, thus reducing penetration depth in the seabed during commercial operations.

An aligned-rolling footgear with reduced width of seabed contact, drag, and penetration depth would be beneficial for the fishing industry and ecosystem; it could potentially reduce seabed impact and fuel consumption, including CO_2 emissions. Not only fisheries managers are concerned about the consequences of fishing on the ecosystem, but also consumers prefer sustainable seafood certified by different organizations (Grieve et al., 2015; Kaiser et al., 2016). An aligned-rolling footgear technology could aid in the certification of a fishery as sustainable, reducing ecosystem impacts, improving acceptance of seafood products, and increasing the profit of the fishing activity.

3.6. Conclusions

This study documents a novel technique for comparing traditional and experimental footgears using engineering models and simulated seabed conditions in a flume tank. We show that an innovative aligned-rolling footgear performed well over smooth, semi-rough, and rough seabed conditions. The new footgear exhibited significantly lower warp loads compared to traditional footgear and is predicted to produce drastically lower contact with the seabed. Reduced drag was attributed to a reduction in contact points, alignment with towing direction, and rotation of the footgear components, replacing most of the sliding friction by rolling friction forces.

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3.9. Tables

Table 3.1. Studies that measured seabed penetration depth (cm) at-sea of bottom trawls in mud, sand, and gravel.

Study	Components measured	Penetration depth (cm) in: Mud	Sand	Gravel
(Smith et al., 2003)	Whole trawl (Ø not reported)	7-10	0.01-1.6	
(van Marlen et al., 2010)	40.6/45.7 cm Ø rockhopper discs	2.8		
	40.6 cm Ø bobbins	3.46		
(Freese et al., 1999)	0.6 cm Ø tires/0.45 cm Ø rockhopper discs			1-8
(Schwinghamer et al., 1996)	Rockhopper discs (Ø not reported)		4-5	

Table 3.2. Observed mean warp loads (t) and standard error of the mean (SEM) for the traditional and aligned-rolling footgears in smooth, semi-rough, and rough seabed conditions in the bosom and wing section. Warp load reduction (t) from Tukey HSD and percentage reduction in warp load are shown.

	Warp load (t) (SEM)					
	Bosom			Wing		
Footgear	Smooth	Semi rough	Rough	Smooth	Semi rough	Rough
Aligned	12.58 (0.07)	12.68 (0.08)	12.83 (0.01)	12.55 (0.02)	12.75 (0.02)	12.75 (0.05)
Traditional	12.84 (0.05)	13.36 (0.05)	13.57 (0.03)	12.92 (0.09)	13.00 (0.05)	13.05 (0.06)
Warp load reduction (t)	0.26	0.68	0.74	0.38	0.25	0.30
Warp load reduction (%)	2.02%	5.08%	5.45%	2.92%	1.95%	2.33%

Table 3.3. Seabed contact (m), seabed contact percentage (%) with respect to the total footgear width, and contact reduction (%) for the traditional and aligned-rolling footgear in modelled penetration depths of 1, 4, 7, 10, and 13 cm.

Modelled penetration depth (cm)	Seabed contact (m)		Seabed contact (%)		Contact reduction (%)
	Traditional	Aligned	Traditional	Aligned	
1	3.8	9.8	9.4%	24.6%	61.8%
4	4.9	16.0	12.3%	42.3%	69.4%
7	5.4	18.6	13.6%	46.5%	70.8%
10	5.7	19.8	14.4%	49.5%	71.0%
13	6.1	21.4	15.3%	53.5%	71.5%

Table 3.4. Three-way ANOVA table for warp load (t) of aligned-rolling and traditional footgears for smooth, semi-rough, and rough seabed conditions in the bosom and wing sections.

Effect	Degrees of freedom numerator	Degrees of freedom denominator	F statistic	*p*-value	Generalized eta squared
Section	1	48	20.364	<0.001	0.298
Seabed	2	48	39.973	<0.001	0.625
Footgear	1	48	203.946	<0.001	0.809
Section:Seabed	2	48	9.343	0.000374	0.28
Section:Footgear	1	48	16.433	0.000184	0.255
Seabed:Footgear	2	48	3.937	0.026105	0.141
Section:Seabed:Footgear	2	48	8.966	0.000491	0.272

3.10. Figures

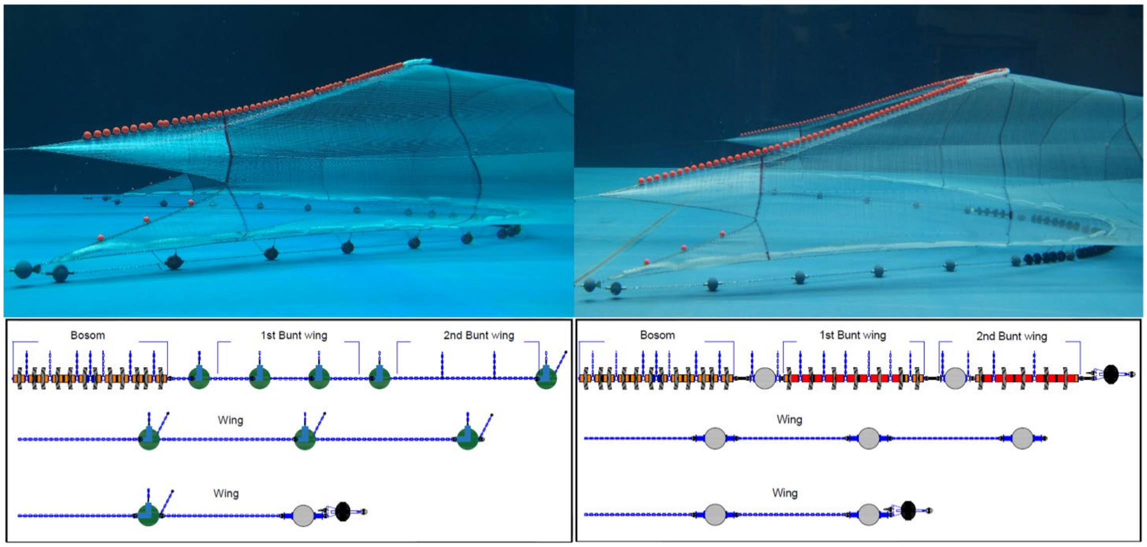

Figure 3.1. Aligned-rolling (left) and traditional roller footgears (right). Bosom section and one side of bunt wing and wing sections are shown for the footgears. Aligned-rolling wheels are shown in green.

Figure 3.2. Schematic drawing of the full-scale prototype of an aligned-rolling wheel in SolidWorks.

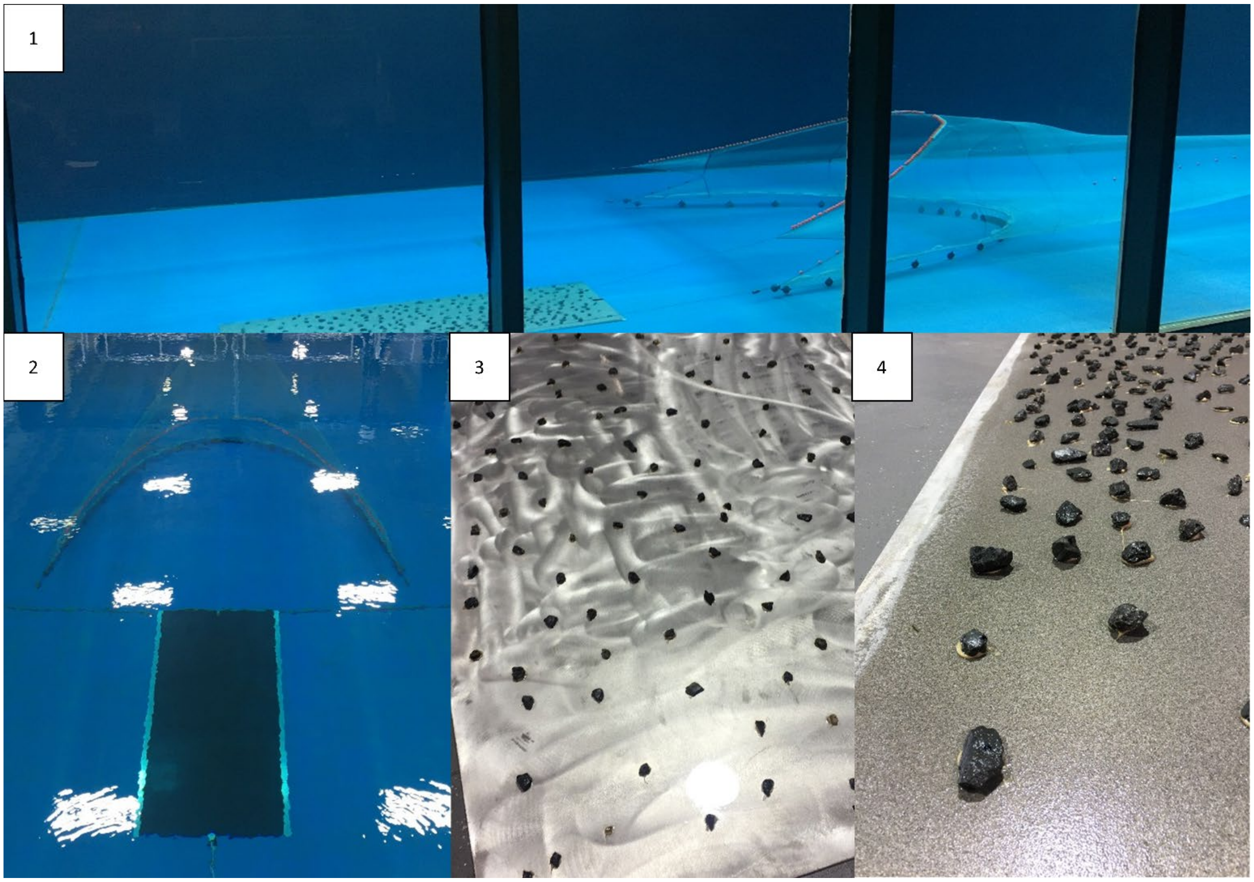

Figure 3.3. (1) Bottom trawl with aligned-rolling footgear during flume tank testing with the rough plate in the wing section. (2) Bottom trawl with aligned-rolling footgear during flume tank testing with the control plate in the bosom section. (3) Close-up view of the semi-rough and (4) rough seabed conditions.

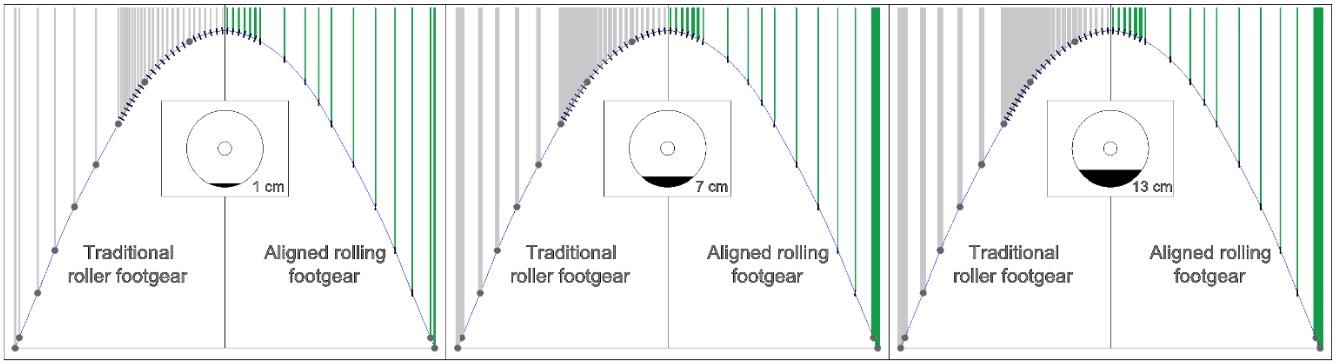

Figure 3.4. Area of seabed contact comparison for traditional and aligned-rolling footgear at three modeled pathway depths (1, 7, and 13 cm). Left drawing shows contact area for the traditional footgear (grey = 24.6%) and aligned-rolling footgear (green = 9.4%) at a modeled pathway depth of 1 cm. Middle drawing shows contact area for the traditional footgear (grey = 46.5%) and aligned-rolling footgear (green = 13.6%) at a modeled pathway depth of 7 cm. Right drawing shows contact area for the traditional footgear (grey = 53.5%) and aligned-rolling footgear (green = 15.3%) at a modeled pathway depth of 13 cm. Lateral view of rubber discs at the different penetration depths are shown for each drawing.

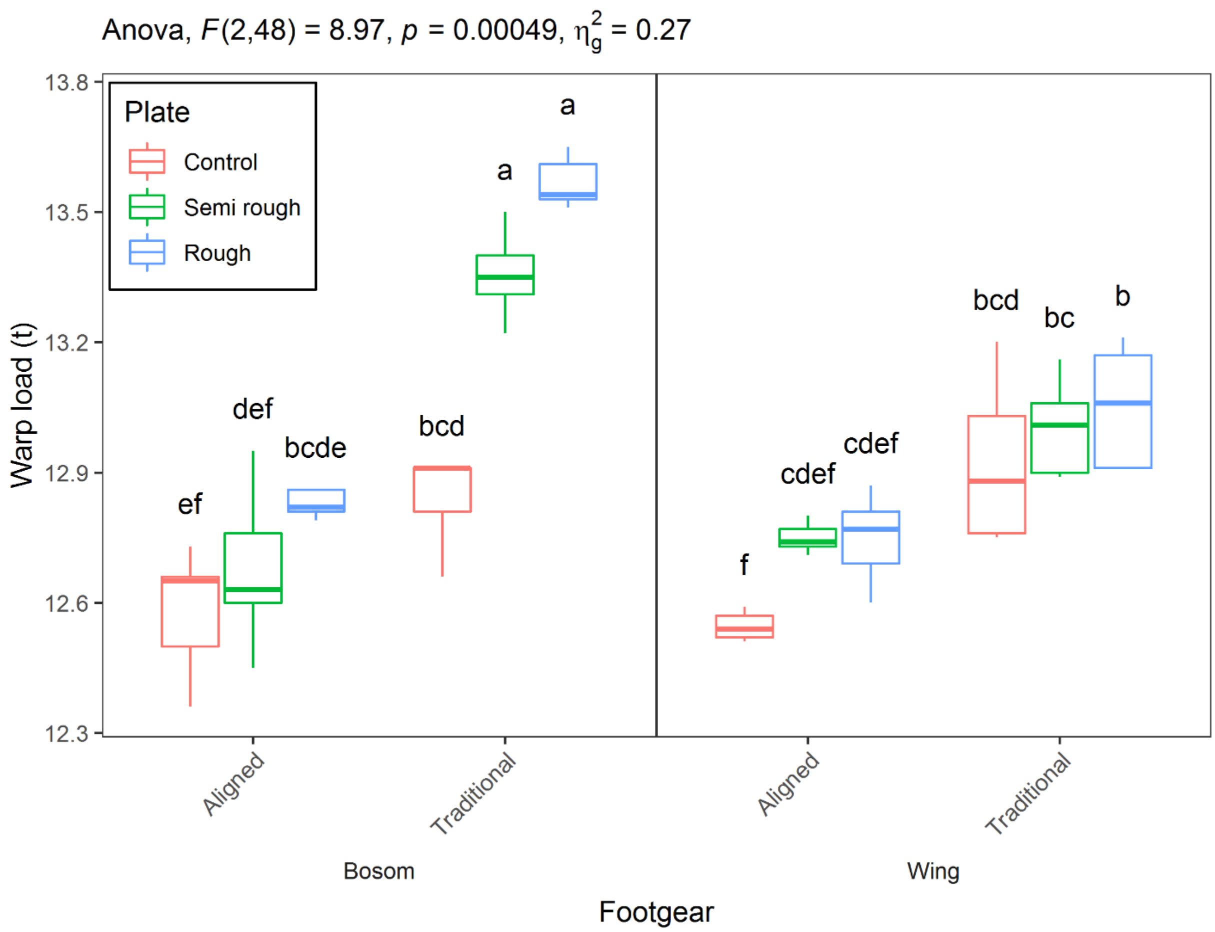

Figure 3.5. Boxplot of warp load for the aligned-rolling and traditional footgears with control, semi-rough, and rough seabed conditions in the bosom and wing footgear sections. Colours represent control, semi-rough, and rough seabed conditions. The horizontal line in the middle of the boxes represents the median load. The lower and upper limit of the boxes shows the first and third quartile, respectively. Lower and upper whiskers represent scores outside the interquartile range. Significant three-way interaction statistics are shown in the upper section. Tukey's HSD compact letter display on top of the boxes are showing which group means are significantly different from each other.

3.11. Appendices

Supplemental table 3.1. Tukey HSD comparisons with difference in warp load (t), lower and upper 95% Confidence intervals (C.I.) and *p*-values are in black.

Comparison	Difference (t)	Lower 95% C.I.	Upper 95% C.I.	*p*-value
Wing:Control:Aligned-Bosom:Control:Aligned	-0.03	-0.29	0.22	1.000
Bosom:Semi rough:Aligned-Bosom:Control:Aligned	0.10	-0.16	0.35	0.974
Wing:Semi rough:Aligned-Bosom:Control:Aligned	0.17	-0.09	0.43	0.507
Bosom:Rough:Aligned-Bosom:Control:Aligned	0.25	-0.01	0.50	0.067
Wing:Rough:Aligned-Bosom:Control:Aligned	0.17	-0.09	0.42	0.525
Bosom:Control:Traditional-Bosom:Control:Aligned	0.26	0.00	0.52	**0.044**
Wing:Control:Traditional-Bosom:Control:Aligned	0.34	0.09	0.60	**0.002**
Bosom:Semi rough:Traditional-Bosom:Control:Aligned	0.78	0.52	1.03	**<0.001**
Wing:Semi rough:Traditional-Bosom:Control:Aligned	0.42	0.17	0.68	**<0.001**
Bosom:Rough:Traditional-Bosom:Control:Aligned	0.99	0.73	1.24	**<0.001**
Wing:Rough:Traditional-Bosom:Control:Aligned	0.47	0.22	0.73	**<0.001**
Bosom:Semi rough:Aligned-Wing:Control:Aligned	0.13	-0.12	0.39	0.827
Wing:Semi rough:Aligned-Wing:Control:Aligned	0.20	-0.05	0.46	0.243
Bosom:Rough:Aligned-Wing:Control:Aligned	0.28	0.03	0.54	**0.020**
Wing:Rough:Aligned-Wing:Control:Aligned	0.20	-0.05	0.46	0.256
Bosom:Control:Traditional-Wing:Control:Aligned	0.29	0.04	0.55	**0.013**
Wing:Control:Traditional-Wing:Control:Aligned	0.38	0.12	0.63	**<0.001**
Bosom:Semi rough:Traditional-Wing:Control:Aligned	0.81	0.55	1.07	**<0.001**
Wing:Semi rough:Traditional-Wing:Control:Aligned	0.46	0.20	0.71	**<0.001**
Bosom:Rough:Traditional-Wing:Control:Aligned	1.02	0.77	1.28	**<0.001**
Wing:Rough:Traditional-Wing:Control:Aligned	0.51	0.25	0.76	**<0.001**
Wing:Semi rough:Aligned-Bosom:Semi rough:Aligned	0.07	-0.18	0.33	0.998
Bosom:Rough:Aligned-Bosom:Semi rough:Aligned	0.15	-0.11	0.41	0.686
Wing:Rough:Aligned-Bosom:Semi rough:Aligned	0.07	-0.19	0.33	0.998
Bosom:Control:Traditional-Bosom:Semi rough:Aligned	0.16	-0.09	0.42	0.579
Wing:Control:Traditional-Bosom:Semi rough:Aligned	0.25	-0.01	0.50	0.071
Bosom:Semi rough:Traditional-Bosom:Semi rough:Aligned	0.68	0.42	0.93	**<0.001**
Wing:Semi rough:Traditional-Bosom:Semi rough:Aligned	0.33	0.07	0.58	**0.004**
Bosom:Rough:Traditional-Bosom:Semi rough:Aligned	0.89	0.63	1.15	**<0.001**
Wing:Rough:Traditional-Bosom:Semi rough:Aligned	0.37	0.12	0.63	**<0.001**

Bosom:Rough:Aligned-Wing:Semi rough:Aligned	0.08	-0.18	0.33	0.996
Wing:Rough:Aligned-Wing:Semi rough:Aligned	0.00	-0.26	0.25	1.000
Bosom:Control:Traditional-Wing:Semi rough:Aligned	0.09	-0.17	0.35	0.986
Wing:Control:Traditional-Wing:Semi rough:Aligned	0.17	-0.08	0.43	0.472
Bosom:Semi rough:Traditional-Wing:Semi rough:Aligned	0.61	0.35	0.86	**<0.001**
Wing:Semi rough:Traditional-Wing:Semi rough:Aligned	0.25	-0.003	0.51	0.055
Bosom:Rough:Traditional-Wing:Semi rough:Aligned	0.82	0.56	1.07	**<0.001**
Wing:Rough:Traditional-Wing:Semi rough:Aligned	0.30	0.05	0.56	**0.009**
Wing:Rough:Aligned-Bosom:Rough:Aligned	-0.08	-0.34	0.18	0.995
Bosom:Control:Traditional-Bosom:Rough:Aligned	0.01	-0.24	0.27	1.000
Wing:Control:Traditional-Bosom:Rough:Aligned	0.10	-0.16	0.35	0.977
Bosom:Semi rough:Traditional-Bosom:Rough:Aligned	0.53	0.27	0.78	**<0.001**
Wing:Semi rough:Traditional-Bosom:Rough:Aligned	0.18	-0.08	0.43	0.454
Bosom:Rough:Traditional-Bosom:Rough:Aligned	0.74	0.48	1.00	**<0.001**
Wing:Rough:Traditional-Bosom:Rough:Aligned	0.22	-0.03	0.48	0.141
Bosom:Control:Traditional-Wing:Rough:Aligned	0.09	-0.16	0.35	0.984
Wing:Control:Traditional-Wing:Rough:Aligned	0.18	-0.08	0.43	0.454
Bosom:Semi rough:Traditional-Wing:Rough:Aligned	0.61	0.35	0.86	**<0.001**
Wing:Semi rough:Traditional-Wing:Rough:Aligned	0.26	0.00	0.51	0.051
Bosom:Rough:Traditional-Wing:Rough:Aligned	0.82	0.56	1.08	**<0.001**
Wing:Rough:Traditional-Wing:Rough:Aligned	0.30	0.05	0.56	**0.009**
Wing:Control:Traditional-Bosom:Control:Traditional	0.08	-0.17	0.34	0.992
Bosom:Semi rough:Traditional-Bosom:Control:Traditional	0.52	0.26	0.77	**<0.001**
Wing:Semi rough:Traditional-Bosom:Control:Traditional	0.16	-0.09	0.42	0.561
Bosom:Rough:Traditional-Bosom:Control:Traditional	0.73	0.47	0.98	**<0.001**
Wing:Rough:Traditional-Bosom:Control:Traditional	0.21	-0.04	0.47	0.197
Bosom:Semi rough:Traditional-Wing:Control:Traditional	0.43	0.18	0.69	**<0.001**
Wing:Semi rough:Traditional-Wing:Control:Traditional	0.08	-0.18	0.34	0.995
Bosom:Rough:Traditional-Wing:Control:Traditional	0.64	0.39	0.90	**<0.001**
Wing:Rough:Traditional-Wing:Control:Traditional	0.13	-0.13	0.38	0.853
Wing:Semi rough:Traditional-Bosom:Semi rough:Traditional	-0.35	-0.61	-0.10	**0.001**
Bosom:Rough:Traditional-Bosom:Semi rough:Traditional	0.21	-0.04	0.47	0.197
Wing:Rough:Traditional-Bosom:Semi rough:Traditional	-0.30	-0.56	-0.05	**0.009**
Bosom:Rough:Traditional-Wing:Semi rough:Traditional	0.56	0.31	0.82	**<0.001**
Wing:Rough:Traditional-Wing:Semi rough:Traditional	0.05	-0.21	0.30	1.000
Wing:Rough:Traditional-Bosom:Rough:Traditional	-0.52	-0.77	-0.26	**<0.001**

CHAPTER 4. Smaller bar spacings in a Nordmøre grid reduces the bycatch of redfish (*Sebastes spp.*) in the offshore Northern shrimp (*Pandalus borealis*) fishery of eastern Canada

4.1. Abstract

The offshore Northern shrimp (*Pandalus borealis*) bottom trawl fishery in eastern Canada currently uses 22 and 28 mm bar spacing Nordmøre grids to limit bycatch from using small mesh codends. However, a recent rebound of juvenile redfish (*Sebastes spp.*), that can pass through the grids, has greatly increased bycatch. To address this concern, this study investigated the effectiveness of 17 and 15 mm bar spacing Nordmøre grids in a twin-trawl (paired) configuration against the traditional 22 mm bar spacing grid. Size selectivity analyses showed that the 17 and 15 mm grids resulted in no significant reduction in shrimp catch across all length classes. The 17 mm grid significantly reduced redfish bycatch for all length classes and the 15 mm grid significantly reduced redfish bycatch for individuals larger than 95 mm total length. Less redfish entered the codend with the experimental grids. However, the overlap in width between redfish and Northern shrimp limits the overall sorting efficiency of the grids, leaving some redfish still vulnerable to capture.

4.2. Introduction

Bottom trawls targeting shrimp usually use small mesh codends, which often result in considerable amounts of bycatch of juvenile fish from commercially important species (Kelleher, 2005; Bayse and He, 2017). Extensive efforts have been made around the world to reduce shrimp fisheries bycatch (Broadhurst, 2000; Eayrs, 2005), including the use of Nordmøre grids (Isaksen et al., 1992), which are employed to mechanically separate shrimp from larger animals. However, bycatch is an issue that persists in many shrimp fisheries because juvenile fish often have a similar size as the target species, can pass through the bar spacings, and are retained in the small mesh codend.

The offshore Northern shrimp (*Pandalus borealis*) bottom trawl fishery in eastern Canada is currently facing an increase in bycatch of juvenile redfish (*Sebastes spp.*) (DFO, 2020). Juvenile redfish biomass and recruitment (redfish < 150 mm in total length) have increased considerably in recent years (DFO, 2020) and fishing vessels are encountering substantial quantities of juvenile redfish in their catches. Bottom trawls in this fishery are constructed with a small mesh size in order to retain shrimp; a minimum of 40 mm mesh size is authorized throughout the bottom trawl (DFO, 2018), therefore a reduction in the unwanted catch of groundfish species is achieved through the mandatory use of a bycatch reduction device (BRD) known as the Nordmøre grid (Isaksen et al., 1992). The Nordmøre grid was introduced in the Canadian shrimp fishery in 1993 and made mandatory in 1997, with maximum bar spacings of 22 and 28 mm depending on the fishing area (DFO, 2018), although the majority of the fishing effort uses 22 mm bar spacing (Newfound Resources Ltd. pers. comm.). Previous work has indicated that there was no difference in shrimp catch between 22 and 28 mm bar spacings in Shrimp Fishing Area (SFA) 6 (Hickey et al., 1993; CAFID, 1997). However, when larger shrimp are captured (which can be typical in SFA 4 and 5), the 22 mm bar spacing was shown to reduce shrimp catch (Orr, 2018). In the 1990s, the use of the Nordmøre grid greatly lessen bycatch in Canada's east coast shrimp fisheries, reducing finfish bycatch from 15% to 2% (> 85% reduction by weight) of the total landings of shrimp (ICES, 1998). However, redfish exclusion was still problematic at the regulated bar spacings (ICES, 1996) as juvenile redfish are small and can transit to the codend instead of being excluded at the grid, thus fishing vessels can encounter large amounts of this species in their catch depending on the juvenile redfish abundance in the fishing area.

There are three species of redfish off the northeast coast of Canada; beaked redfish (*Sebastes mentella*) and Acadian redfish (*S. fasciatus*) are commercially important species, while golden redfish (*S. norvegicus*) is found in smaller abundance (Government of Canada, 2021). They are long-lived and have slow growth rates (Campana et al., 1990), maturing at a size of 22 - 24 cm for *S. fasciatus* and *S. norvegicus* (Sévigny et al., 2007), and grow up to 38 - 39 cm (total length) for *S. mentella* (Magnússon and Magnússon, 1995). Both of the main commercial species of redfish were considered threatened under the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2010, and are currently being considered for Schedule 1 classification (Government of Canada, 2021). Therefore, the mortality of juvenile redfish is of concern and could have a negative impact on the stock's recruitment, biomass, recovery and the future of an emerging redfish fishery, as well as an impact on the trophic structures of communities, affecting other important commercial fisheries (Dayton et al., 1995; Devine and Haedrich, 2011).

Recently, conditions of licence have permitted up to 2.5% or 100 kg total weight of incidental catch of groundfish species per tow (DFO, 2018). When the greater of 2.5% or 100 kg is exceeded, a move-away protocol is triggered, and the vessel must change the fishing area by a minimum of 10 nautical miles from the last tow (DFO, 2018). Thus, vessels are potentially forced to leave shrimp-abundant fishing areas and move to potentially less lucrative areas. This can increase time-at-sea and fuel consumption, which in turn increases the operational costs for the fishing fleet and carbon dioxide emissions. Furthermore, increased amounts of juvenile fish bycatch can reduce shrimp quality and represent a sorting problem in the processing of the shrimp in the onboard factory.

Extensive research has previously been conducted on sorting grids in response to ecological and operational challenges, as well as to reduce the catch of small or undersized shrimp, including bar spacing experiments (Hickey et al., 1993; CAFID, 1997; Orr, 2018; He and Balzano, 2012; Silva et al., 2012), new grid designs (Grimaldo and Larsen, 2005; Grimaldo, 2006; He and Balzano, 2007, 2011, 2013; Veiga-Malta et al., 2020) and sorting grid configurations (Riedel and DeAlteris, 1995; Larsen et al., 2018b). However, reducing bar spacing and its potential to reduce juvenile redfish bycatch has not yet been fully assessed. Northern shrimp carapace width (CW) is about 50% of its carapace length (CL) (He and Balzano, 2012), hence even large shrimp with 30 mm CL and 15.05 mm CW have a high probability of passing through the 22 and 28 mm bar spacing grids currently in use. This represents an opportunity to further reduce bar spacing without, in theory, significantly affecting shrimp catches across larger length classes. Yet, mechanical separation alone may not reduce the catch of all juvenile redfish sizes. The size range (body width) of juvenile redfish can overlap the size range (carapace width) of Northern shrimp, therefore the Nordmøre grid is not the ultimate solution, but it could reduce the capture of redfish sizes that do not overlap and still greatly reduce bycatch.

This study compared the size-selectivity of experimental 17 and 15 mm bar spacing Nordmøre grids against the traditional 22 mm bar spacing Nordmøre grid for Northern shrimp and redfish onboard an offshore factory freezer trawler during commercial fishing operations using the catch comparison method (Wileman et al., 1996). It builds upon previous bar spacing experiments in Canadian waters (Hickey et al., 1993; CAFID, 1997; Orr, 2018). Our objective was to investigate if smaller bar spacings could reduce the incidental bycatch of juvenile redfish while maintaining the catch of targeted Northern shrimp. A reduction in redfish bycatch could alleviate the operating pressures for the fishery when fishing in areas with an abundance of redfish, while also reducing the fishery's impact on redfish biomass. Furthermore, we assessed which Northern shrimp and redfish body-width-size classes overlapped and would mechanically fit between grid bar spacings and developed the morphometric relationships between commonly measured indices for shrimp (carapace length) and redfish (total length) to body width, which likely has more of a direct effect on sorting at the grid. Finally, the grid systems were separately video recorded during fishing with underwater cameras to assess their performance in terms of guiding panel shape, the general movement of species, flow to the grid, and obstruction of the grid.

4.3. Methods

4.3.1. At-sea trials

Comparative fishing was carried out in SFA 4 and 5 (Figure *4.1*) onboard the commercial factory freezer trawler *Newfoundland Victor* (length 79 m, width 16.6 m, gross tonnage 4,642 t) between May 9 and June 5th, 2021. The catch comparison method (Wileman et al., 1996) was used with a side-by-side twin-trawling setup to compare a traditional 22 mm bar spacing Nordmøre grid against 17 (trial 1) and 15 mm (trial 2) experimental Nordmøre grids. Comparison of the 17 and 22 mm grids took place in SFA 4, while the comparison of the 15 and 22 mm grids took place in SFA 5 (Figure *4.1*). Position, tow duration, depth and bottom water temperature were recorded for each of the paired tows (Table *4.1*). Headline height, door spread, and grid angles were monitored during twin trawling to ensure comparable trawl geometry in traditional and experimental trawls. Headline height ranged between 8 and 10 m, door spread between 120 and 140 m, and grid angles between 50° and 53°. Tows that had damage to the trawls, gear entanglement, or gear malfunction were not sampled and excluded from the experiment.

4.3.2. Fishing gear

Two Vónin 3440 mesh commercial Northern shrimp bottom trawls were used for the study. They had 71 m headlines, 75.2 m fishing lines, and 75 m roller footgears. The trawls had a four-panel design and were each equipped with a trouser codend with a 40 mm nominal mesh size. Following Fonteyne (2005) procedures, codend meshes were measured in both bottom trawls using an OMEGA gauge to ensure they were identical. The starboard trawl had a mean mesh size of 41.68 mm (standard error of the mean (SEM) 0.16 mm) and the port trawl had a mean mesh size of 41.43 mm (SEM 0.22 mm). The trawling system was towed using a pair of 14 m^2 trawl doors and a center clump (10,000 kg). See Montgomerie (2015) for a further description of twin trawling. Experimental Nordmøre grids with 17 and 15 mm bar spacings were manufactured by Selector Systems Inc. and assembled into full-scale grid systems by Vónin Canada Ltd. for comparison against the traditional 22 mm bar spacing grid currently used by industry and the fishing vessel. Experimental grids were designed and constructed according to the current configuration used by the fishing vessel to have identical traditional and experimental trawls, except for the Nordmøre grid's bar spacing. The traditional bottom trawl was equipped with a nominal 22 mm (mean 21.14 mm, SEM 0.34 mm) bar spacing Nordmøre grid, while the experimental bottom trawls were equipped with a nominal 17 mm (mean 17.10 mm, SEM 0.07 mm) and a nominal 15 mm (mean 14.68 mm, SEM 0.08 mm) bar spacing Nordmøre grids (Figure 4.2).

Grids were constructed of high-density polyethylene (HDPE) and had a total area of 5.1 m^2. Bar thickness was 9.81 mm for all grids. Area coefficients, also known as grid porosity (the ratio of the area of effective filtration/total area where 1.0 is solid) were 0.57, 0.53 and 0.50 for the 22, 17, and 15 mm bar spacing grids, respectively, which also can be considered as the solid area increased 9.3% for the 17 mm grid and 16.3% for the 15 mm grid when compared to the 22 mm grid. The 22 mm bar spacing grid had 64 bars, while the 17 and 15 mm grids had 74 and 81 bars, respectively.

4.3.3. Sampling procedure

The trawl nets were hauled back when the catch sensors mounted in the trawl codends were approximately 10,000 kg. Once the codends reached the vessel, the traditional and experimental trawl catches were transferred separately to the below deck compartments for onboard processing. In the factory, 500 shrimp were randomly sampled and measured to the nearest 0.5 mm CL and 300 redfish were randomly sampled and measured to the nearest 1 mm total length (TL) for the traditional and experimental trawls (1,000 shrimp and 600 redfish measured in total, per haul), using digital calipers (ABSOLUTE Coolant Proof Caliper Series 500, Aurora, Illinois, USA) connected to a laptop. Total weights were obtained for both shrimp and redfish samples. All redfish were collected in the factory in baskets at various locations (holding tank, bycatch separator, and picking belts), and then weighed to obtain the total redfish catch for each trawl. Total shrimp catch was calculated from the total shrimp production from each of the below-deck compartments (traditional or experimental) that were processed separately for this purpose.

For the morphometric analysis, 246 shrimp were sampled; their CL and CW were measured to the nearest 0.01 mm, and their maturity stage (i.e., ovigerous or non-ovigerous) was recorded. For redfish, 350 individuals were sampled; their body width (BW) (measured at the endpoint of each operculum) and TL were measured to the nearest 0.01 mm (Figure *4.3*). Measurements were performed with digital calipers (ABSOLUTE Coolant Proof Caliper Series 500, Aurora, Illinois, USA) connected to a laptop.

4.3.4. Statistical analysis

All statistical analyses were performed using R statistical software (R Core Development Team 2015). Size selectivity data was analyzed with the package selfisher (Brooks et al., In press) using the catch comparison method (both gears are selective; Wileman et al., 1996). The relative retention probability was modelled using a generalized linear model of the proportion of individuals caught in the experimental and traditional gear as a function of length class (Holst and Revill 2009). The logit [experimental/(experimental + traditional)] of the catches-at-length were estimated by low-order polynomials (degree 1–4)) and splines (3-5 degrees of freedom), using ns function in the splines package. Due to large catch sizes, a subsampling ratio was used as an offset in the model (Holst and Revill, 2009). If the retention was 0.5, then there was no difference in catch between treatments at the particular length class. If 0.75, then 75% of the catch-at-length was captured by the experimental and 25% by the traditional; if 0.25, then 25% of the catch-at-length was captured by the experimental and 75% by the traditional. Model fit was investigated following Wileman et al. (1996) and Brooks et al. (2020) procedures.

The catch ratio analysis (Sistiaga et al., 2015) was used to give a direct relative value of catch efficiency between the traditional and experimental trawls using the formula, $cr = cc/(1 - cc)$, where cr is the catch ratio and cc is the catch comparison rate. A cr of 1.0 means that there is no difference in the catch between the traditional and experimental trawl at a particular length class, 0.75 means that the experimental trawl catches 75% of the number of individuals as the traditional at a particular length class, and 1.5 means that the experimental catches 50% more than the traditional at a particular length class.

Model selection was based on the model with the lowest AIC (Akaike, 1974), using the function AICtab in the bbmle package (Bolker and R Development Core Team, 2020). Confidence intervals for catch comparison and catch ratio curves were generated using the bootSel function of the selfisher package, where 95% Efron confidence intervals (CIs; Efron, 1982) were generated by 1,000 bootstrap simulations that account for within- and between-tow variation (Millar, 1993). For relative retention probability, if 0.5 was contained within the CIs then there was no difference between treatments. For catch ratio, if 1.0 was contained within the CIs then there was no difference between treatments.

Morphometric relationships between shrimp CL and CW, and between redfish TL and BW were estimated using linear regression analyses. Detrended normal Q-Q plots of the residuals, known as worm plots (Rigby and Stasinopoulos, 2010), were used in the gamlss package (Rigby and Stasinopoulos, 2005) to determine model distribution adequacy.

A correlation test was performed in the ggpubr package (Kassambara, 2020) to test if redfish size and depth were correlated. Redfish lengths were averaged for each of the tows using the traditional trawl (n = 20 total) at each depth. Data were not normally distributed; thus, Kendall's rank correlation test was used (Kendall, 1938).

4.3.5. Underwater video

Due to the possibility of altering species behaviour with the lights used during underwater video, only video of the grids during non-experimental tows (i.e., tows not used in the catch comparison analysis) was collected. The self-contained underwater camera system consisted of a GoPro hero 4 black action camera, with a GoPro "Bacpac" battery, and an external battery (4,000 mAh, 3.7 V) similar to those described by Madsen et al. (2021). The external battery was plugged into a Powerboost (Adafruit industries) and then into the GoPro camera with a 90-degree USB cable. This allowed the camera to simultaneously charge while recording video with 1,000 mAh and 5.0 V until the external battery was drawn. Two DIV08W diving lights from Brinyte Technology Ltd. were used to illuminate the camera field of view. These 120 degrees LED diving lights (luminous intensity of 629 cd) were capable of producing red light (350 lumens). An internal LC 26650, 5,000 mAh and 3.7V battery was used to power the lights. Underwater housings from Group B Distribution Inc. were used (certified to a depth of 1,500 m) for the camera and lights. The system was similar to the one used by Araya-Schmidt et al. (2021). A plate was designed to hold the camera and lights, which was mounted on the grid's upper edge looking down at the grid, and on the upper panel before the grid looking back at the grid (Figure 4.2). The video was qualitatively observed to obtain information on guiding panel shape, the general movement of species and flow to the grid, and any obstruction of the grid. Tows containing the underwater camera system were not sampled for size-selectivity as red light could affect shrimp behaviour (Ingólfsson et al., 2021)

4.4. Results

4.4.1. Catch data

A total of 10 paired tows were carried out for each traditional versus experimental Nordmøre grid trial (a total of 20 tows for both experiments;

Table 4.2). Total shrimp catch ranged between 2,964 and 5,827 kg for the 22 mm grid in trial 1, while the 17 mm grid total shrimp catch ranged between 3,260 and 7,073 kg. Redfish total catch ranged between 86.6 and 961.8 kg for the 22 mm grid, and between 69.5 and 583 kg for the 17 mm grid. Furthermore, redfish bycatch ranged between 1.93 and 24.03% for the 22 mm grid, and between 1.56 and 15.08% for the 17-mm grid in trial 1 (

Table 4.2), with an overall 27.7% (± 5.4% SEM) mean bycatch reduction.

In one tow during trial 1, the 22 and 17 mm Nordmøre grid bottom trawls caught in total ~ 7,000 kg of juvenile redfish (visually estimated), with visibly no shrimp in the catch and no noticeable difference in the amount of redfish between traditional and experimental codends. The catch was transferred to the below deck compartments separately but could not be sampled due to the large amount of redfish and was rapidly discarded to continue with the experimental twin-trawling.

For trial 2, shrimp total catch ranged between 2,582 and 9,630 kg for the 22 mm grid, while the 15 mm grid caught between 2,658 and 10,982 kg of shrimp. Redfish total catch ranged between 43.7 and 493.3 kg for the 22 mm grid, and between 41.7 and 310 kg for the 15 mm grid. Additionally, redfish bycatch ranged between 0.85 and 14.95% for the 22 mm grid, and between 0.52 and 8.81% for the 15 mm grid in trial 2 (

Table 4.2), with an overall 23.6% (± 4.4% SEM) mean bycatch reduction.

A total of 10,000 shrimp and 6,000 redfish were measured for each trial. Shrimp sub-sampling ratios, for the trials, ranged between 0.000091 and 0.000387, and redfish sub-sampling ratios ranged between 0.001039 and 0.023980 (

Table 4.2). Length classes that had < 10 individuals were removed before modelling. Except for the 15 versus 22 mm redfish model, all models were overdispersed. However, the residuals showed no patterns, suggesting that the models adequately described the data.

4.4.2. Trial 1: 17 versus 22 mm Nordmøre grids

For Northern shrimp, most retained proportions were within close proximity (~0.05) of the 0.5 line indicating no catch difference (Figure 4.4). Following the AIC criterion, the best size selectivity model was the logit-linear (Figure 4.4, Table *4.3*), which had a slight increasing slope for both the proportion retained and the catch ratio. Confidence intervals showed that there was no statistically significant difference in retention probability or catch ratio across all length classes. Most redfish retained proportions were below the 0.5 line, and the best model was the logit-constant that was entirely below the 0.5 line (Table *4.3*). Confidence intervals showed that the 17-mm bar spacing grid caught significantly fewer redfish for all length classes (Figure 4.4). Size classes of shrimp (n=6) and redfish (n=19) with less than ten individuals were removed from the statistical analysis.

4.4.3. Trial 2: 15 versus 22 mm Nordmøre grids

Most retained proportion values were close to or on the 0.5 line of no catch difference for Northern shrimp (Figure *4.5*). For the proportion retained and catch ratio, the best model was the logit-constant located slightly above the 0.5 line (Table *4.3*). For both, CIs did not contain the 0.5

or 1.0 line indicating no catch difference, showing that the 15 mm grid caught slightly more shrimp across all length classes (Figure *4.5*). Redfish retained proportion values decreased with larger redfish lengths (Figure *4.5*). The best size selectivity model was the logit-linear (Table 4.3), and for proportion retained and catch ratio, CIs showed that the traditional gear captured more redfish for length classes > 95 mm with no difference for lengths < 95 mm (Figure *4.5*). Size classes of shrimp (*n*=7) and redfish (*n*=9) with less than ten individuals were removed from the statistical analysis.

4.4.4. Morphometric relationship between length and width

Shrimp CL ranged between 19.25 and 28.99 mm, while CW ranged between 9.34 and 15.50 mm, for the 246 sampled individuals. Ovigerous females were observed and had a CL of 22.94 mm or larger, while non-ovigerous shrimp were observed across all size ranges. Results showed that the relationship between CW and CL is CW=0.54103*CL-0.76722 and the estimated regression line reached just below the 15 mm CW intersection point (Figure *4.6*). The large majority of the individuals sampled had a CW smaller than 15 mm (Figure *4.6*).

Redfish TL ranged between 74.69 and 145.59 mm, while BW ranged between 8.62 and 19.03 mm, for the 350 sampled individuals. The linear regression relationship between redfish BW and TL is BW = 0.132411*TL-0.547830, redfish larger than 117.42 mm TL would not go through the 15 mm bar spacing Nordmøre grid and redfish larger than 132.53 mm would not go through the 17 mm bar spacing grid (Figure *4.6*). All redfish sampled would mechanically go through the traditional 22 mm bar spacing Nordmøre grid (Figure *4.6*).

4.4.5. Redfish total length and fishing depth correlation

Results showed that depth and mean redfish length caught in the traditional trawl (n=20) are significantly correlated with a positive relationship (T = 0.77; p-value < 0.001) (Figure *4.7*).

4.4.6. Underwater video of the Nordmøre grid system

In total, 12 tows were recorded during the sea trials: 6 tows for the 22 mm grid, 4 tows for the 17 mm grid and 2 tows for the 15 mm grid. Total duration was 16.1, 7.7, and 2.4 hours of video for the 22, 17 and 15 mm Nordmøre grids, respectively. All grid systems experienced a gradual increase in the guiding panel exit opening as animals meshed and accumulated in the guiding panel meshes over the course of a tow (Figure *4.8*), especially in areas with a high abundance of shrimp, where the guiding panel exit was nearly the same size as the trawl section (i.e. four panels attached to the edges of the grid). During this phenomenon, animals were seen being directed at different grid heights (e.g., higher), at lower speeds, and it seemed were more likely to exit through the grid opening, when compared to the initial guiding panel performance (e.g., directed animals to the base of the grid). Furthermore, there was evident turbulence going in different directions. Videos showed that larger-sized fish can get impinged to the grid, especially flatfish (Pleuronectiformes) and skates (Rajidae). However, except for one tow where the abundance of skates was high, there was no evidence of obstructed grids where shrimp could not transit to the codend through the grid bar spacings.

4.5. Discussion

Reducing the Nordmøre grid bar spacings from 22 to 17 and 15 mm significantly reduced juvenile redfish bycatch while maintaining, or slightly increasing Northern shrimp catches. Even though the two species' size ranges overlap (Figure *4.6*), it is possible to improve the separation of some size-classes of redfish. For Northern shrimp, the main concern was the catch reduction of larger size classes and to maintain commercial capture levels with the smaller bar spacings. The tested grids either showed no difference in comparison to the traditional (17 mm), or showed an increase in capture, though at very slight levels (15 mm). We expected that a reduction in bar spacing could decrease the catch of the largest shrimp. However, this was not the case. Observed shrimp CWs were mostly smaller than both experimental bar spacings, with all observed shrimp able to mechanically fit through the 17 mm grid and the vast majority through the 15 mm grid (Figure *4.6*), and is perhaps why no shrimp reductions were observed. However, if larger shrimp would have been present in trial 2, it is likely that the 15 mm bar spacing grid would have excluded the size classes larger than 29.14 mm CL, which have a predicted CW of 15 mm.

The underwater video showed that over the course of a tow there was a gradual increase in the guiding panel exit opening as shrimp and fish meshed and accumulated in the guiding panel meshes (Figure *4.8*). The gradually increasing amount of space between the guiding panel and the front of the grid seemed to reduce the efficiency of the panel to direct shrimp and other species to the bottom of the grid. Thus, considerable amounts of shrimp, and other species, were observed exiting the trawl when catch rates were high, likely due to a change in contact location between shrimp and the grid (i.e., contacting the grid at a higher point) as catch rates increased with increasing space between the guiding panel and the grid. For grids with no guiding panel, or in this case, with a guiding panel that is not properly directing the catch, individual shrimp would have a more variable contact location on the grid, resulting in the escapement of shrimp that hit the grid closer to the opening (Riedel and DeAlteris, 1995). Animals accumulating in the guiding panel meshes increases the webbing solidity, which might reject catch at the guiding panel or panel entrance, create turbulence, and/or increase the time until the shrimp makes contact with the grid (Riedel and DeAlteris, 1995). Each of these likely reduced the selective efficacy of the grid system and may be why there were unexpected observations, such as smaller bar spacings catching more shrimp and smaller redfish caught with the 15 mm grid and not the 17 mm grid.

The ideal BRD will function reliably in all fishing conditions. However, at-sea observations consistently show that a variety of hydrodynamic and behavioural factors affect BRD performance (Winger et al., 2010), often changing over the duration of a single tow. In this study, underwater observations showed evidence that at moderate to high catch rates, the grid systems are less than optimal. In these cases, the catch hits the grid at different heights, shrimp accumulate on the grid face and exit through the opening, and there is evident turbulence going in different directions. All of these factors may have affected the size selection of Northern shrimp and redfish, leading to surprising results such as smaller bar spacings (15 mm) catching fewer, smaller redfish and slightly more Northern shrimp. The guiding panel malfunction and turbulent water flow going in different directions might have increased the chances of smaller shrimp and redfish to contacting the grid and subsequently transit to the codend.

Increasing the solid area of a grid will change water flow dynamics on the grid system, increasing rejected water flow and decreasing the water flowing through the grid (Grimaldo and Larsen, 2005; Veiga-Malta et al., 2020). However, recent flume tank observations demonstrated only a minor reduction in water velocity (approx. 4.1% and 5.1%) behind a Nordmøre grid when bars spacings were reduced from 22 mm to 17 mm and 15 mm, respectively (Araya-Schmidt, unpublished data, 2020). This is consistent with the camera observations in this study, which did not reveal any obvious difference in the amount of shrimp rejected for the different grids evaluated in this study. Similarly, Hickey et al. (1993) hypothesized that substantially lower grid angles than its initial value of 48˚ and dense shrimp concentrations were the main causes for significant shrimp losses, thus the reductions in bar spacing seemed to not increase shrimp losses.

Redfish length-frequency graphs showed that most of the redfish were between 80 to 90 mm (10.05 to 11.67 mm BW), and between 110 to 130 mm (14.02 to 16.67 mm BW) size classes, which likely indicates a strong presence of two cohorts of redfish overlapping in the fishing area. Saborido-Rey et al. (2004) estimated that previous redfish (*S. mentella*) cohorts (1986-1999) in the Flemish Cap had mean lengths of 90 and 127 mm, for ages 1 and 2, respectively. These results provide some level of confidence that the population we encountered was comprised of two redfish cohorts. Granted, the Flemish Cap is a different location (~ 1000 km to the Southeast of our sampling area), and we did not determine the species of our samples, though a recent survey (3 months prior; Jan.-Feb. 2021) did determine that some redfish captured (100% sampled for species identity) in the same fishery and fishing area were *S. mentella* (DFO, personal communication). The 17 mm Nordmøre grid reduced the catch of redfish for all size classes, even though the majority of redfish could mechanically pass through the 17 mm grid bar spacings (i.e., only redfish larger than 132.53 mm TL had BW larger than 17 mm). This is likely because not all of the redfish contacted the grid (Larsen et al., 2017) and possibly exited the trawl following the strong water flows directed towards the grid opening (Grimaldo and Larsen, 2005). However, only size classes larger than 95 mm that had a predicted 12.03 mm BW were caught in significantly lower quantities when using the 15 mm grid, which shows that the effectiveness of this grid at reducing redfish bycatch is lower for the cohort of smaller redfish (between 80 and 90 mm). Perhaps, the flow was altered in front of the 15 mm grid in such a way that allowed increased capture efficiency of the smallest animals observed (for redfish and shrimp). Increased turbulence was observed in front of the grid on video, where small shrimp and redfish would swirl around in the area just in front of the grid. Perhaps this added turbulence, when compared to the 17 mm grid, prevented the small animals from escaping out of the trawl, but only for the relatively larger redfish and not for the shrimp whose captures were higher for all sizes (Figure 4.4 and Figure *4.5*). Thus, given the long-lived, slow-growing nature of redfish populations, using a grid that prevents the captures of both cohorts is a preferred option.

Recent conditions of licence permitted up to 2.5% or 100 kg total weight of incidental catch of groundfish species per tow (DFO, 2018), although recent amendments have been temporarily permitted for higher levels of bycatch (DFO, 2021). The 15 and 17 mm bar spacing grids were not effective at reducing redfish bycatch below these levels. In trial 1, from 20 opportunities (2 codends twin trawling over 10 tows), the 17 mm grid produced 2 tows with redfish bycatch below 2.5% or 100 kg, while the 22 mm grid produced 1. In trial 2, both the 15 and 22 mm grids produced 5 of 20 opportunities within the permitted amount of redfish bycatch from a total of 10 tows. Redfish can be caught in large quantities (~ 7,000 kg for one tow), which emphasizes the need to address this bycatch issue. It is common to find small amounts of other groundfish species in the catch, which means that the redfish bycatch needs to be even further reduced to comply with conditions of licence. Juvenile redfish greatly overlap with Northern shrimp in the fishing area and is a slow-growing species, which means a higher probability of redfish passing through the Nordmøre grid and a higher bycatch relative to several other groundfish species over at least the near future (Orr et al., 2008). Even though the experimental grids did not prevent capturing redfish over permitted limits, we recommend its use, as any reduction in resource waste is beneficial from an ecological and operational point of view.

Different proportions of the two redfish cohorts observed during the experiment were mixed depending on fishing depths, which lead to a strong correlation between average redfish length and fishing depth. These results coincide with previous findings that relatively larger individuals appear to concentrate at greater depths (Senay et al., 2021). This is an important factor to consider since the bycatch reduction effectiveness of a 17 or 15 mm bar spacing Nordmøre grid could be greatly affected in shallower areas where larger proportions of smaller redfish are present. From the fisheries management perspective, this is especially interesting since it could lead to regulating Nordmøre grid bar spacing based on fishing depths. Alternately, fishing enterprises could avoid shallower fishing areas where the efficiency of the grids at reducing redfish is low. The scale of this size segregation is unknown, research investigating the regional extent is recommended.

Nordmøre grids with smaller bar spacing tested in this study significantly reduced juvenile redfish bycatch while maintaining Northern shrimp catches. Even though the size of shrimp and redfish overlap, the results showed that it is possible to improve the sorting of these two species. Since shrimp CW of large individuals can reach 15 mm, further reductions in the bar spacing will likely lead to a reduction in catch rates of the larger and more valuable shrimp. Therefore, purely mechanical separation using Nordmøre grids with reduced bar spacing is not the definitive solution and should be combined with other BRDs exploiting behavioural differences between species, such as escape panels (Cerbule et al., 2021; Larsen et al., 2018c), artificial lights (Larsen et al., 2017, 2018a) or other devices to aid in the bycatch reduction efforts. For the time being, until an effective combination of BRDs is found, fisheries management and fishers' decisions could play a key role in reducing redfish bycatch by avoiding areas with smaller individuals and high abundance of redfish.

4.6. Acknowledgments

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4.8. Tables

Table 4.1. Operational conditions for trials 1 and 2, including paired tow number, the grid used, Shrimp Fishing Area (SFA), bottom temperature, tow duration and depth.

Tow	Grids (mm)	SFA	Temp (°C)	Tow Duration (hm)	Depth (m)
1	17 and 22	4S	4.4	3h15m	374
2	17 and 22	4S	4.2	4h	379
3	17 and 22	4S	4	2h35m	354
4	17 and 22	4S	4.5	4h	349
5	17 and 22	4S	2.8	1h10m	241
6	17 and 22	4S	3.5	1h40m	248
7	17 and 22	4S	4.4	2h30m	355
8	17 and 22	4S	3.5	1h30m	238
9	17 and 22	4S	2.6	1h30m	254
10	17 and 22	4S	4.4	1h45m	253
11	15 and 22	5	3.3	2h45m	276
12	15 and 22	5	3.2	1h55m	260
13	15 and 22	5	2.1	1h45m	267
14	15 and 22	5	2.2	2h	247
15	15 and 22	5	2.2	2h	241
16	15 and 22	5	2.2	3h	263
17	15 and 22	5	2.6	2h40m	320
18	15 and 22	5	4.4	3h30m	301
19	15 and 22	5	3.4	4h	295
20	15 and 22	5	3.4	3h	296

Table 4.2. Total Northern shrimp and redfish catch (kg), redfish bycatch (%) and sub-sampling ratios for the 22 and 17 mm, and the 22 and 15 mmm Nordmøre grids trials (1 and 2, respectively). Total redfish (kg) and bycatch (%) that are higher than Fisheries and Oceans Canada condition of licence thresholds are shown in bold.

Trial	Tow	Grid (mm)	Total shrimp (kg)	Total redfish (kg)	Bycatch (%)	Shrimp sub-sampling ratio	Redfish sub-sampling ratio
1	1	22	5827	**112.2**	1.93%	0.000172	0.008913
		17	4910	87.6	1.78%	0.000204	0.011416
	2	22	3733	86.6	2.32%	0.000268	0.011547
		17	5590	**105.6**	1.89%	0.000179	0.009470
	3	22	4623	**183.3**	**3.96%**	0.000216	0.005456
		17	7073	**110.2**	1.56%	0.000141	0.009079
	4	22	2964	**417.0**	**14.07%**	0.000337	0.002398
		17	3573	**320.9**	**8.98%**	0.000280	0.003116
	5	22	5120	**259.8**	**5.07%**	0.000195	0.003849
		17	4669	**196.7**	**4.21%**	0.000214	0.005084
	6	22	5608	**331.3**	**5.91%**	0.000178	0.003018
		17	5965	**305.2**	**5.12%**	0.000168	0.003277
	7	22	4003	**961.8**	**24.03%**	0.000250	0.001040
		17	3865	**583.0**	**15.08%**	0.000259	0.001715
	8	22	5054	**326.7**	**6.46%**	0.000198	0.003061
		17	3957	**164.4**	**4.15%**	0.000253	0.006083
	9	22	5144	**145.4**	**2.83%**	0.000194	0.006878
		17	3978	69.5	1.75%	0.000251	0.014388
	10	22	3586	**448.8**	**12.52%**	0.000279	0.002228
		17	3260	**356.5**	**10.94%**	0.000307	0.002805
2	11	22	9630	82.3	0.85%	0.000104	0.012151
		15	10982	56.6	0.52%	0.000091	0.017668
	12	22	4303	53.9	1.25%	0.000232	0.018553
		15	4556	52.9	1.16%	0.000219	0.018904
	13	22	4091	**139.6**	**3.41%**	0.000244	0.007163
		15	4846	**134.3**	**2.77%**	0.000206	0.007446
	14	22	5612	**129.9**	**2.31%**	0.000178	0.007698
		15	6062	**112.6**	**1.86%**	0.000165	0.008881

15	22	3092	60.2	1.95%	0.000323	0.016611
	15	3011	41.7	1.38%	0.000332	0.023981
16	22	3557	43.7	1.23%	0.000281	0.022883
	15	4242	49.1	1.16%	0.000236	0.020367
17	22	5664	62.8	1.11%	0.000177	0.015924
	15	5582	56.8	1.02%	0.000179	0.017606
18	22	3349	**195.3**	**5.83%**	0.000299	0.005120
	15	3723	**142.0**	**3.81%**	0.000269	0.007042
19	22	2582	**230.8**	**8.94%**	0.000387	0.004333
	15	2658	**161.0**	**6.06%**	0.000376	0.006211
20	22	3300	**493.3**	**14.95%**	0.000303	0.002027
	15	3518	**310.0**	**8.81%**	0.000284	0.003226

Table 4.3. Differences of the Akaike information criterion (ΔAIC) and degrees of freedom (df) for the different models for shrimp and redfish in trials 1 and 2. Values in bold highlight the best fitting models.

Model	Trial 1: 22 vs 17 mm grid				Trial 2: 22 vs 15 mm grid			
	Shrimp		Redfish		Shrimp		Redfish	
	ΔAIC	df	ΔAIC	df	ΔAIC	df	ΔAIC	df
Logit-constant	7.0	1	**0.0**	**1**	**0.0**	**1**	41.7	1
Logit-linear	**0.0**	**2**	1.0	2	0.7	2	**0**	**2**
Logit-quadratic	0.8	3	2.3	3	2.5	3	1.3	3
Logit-cubic	2.7	4	3.9	4	4.5	4	0.7	4
Logit-quartic	2.5	5	5.7	5	6.3	5	2.7	5
Spline 2nd order	0.6	3	2.3	3	2.5	3	1.4	3
Spline 3rd order	2.4	4	3.7	4	4.2	4	0.5	4
Spline 4th order	3.9	5	5.8	5	6.1	5	2.5	5
Spline 5th order	4.9	6	7.4	6	6.3	6	4.5	6

4.9. Figures

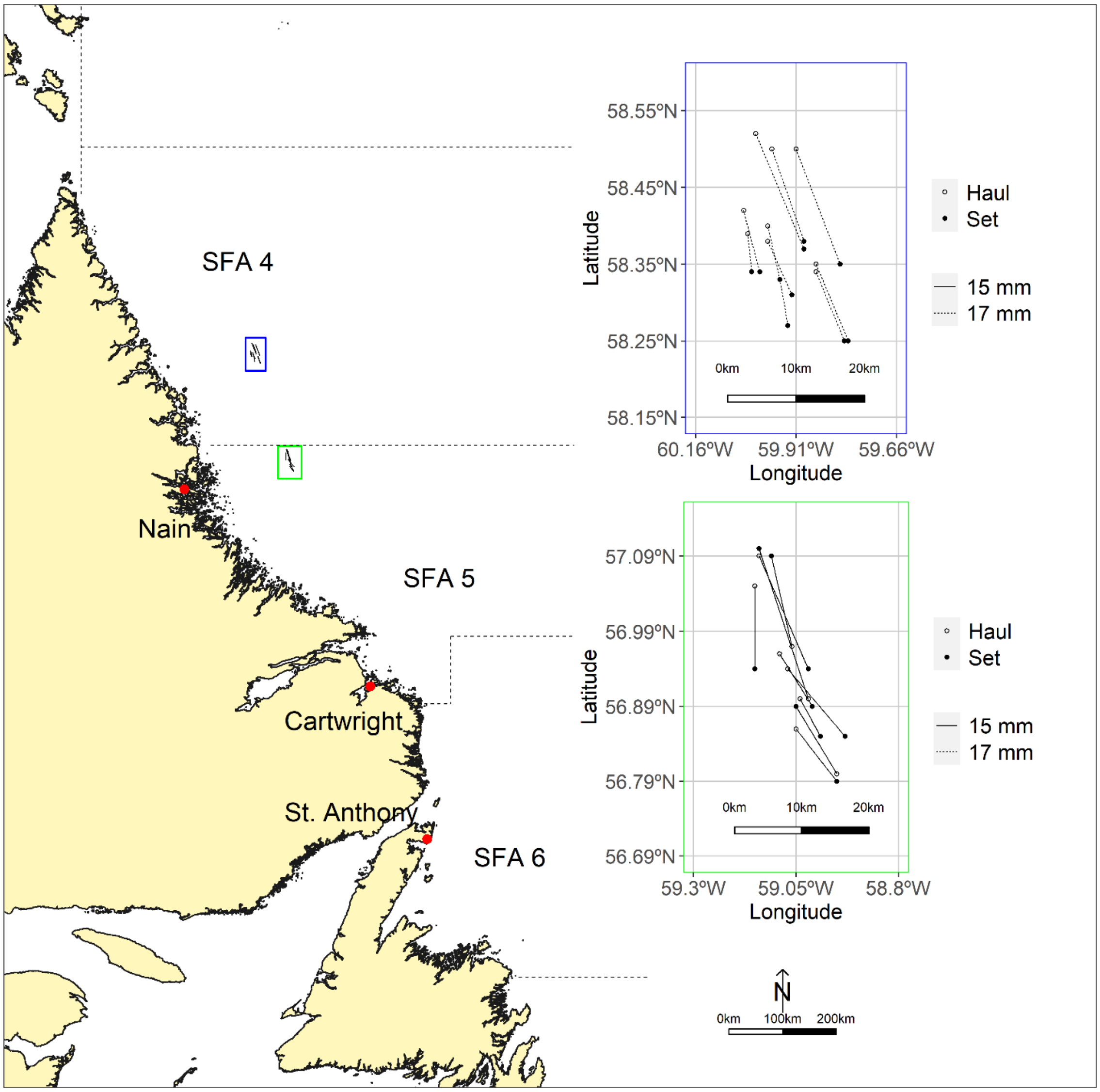

Figure 4.1. Shrimp Fishing Areas (SFA; denoted by dashed lines) where the trials took place are shown, located in the Labrador Sea off the coast of Nain, Newfoundland and Labrador. Inset maps are shown for the two main study areas (blue (trial 1) and green (trial 2) rectangles). Map data from the GADM database of Global Administrative Areas (http://gadm.org/). Mercator projection WGS 84 was used.

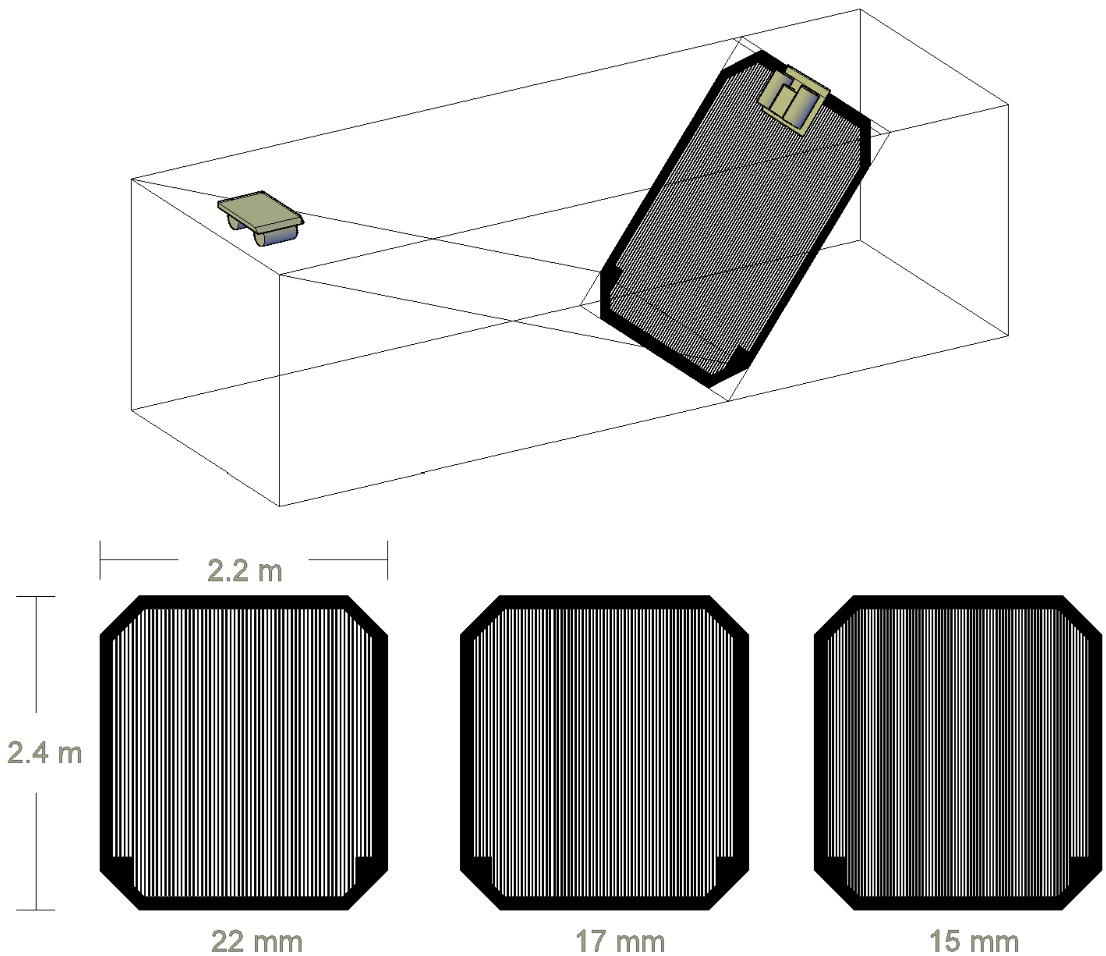

Figure 4.2. Nordmøre grid section (top), 22, 17, and 15 mm bar spacing Nordmøre grids (bottom) used in the experiment. Camera system mounted on the upper panel and grid are shown on the Nordmøre grid section drawing (top).

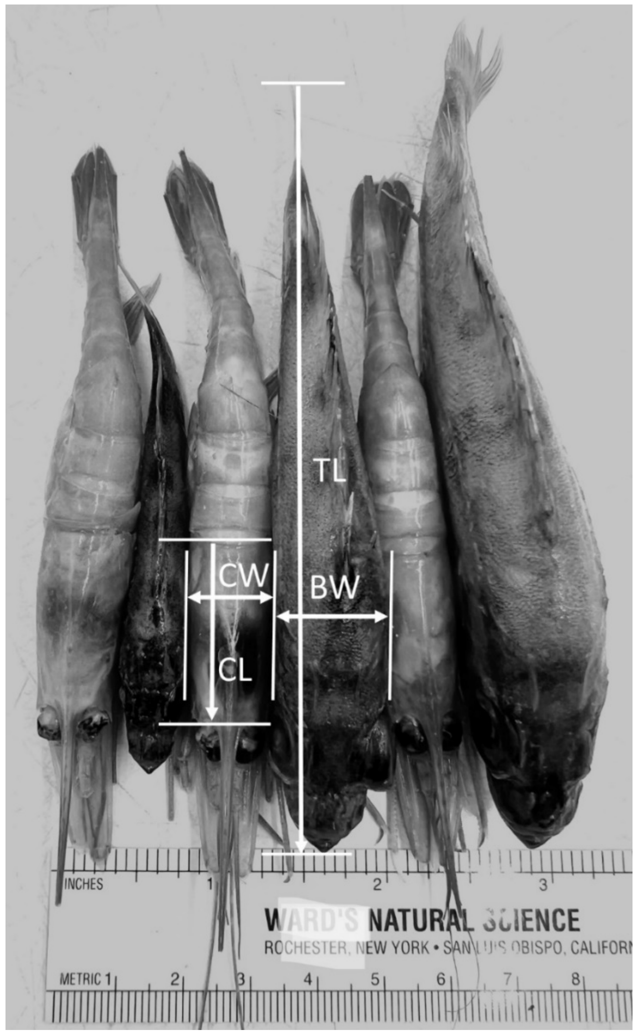

Figure 4.3. Morphometric measurements of Northern shrimp (Pandalus borealis) and redfish (Sebastes spp.). Shrimp carapace length (CL), shrimp carapace width (CW), redfish body width (BW) and redfish total length (TL) measurements are shown for the two individuals in the center of the image.

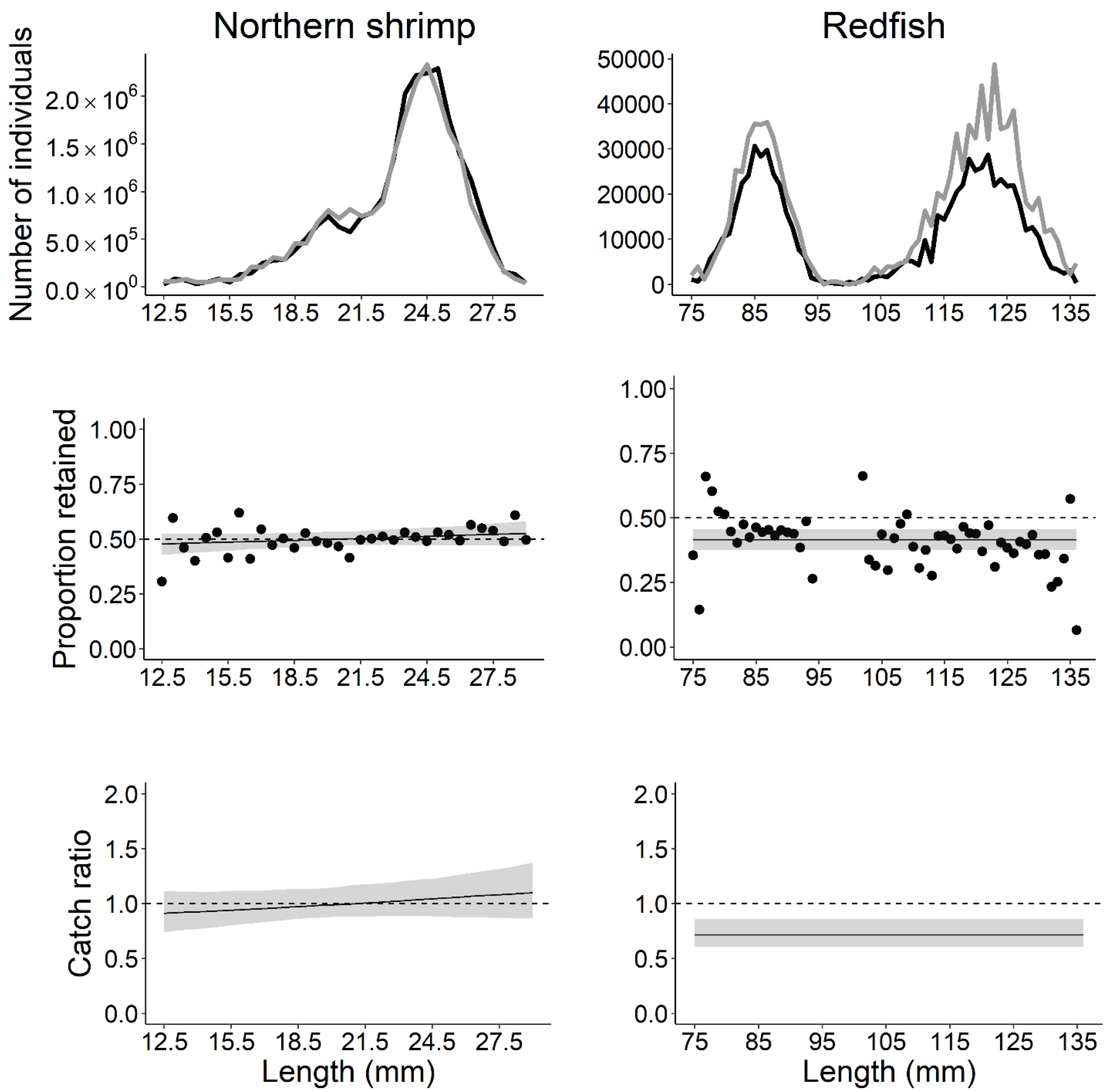

Figure 4.4. Catch comparison and catch ratio plots for Northern shrimp (Pandalus borealis) and redfish (Sebastes spp.) for the 17- and 22-mm bar spacing Nordmøre grid trawls. Top: Length frequency distribution of Northern shrimp and redfish caught by the 17 mm grid trawl (black line) and 22 mm grid trawl (grey line). Middle: Mean curve from the generalized linear mixed model (GLMM) modeled proportions (black line) with 95% confidence regions (grey area).

Black dots represent observed proportions retained. A value of 0.5 indicates an even split between the 17 and the 22 mm grids trawl, whereas a value of 0.75 indicates that 75% of the total individuals at that length were caught in the 17 mm grid trawl and 25% were caught in the 22 mm grid trawl. Bottom: Estimated catch ratio (black curve) with 95% confidence regions (grey area). Stripped line at 1.0 represents the point at which both gears have an equal catch rate.

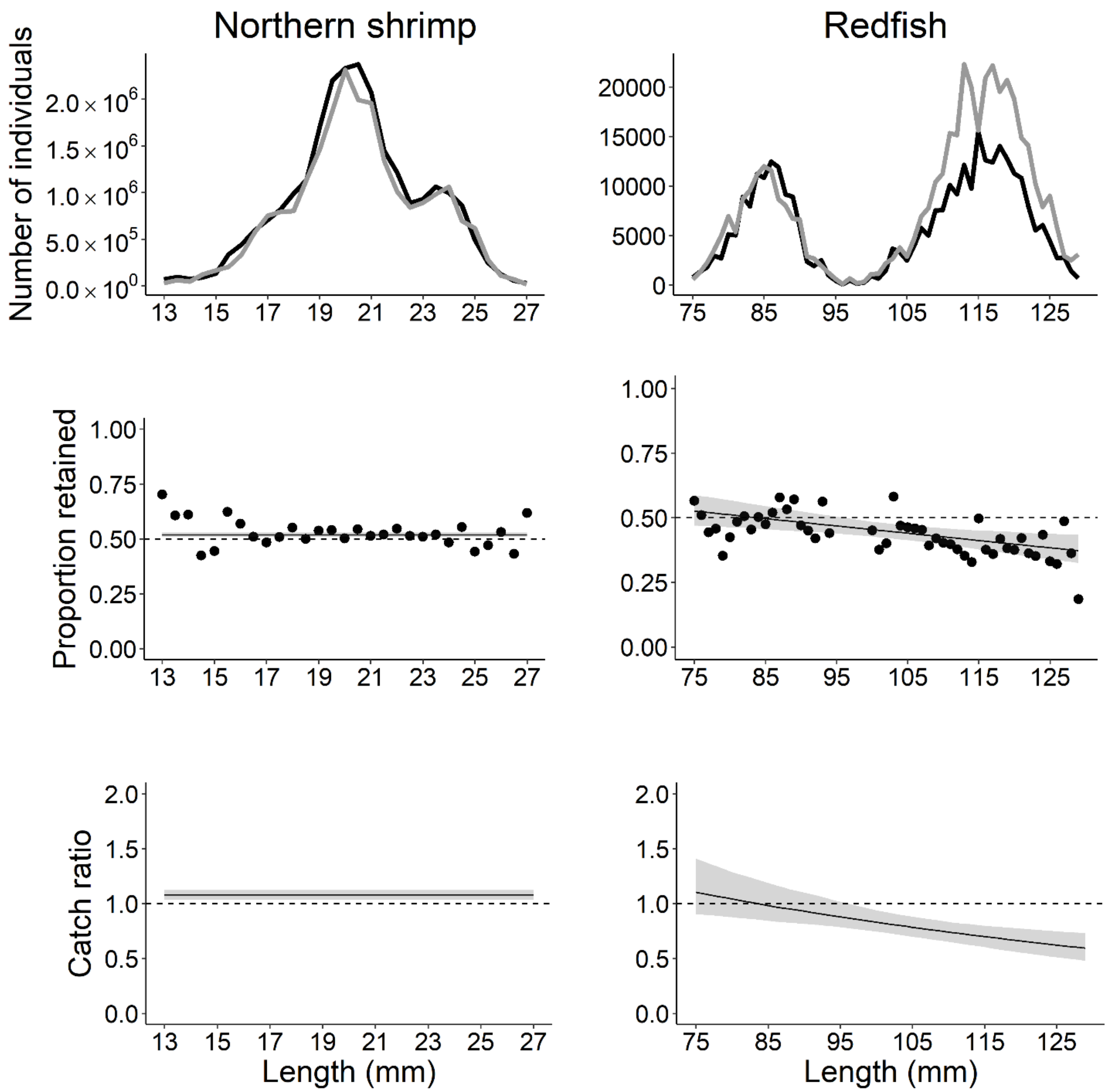

Figure 4.5. Catch comparison and catch ratio analysis for Northern shrimp (Pandalus borealis) and redfish (Sebastes spp.) for the 15- and 22-mm bar spacing Nordmøre grid trawls. Top: Length frequency distribution of shrimp and redfish caught by the 15 mm grid trawl (black line) and 22 mm grid trawl (grey line). Middle: Mean curve from the generalized linear mixed model (GLMM) modeled proportions (black line) with 95% confidence regions (grey area). Black dots

represent observed proportions retained. A value of 0.5 indicates an even split between the 15 and the 22 mm grids trawl, whereas a value of 0.75 indicates that 75% of the total individuals at that length were caught in the 15 mm grid trawl and 25% were caught in the 22 mm grid trawl. Bottom: Estimated catch ratio (black curve) with 95% confidence regions (grey area). Stripped line at 1.0 represents the point at which both gears have an equal catch rate.

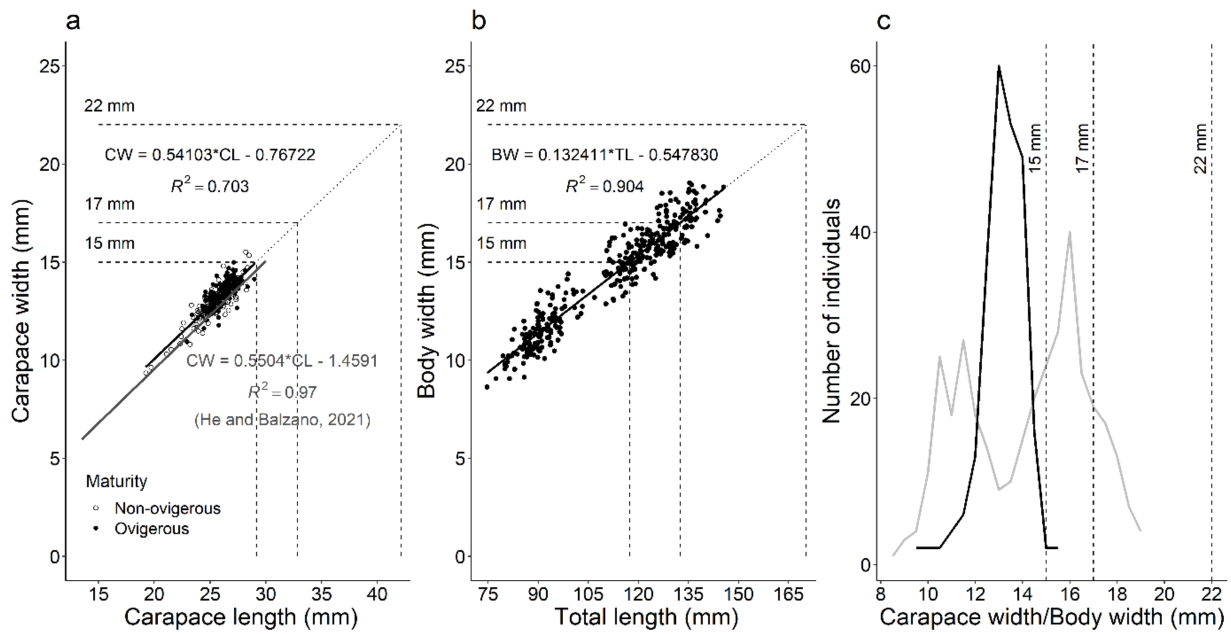

Figure 4.6. Morphometric relationship between length and width of Northern shrimp and redfish. a: Northern shrimp carapace length (CL) and carapace width (CW) relationship, b: Redfish total length (TL) and body width (BW) relationship and c: Frequency distribution of shrimp (black line) and redfish (grey line) sampled. Dots show the observed data for northern shrimp and redfish. In the case of shrimp dots also show the maturity stage (i.e., ovigerous or non-ovigerous). Black solid lines show the linear model regression and dotted lines represent the projection of the linear regressions. Grey solid line shows the linear regression obtained in the

study performed by He and Balzano (2021). Dashed lines show the traditional and experimental Nordmøre grid bar spacings and their related CL or TL according to the linear regressions. Regression equations and coefficients of determination (R^2) are also presented in the figure next to their respective regression line.

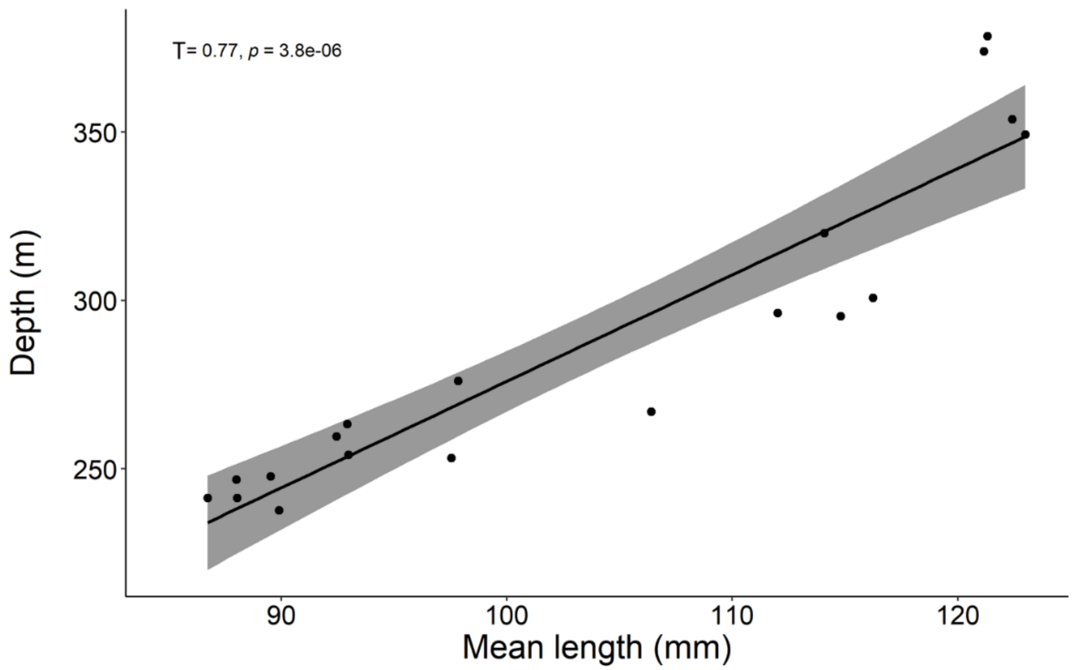

Figure 4.7. The correlation of depth fished as a function of redfish mean length for 20 tows using the 22 mm bar spacing grid. T coefficient and p-value from the correlation analysis are in the top left corner.

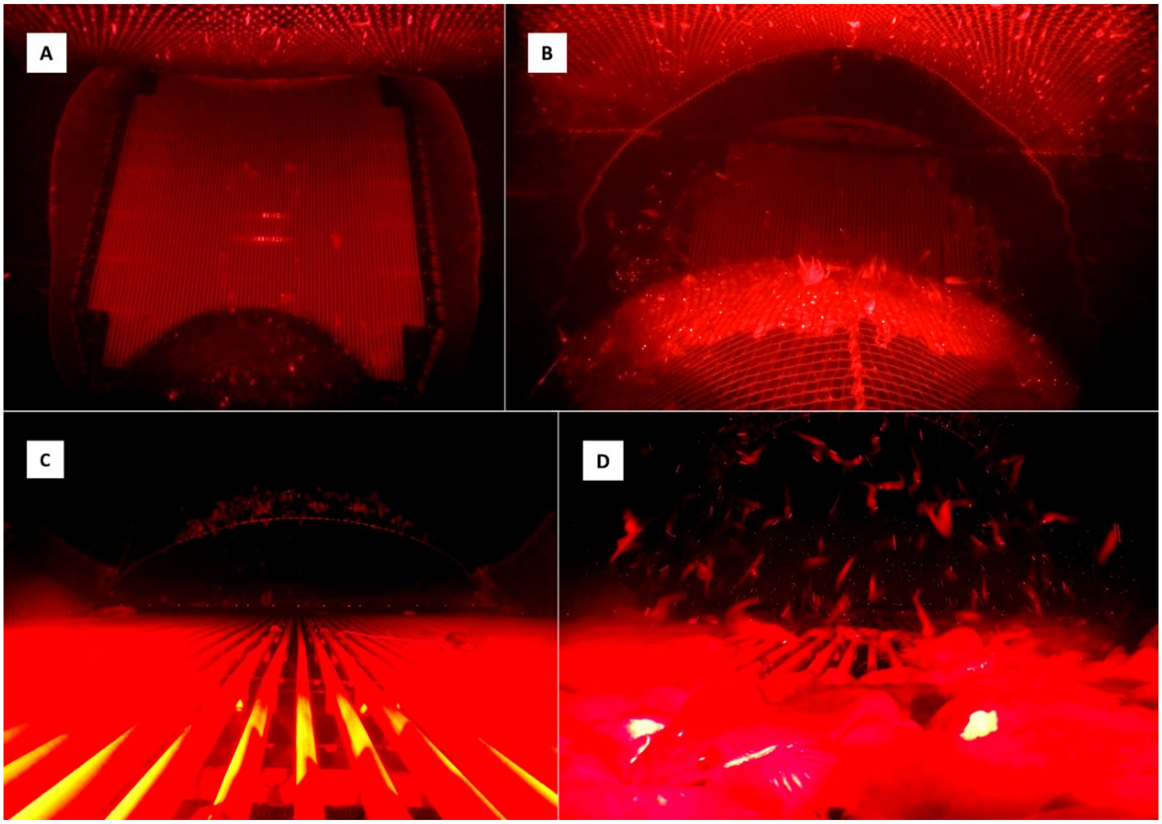

Figure 4.8. Guiding panel deformation during tow. A: frontal view of a 17 mm bar spacing Nordmøre grid at the beginning of the tow showing a guiding panel that is directing flow at the base of the grid. B: frontal view of a 22 mm bar spacing grid towing for 2 hours showing a deformed guiding panel that has meshed shrimp and fish. C: top view of a 15 mm bar spacing grid at the beginning of the tow showing a guiding panel similar to A. D: top view of a 17 mm bar spacing grid towing for 1.5 hours showing a guiding panel similar to B.

CHAPTER 5. Juvenile redfish (*Sebastes spp.*) behaviour in response to Nordmøre grid systems in the offshore Northern shrimp (*Pandalus borealis*) fishery of eastern Canada

5.1. Abstract

A recent rebound of juvenile redfish (*Sebastes spp.*) in areas where the Northern shrimp (*Pandalus borealis*) bottom trawl fishery in eastern Canada occurs has been challenging the fishing industry to maintain bycatch of this species within acceptable levels. Using self-contained underwater cameras and red lights, this study investigated the behaviour of juvenile redfish in response to bycatch reduction devices, called Nordmøre grids. Fish behaviour was analyzed for grids with different bar spacings, including the traditional (22 mm) and experimental (19 mm) bar spacing. A total of 10.3 hours of useable underwater video was collected during commercial fishing conditions. Generalized linear models and behavioural trees were used to analyze the data. Results suggest that reducing bar spacings to 19 mm slightly reduced redfish bycatch and behaviours exhibited by redfish were similar for both grids. As time in front of the grid increased and redfish had upwards or steady grid reactions, retention was drastically reduced. These were important variables that significantly explained the capture fate of redfish. The most common behavioural sequence that led to an escape were redfish that approached upwards, had no contact with the grid and reacted to the grid by continuously moving upwards to finally exit through the escape opening.

5.2. Introduction

Nordmøre grids are employed in shrimp bottom trawls to mechanically separate the targeted shrimp from larger animals, such as roundfish, flatfish, skates, among others (Isaksen et al., 1992). However, relatively small juvenile fish with a similar size as the targeted shrimp can pass through the Nordmøre grid bar spacings, transit to the small mesh codend and be caught. This can result in considerable amounts of bycatch of commercially important species (Kelleher, 2005; Bayse and He, 2017). Despite extensive efforts made around the world to reduce bycatch in shrimp fisheries (Broadhurst, 2000; Eayrs, 2007), the incidental catch of juvenile fish persists.

In the 1990s, the Nordmøre grid was introduced in Canada's east coast Northern shrimp *(Pandalus borealis)* fishery; mandatory maximum bar spacings of 22 and 28 mm are permitted, although the majority of the fishing effort uses a 22 mm bar spacing grid (Ocean Choice International pers. comm.). The introduction of Nordmøre grids reduced finfish bycatch from 15% to 2% (> 85% reduction by weight) of the total landings of shrimp (ICES, 1998). However, juvenile redfish (*Sebastes* spp.) abundance (total length < 150 mm) has increased considerably in recent years (DFO, 2020) and its exclusion is problematic at the regulated bar spacings (ICES, 1996). Once juvenile redfish pass through the Nordmøre grid bars there is a small chance of escapement as bottom trawls in this fishery are constructed with mesh sizes as small as 40 mm (minimum mesh size authorized) in order to retain small shrimp (DFO, 2018). Resulting in various levels of juvenile redfish bycatch depending on its abundance in the fishing area.

Beaked redfish (*Sebastes mentella*) and Acadian redfish (*S. fasciatus*) are commercially important species off the northeast coast of Canada (Government of Canada, 2021). They were both considered threatened under the Committee on the Status of Endangered Wildlife in Canada

(COSEWIC) in 2010, and are currently being considered for Schedule 1 classification (Government of Canada, 2021). Their slow growth rates, long-lived nature (Campana et al., 1990) and late maturity (Sévigny et al., 2007) make mortality of juvenile redfish of concern and its incidental catch could have a negative impact on the stock's recruitment, biomass, recovery and the future of an emerging redfish fishery. Furthermore, the mortality of juvenile redfish can have an impact on the trophic structures of communities, affecting other important commercial fisheries (Dayton et al., 1995; Devine and Haedrich, 2011).

According to recent conditions of licence, a move-away protocol is triggered, and the vessel must change the fishing area by a minimum of 10 nautical miles from the previous tow if the incidental catch of groundfish exceeds 2.5% of the total catch or 100 kg in total weight (DFO, 2018). Due to the current circumstances, recent amendments have been temporarily permitted for higher levels of bycatch (DFO, 2021). The movement protocol has unintended negative effects, increasing operational costs (e.g., fuel consumption) and environmental impacts (e.g., time-at-sea, carbon dioxide emissions). Even further, shrimp quality is greatly reduced by physical damage from the increased amounts of juvenile redfish bycatch and can also represent a sorting problem in onboard factories.

The performance in terms of catch and size selectivity of bycatch reduction devices (BRD), and other selective devices in general, is assessed based on catch data following robust methodologies and statistical analyses (Wileman et al., 1996). Previous experiments on grid bar spacings (Hickey et al., 1993; CAFID, 1997; Orr, 2018; He and Balzano, 2012; Silva et al., 2012; Araya-Schmidt et al., submitted), new grid designs (Grimaldo and Larsen, 2005; Grimaldo, 2006; He and Balzano, 2007, 2011, 2013; Veiga-Malta et al., 2020) and sorting grid configurations (Riedel and DeAlteris, 1995; Larsen et al., 2018a) have used these procedures. These catch comparisons studies between traditional and experimental gears often provide conclusive results on the catch performance. However, the specifics on how the species in question react to the device are generally unknown.

The increased availability of low-cost and high-quality image underwater cameras in recent years (Madsen et al., 2021) has enabled fishing gear technologists to qualitatively assess fish behaviour to understand the mechanics behind selection processes (Queirolo et al., 2010; Grimaldo et al., 2018; Larsen et al., 2018b). Even further, many studies have quantitatively analyzed the data gathered from underwater video to assess the selective device or fishing gear performance, and species behaviour (Bayse et al., 2014, 2016; Underwood et al., 2015; Queirolo et al., 2019; Santos et al., 2020; Ahumada et al., 2021; Araya-Schmidt et al., 2021; Chladek et al., 2021ab). The observed fish behaviours are usually tracked from the first detection to the final outcome of the selection process and categorized in stages. Generalized linear models (Underwood et al., 2015; Bayse et al., 2016) and behavioural trees (Santos et al., 2020; Chladek et al., 2021ab) have been used to analyze the observed behaviours and relate them to capture fate.

The purpose of this study was to investigate whether reducing the bar spacing in Nordmøre grids from 22 to 19 mm could reduce juvenile redfish bycatch. It builds upon previous experiments in Canadian waters (Hickey et al., 1993; CAFID, 1997; Orr, 2018; Araya-Schmidt et al., submitted). We use underwater video collected during commercial fishing operations to document the behaviour of juvenile redfish in response to traditional and experimental grids. The data was quantitatively assessed using both a generalized linear model (GLM) and a behavioural tree approach. The advantages and disadvantages of both methods are discussed.

5.3. Materials and Methods

5.3.1. Fishing gear

Two Cosmos 3000 commercial shrimp bottom trawls were used in this study. They had 65.4 m headlines, 70.1 m fishing lines, and 70.1 m roller footgears. The trawls had a four-panel design and were each equipped with a trouser codend with a 40 mm nominal mesh size. The traditional (control) and experimental trawls were identical, except for the Nordmøre grids bar spacing. The control bottom trawl was equipped with a 22 mm (mean 21.74 mm, standard error 0.07 mm) bar spacing Nordmøre grid, while the experimental bottom trawl was equipped with a 19 mm (mean 18.83 mm, standard error 0.08 mm) bar spacing Nordmøre grid.

Hydrodynamic testing of the full-scale grid systems was conducted prior to sea trials using the flume tank (Figure 5.1) located in St. John's, NL, Canada (Winger et al., 2006). Grid angles were measured for quality control, recorded as 62 and 63 degrees for the 22 and 19 mm grids, respectively. Water velocity was measured before and after the grids to document the effect of reduced bar spacing on water velocity, which was minor (approx. 6.1% reduction). Water velocity (m/s) was measured using a two-axis electromagnetic current meter (Valeport Model 802, Valeport, St Peter's Quay, Totnes, UK). See Cheng et al. (2022) for further description.

5.3.2. Underwater video observations

Video recordings were collected onboard the commercial factory freezer trawler *Newfoundland Lynx* (length 67.7 m, width 13.0 m, gross tonnage 2409) during January 19 and February 13, 2021, in the offshore shrimp fishing areas (SFA) 4, 5 and 6 off eastern Canada. The camera system was attached to the top of the Nordmøre grid and consisted of a GoPro hero 4 black action camera, with a GoPro "Bacpac" battery, and an external battery (4000 mAh, 3.7 V) (Figure 5.2). Two DIV08W diving lights from Brinyte Technology Ltd. were used to illuminate the camera field of view. This 120-degree LED diving light (luminous intensity of 629 cd) was used at a red light setting (350 lumens). Underwater housings from CamDo Solutions Inc. and Group B Distribution Inc. were used (certified to a depth of 1500 m) for the camera and lights, respectively (Figure 5.2).

5.3.3. Behavioural data

Behaviours of individual redfish were evaluated at the Nordmøre grid section of the experimental and traditional bottom trawls (i.e., 19 and 22 mm Nordmøre grid bar spacings). Behaviours were recorded within five behavioural stages (1) Body orientation, (2) Approach, (3) Grid contact, (4) Grid reaction and (5) Fate (Figure 5.2). These included the moment the redfish entered the camera field of view, below the guiding panel, up to when the individual was either, retained (i.e., transited to the codend through the Nordmøre grid bars) or excluded through the opening on the upper panel of the grid section (Figure 5.2). Upon entry of the redfish to the field of view, body orientation was recorded as "towards", "sideways" or "away" with respect to the fish's head in orientation to the grid. After entry, the path followed by the fish approaching the grid was recorded; fish were considered to move "upwards", remain "steady" or move "sideways" (i.e., port or starboard). Following the approach stage, fish either had "contact" or “no contact” with the Nordmøre grid. Fish that did not contact the grid all moved up toward the escape opening and were considered to have a grid reaction “upwards”, fish that contacted the grid reacted by moving “upwards”, remaining “passive”, moving “towards” the grid (i.e., through the bars) or by swimming “forward” in the opposite direction from the grid. Finally, redfish that were positioned on the front side of the grid (towards the vessel) and moved up past the camera field of view were considered “escaped” and exited the grid section through the opening, fish that transited to the codend through the grid bars were considered “retained”. Total time elapsed from redfish first detection to fate stage (t) was recorded for each individual. Behavioural data was recorded from underwater video using the BORIS software (Friard and Gamba, 2016).

5.3.4. Generalized linear model

A GLM with a binomial error was constructed using the lme4 package (Bates et al., 2015). All statistical analyses were performed in R (R Development Core Team, 2017). Redfish fate was the dependent variable (i.e., escaped or retained). Explanatory variables, when appropriate, included “grid”, “body orientation”, “approach”, “grid contact”, “grid reaction”, “time” and “tow”. Model selection was based on the model with the lowest AICc (Akaike, 1974), using the function AICctab in the bbmle package (Bolker and R Development Core Team, 2020). Model fit was assessed with a combination of a QQ plot, residual investigation, and dispersion test in the DHARMa package (Hartig, 2021).

5.3.5. Behavioural trees

Following Santos et al. (2020) procedures, the behaviours observed at each stage describe a specific behavioural sequence that could explain the fate of the observed redfish (i.e., escaped or retained). The behaviours collected for each fish at the different behavioural stages were pooled within and between hauls separately for each grid type (i.e., 22 and 19 mm bar spacing Nordmøre grids). The data for each grid was arranged in behavioural trees using data.tree (Glur, 2018) and DiagrammeR (Iannone, 2019) packages. The root represents the total number of redfish observed, which is connected to the nodes counting the number of times a specific behaviour occurred. The nodes were organized in five levels following the five behavioural stages, which were connected by the tree branches following the observed behavioural sequences. Finally, the tree leaves at the bottom contain the number of redfish that after following a specific behavioural sequence were retained or excluded.

Marginal and conditional probabilities were calculated (Santos et al., 2020) for each of the behavioural trees generated. Marginal probability (MP) was calculated as:

$$MP_{z,j} = P\left(N_{z,j}\right) = \frac{N_{z,j}}{Root} \tag{1}$$

where $MP_{z,j}$ is the marginal probability for a given behavioural event j from behavioural stage z to happen. $N_{z,j}$ is the node representing the total number of redfish that had a behaviour j in behavioural stage z, while Root is the total number of redfish observed for each Nordmøre grid.

Conditional probability (CP) was calculated as:

$$CP_{B,j} = P\left(N_{B,j} | N_{B-1,k}\right) = \frac{N_{B,j}}{N_{B-1,k}} \tag{2}$$

where $CP_{B,j}$ is the conditional probability that event j from behavioural stage $B \in \{2,3,4,5\}$ could happen, given that the parent attribute k from behavioural stage $B - 1$ happened.

The rate of observed redfish that were excluded at the 22 and 19 mm Nordmøre grid systems were calculated as:

$$Rate\ of\ redfish\ excluded = 100\ x\ \left(\frac{n\ excluded}{n\ excluded + n\ retained}\right) \tag{3}$$

where *n excluded* is the number of redfish excluded and *n retained* is the number of redfish retained.

Finally, 95% Efron confidence intervals (95% CI) were estimated for MP, CP, rate of redfish excluded and t using a double bootstrap technique (Santos et al., 2020) which produced a total of 1000 artificial trees.

5.4. Results

Six tows were recorded during the fishing trip with a total fishing time of 16.2 hours. Grid systems experienced an increase in the guiding panel exit opening at the beginning of each tow as animals meshed and accumulated in the guiding panel meshes. Redfish behaviour was obtained after the guiding panel opened for each tow as it remained in this position for the rest of the fishing time (Figure 5.3). Within each tow, some events prevented us from assessing redfish behaviour, such as fish in front of the camera blocking the field of view, turbidity and large amounts of northern shrimp. In all of these cases, the video was discarded for those periods. The relatively short periods (< 10 s) for interesting behaviours prevented any concern of missed data from discarded video. The first two tows were discarded due to high turbidity conditions that did not allow us to observe redfish behaviour properly. The remainder of the tows were used to assess redfish behaviour; two tows used the 22 mm bar spacing Nordmøre grid, and two tows used the 19 mm bar spacing Nordmøre grid, with a total useable fishing time of 6.5 and 3.8 hours, respectively. Overall, there were 442 redfish recorded for the 22 mm Nordmøre grid and 489 redfish for the 19 mm Nordmøre grid.

Initially, the data was analyzed using a generalized linear mixed model (GLMM), to incorporate random variation from different tows within the model. However, model fit indicated singularity when the variables grid reaction and grid contact were included, together or individually. Thus, a GLMM was not deemed reasonable as these explanatory variables were important and the analysis shifted to fitting a GLM. Since tow could not be included as a random effect, we attempted using it as an explanatory variable, however, large AICc values showed it was not an important variable during initial data investigation and it was excluded from the model selection process for simplicity. Additionally, grid was the independent variable of interest (capture fate between different grids) and generally, its inclusion produced low AICcs values during initial data investigation, hence, it was decided to maintain the grid variable in every fitted model. Further, the model fit was improved by reducing the number of categories in the grid reaction variable (i.e., originally it had 4 categories), forward and towards behaviours were combined as all redfish were retained when exhibiting these behaviours. The model with the lowest AICc included grid, grid contact, grid reaction and time as explanatory variables (Table 5.1).

Model output suggested that there was a 99.68% probability of retention (or 0.32% of escaping) for redfish that had contact with the 22 mm grid and reacted by swimming forward or towards when time = 0 s. If we move to the 19 mm bar spacing grid, the probability of escaping increased by 56.52% (p-value = 0.243), maintaining the other reference groups constant (i.e., grid reaction forward or towards and time = 0 s) (Table 5.1). Behavioural tree analysis indicated that the rate of redfish excluded for the 22 mm grid was 46.64% (95% CI: [40.36 – 58.51%]), while the 19 mm grid excluded 48.47% of the individuals (95% CI: [38.07 - 56.16%]).

Redfish that had no contact with the grids had a 100% probability of escaping (p-value = 0.980). Regarding grid reaction, the model results indicated that the probability of escaping was increased by 97.13% and by 99.90% for redfish that remained steady and reacted by swimming upwards, respectively, when compared to redfish that had towards or forward grid reactions (p-values < 0.001) (Table 5.1). Finally, for a one unit increase in the time that redfish spent in front of the grid (i.e., 1 s) the probability of escaping was increased by 58.85% (p-value < 0.001). The mean time from detection to fate (t) was 1.95 s (95% C.I.: 1.72 – 2.44 s) and 1.75 s (95% C.I.: 1.39 - 2.34 s) for the 22 mm and 19 mm Nordmøre grids, respectively, according to the results of the behavioural trees. The mean observed raw time from first redfish detection to outcome was 2.01 s (Standard error of the mean (SEM) ± 0.06) and 1.70 s (SEM ± 0.05) for escaped and retained redfish, respectively (Table 5.2). Even though redfish orientation and approach behavioural stages were excluded from the GLM, redfish that were oriented away or sideways and approached upwards had the highest observed percentages of escape (

Table 5.3).

The size of the behavioural trees was reduced by excluding stage 1 (i.e., body orientation) in order to improve their readability. Raw trees with all stages are found in Supplemental figure 5.1. For stage 2, redfish that approached upwards did not contact the grid in stage 3 and reacted by moving upwards in stage 4, were excluded; there were 90 (MP = 20.4%, 95% C.I.: 16.0 – 24.2%) and 132 (MP = 27.0%, 95% C.I.: 12.7 – 37.8%) redfish that followed this behavioural sequence for the 22 and 19 mm Nordmøre grids, respectively and all the remaining fish had contact with the grids (Figure 5.4). Conversely, redfish that reacted to the grid by swimming forward or towards in stage 4 (i.e., grid reaction) were always retained; 75 and 84 redfish exhibited these behaviours in the 22 and 19 mm Nordmøre grids, respectively (Figure 5.4). Fish that reacted upwards were more likely to escape than the ones that remained passive, after contact with the grids. Behavioural sequences that were more likely to occur (i.e., with the higher marginal probabilities at the leaves) were upwards-no contact-upwards-excluded, steady-contact-passive-retained and upwards-contact-passive-retained, for both the 22 and 19 mm Nordmøre grids (Figure 5.4).

5.5. Discussion

Reducing the bar spacing from 22 to 19 mm slightly reduced the number of retained redfish (by 1.83%), however, grid reaction and time were more important variables in the GLM (*p*-values <0.001). Furthermore, the behavioural tree analysis produced trees with very similar results for both grids tested (Figure 5.4). Juvenile redfish captured and measured during the sea trials were < 150 mm total length (TL), which translates in body width (BW) < 19 mm, according to the morphometric measurement of redfish performed in the same fishing area (Araya-Schmidt et al. submitted). This suggests that juvenile redfish encountered during the experiment can pass through the 19 mm bar spacing grid due to their small size, hence a slight difference in retention of redfish was found between grids.

Over half of the redfish that entered the bottom trawl passed through the Nordmøre grids bars spacings and were retained, which explains why fishing vessels are encountering considerable amounts of juvenile redfish in their catch when considering that they are currently found in large numbers. However, results showed that a fair proportion of redfish (62.85%) reacted (upwards or sideways) when approaching the grid and once contact is made with the grid only 42.18 % remained passive, which suggest that despite their small size and limited swimming capabilities, a proportion is still able to swim or react at that point in the bottom trawl. This is especially interesting since using other devices to deter or attract redfish out of the bottom trawl could be feasible.

Similar to Larsen et al. (2017), we observed that a significant proportion of juvenile redfish (approx 26%) did not make contact with the grids. They simply approached the grid, rose, and escaped through the opening at the top of the BRD. We speculate that these redfish may have exited the trawl by following the water that is rejected through the grid opening. The phenomenon of rejected water was first described by Riedel and DeAlteris (1995). The concept was developed further by Grimaldo and Larsen (2005) and has been cited as the possible reason for the escapement of shrimp. Looking at the behavioural trees, the probability of no contact with the 19 or 22 mm grid were similar (only 6.6% higher for the 19 mm grid). This finding coincides with our flume tank observations of the grids, where there was only a minor reduction in water velocity (6.1%) behind the 19 mm grid when compared to the 22 mm grid. Therefore, water flows directed towards the opening and through the bars were generally similar, which could explain the similar contact and escapement probability of redfish between the grids tested.

Regression models and behavioural trees are complementary tools for the analysis of underwater video observations. The GLM analysis allows for answers to specific research questions, such as estimating the escape/retention probability of redfish according to the relationships between variables, while the behavioural trees provided the probabilities of escape or retention of redfish following a sequence of behavioural events, including confidence intervals at each leaf. The GLM showed that steady and upwards grid reactions drastically increased the probability of escaping, however, understanding which previous behaviours led more frequently to an upwards grid reaction are unknown using only this analysis. Behavioural trees showed that redfish that approached upwards and had no contact with the grids, were more likely to exhibit an upwards grid reaction. Therefore, both techniques combined provided comprehensive results revealing the importance of each variable on redfish outcome, but also identify the most frequent behavioural paths.

The GLM analysis showed that time (t) was an important variable; the more time redfish spend in front of the grid, the higher probability of escape (1 s increased by 58.85% the probability of escape, p-value < 0.001). Even though behavioural tree analysis provided 95% CIs for time, this variable cannot be included in the tree itself, demonstrating once more the value of performing both approaches. Even further, multiple categories in the behavioural stages and multiple behavioural stages can drastically increase the tree size, hence making it more difficult to interpret. In this particular case, only orientation stage was removed to improve tree readability, however, more complex experiments might need to exclude several behaviours in order to produce a tree that can be easily interpreted.

Understanding how species behave in response to BRD devices is key to enhancing their escapement/retention performance (Winger et al., 2010). In this study, a large proportion of redfish were initially oriented away from the grid (49 and 48% for the 19 and 22 mm grids, respectively) and approached upwards, these fish had a ~50% probability of not contacting the grid and escaping. For redfish to escape the Nordmøre grid system an upwards approach and upwards grid reaction increases the escapement probability. Therefore, designing or modifying a selection device to trigger these behaviours could greatly reduce bycatch. Isaksen et al. (1992) found that in a 19 mm bar spacing grid, angled 48°, all redfish (*Sebastes* sp.) escaped through the grid outlet. Likely lower grid angles could reduce contact with the grid and increase escapement as redfish would need to move upwards less in order to escape when compared to the 63° and 62° grids used in this experiment.

The guiding panel exit opening was observed for all tows as animals meshed and accumulated in the guiding panel meshes, this was also observed by Araya-Schmidt et al. (submitted) in a similar Nordmøre grid system. Once the guiding panel exit opened, there were no redfish seen contacting the guiding panel netting, which suggests that redfish could be avoiding the netting or water flow prevents redfish from contacting the netting. Furthermore, if the guiding panel exit were to remain in its initial position (directing catch to the lower section of the grid), redfish bycatch would likely be even higher than observed in this study. Redfish directed to the lower part of the grid would be less capable of approaching upwards to the escape opening and avoid contact with the grid. Even though northern shrimp behaviours were not quantitatively assessed, the opening of the guiding panel directed more shrimp to the top of the grid, and at high catch rates, considerable amounts of shrimp were seen exiting the grid systems as they were directed towards the grid outlet following the rejected water flow.

The Nordmøre grid with smaller bar spacings (19 mm) slightly reduced the number of redfish that were retained, according to underwater video collected in the grid system. However, the time that redfish spent in front of the grid and grid reaction better explained redfish probability of escaping; one unit increase in time and upwards or steady grid reactions drastically decreased the probability of retention. The GLM was useful for estimating retention probabilities relating all explanatory variables at once and behavioural trees showed probabilities accounting for the stepwise nature of the behaviours. Both approaches together gave a comprehensive view of the results, which is extremely useful at perfecting or developing any BRD to address juvenile redfish bycatch and/or to maintain the commercial shrimp catch rates. The most favourable behavioural sequence for redfish to escape was an upwards approach, no contact with the grid and an upwards grid reaction. Nordmøre grid systems that enhance upwards behaviour could reduce juvenile redfish bycatch, however, there should be caution as shrimp could also react to the device and escape.

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5.8. Tables

Table 5.1. Generalized linear model outcome including all variables in the lowest AICc model, estimates, standard error (SE), z-value and p(>z). * is used to show statistical significance.

Variables	Estimate	SE	z-value	p(>z)
Intercept	-5.747	1.027	-5.595	<0.001*
Time	0.358	0.088	4.089	<0.001*
Grid				
19 mm	0.264	0.227	1.167	0.243
Grid contact				
No contact	17.762	716.936	0.025	0.980
Grid reaction				
Passive	3.522	1.013	3.477	<0.001*
Upwards	6.853	1.036	6.617	<0.001*

Table 5.2. Outcome of juvenile redfish in 19 and 22 mm Nordmøre grids. Number of observations (n), percentage of the total fish observed (% total), maximum time, minimum time, mean time and standard error of the mean time from first detection to outcome (SEM) are shown.

Outcome	n	% Total	Maximum time	Minimum time	Mean time	SEM
Escaped	442	47.48%	9.39	0.52	2.01	0.06
Retained	489	52.52%	8.14	0.28	1.70	0.05

Table 5.3. Outcome of juvenile redfish in 19 and 22 mm bar spacing Nordmøre grids for the different behaviours observed. Number of observations (n), percentage of the total fish observed (% total), number of escaped fish, number of retained fish and percentage of fish that escaped are shown.

Variables	*n*		% Total		*n* Escaped		*n* Retained		% Escaped	
	19 mm	22 mm	19 mm	22 mm	19 mm	22 mm	19 mm	22 mm	19 mm	22 mm
Orientation										
Away	239	210	48.88%	47.51%	129	119	110	91	53.97%	56.67%
Sideways	62	94	12.68%	21.27%	33	43	29	51	53.23%	45.74%
Towards	188	138	38.45%	31.22%	75	43	113	95	39.89%	31.16%
Approach										
Sideways	32	48	6.54%	10.86%	9	16	23	32	28.13%	33.33%
Steady	173	187	35.38%	42.31%	49	59	124	128	28.32%	31.55%
Upwards	284	207	58.08%	46.83%	179	130	105	77	63.03%	62.80%
Grid contact										
Contact	357	352	73.01%	79.64%	105	115	252	237	29.41%	32.67%
No contact	132	90	26.99%	20.36%	132	90	0	0	100.00%	100.00%
Grid reaction										
Forward	18	17	3.68%	3.85%	0	0	18	17	0.00%	0.00%
Passive	209	186	42.74%	42.08%	47	37	162	149	22.49%	19.89%
Towards	66	58	13.50%	13.12%	0	0	66	58	0.00%	0.00%
Upwards	196	181	40.08%	40.95%	190	168	6	13	96.94%	92.82%

5.9. Figures

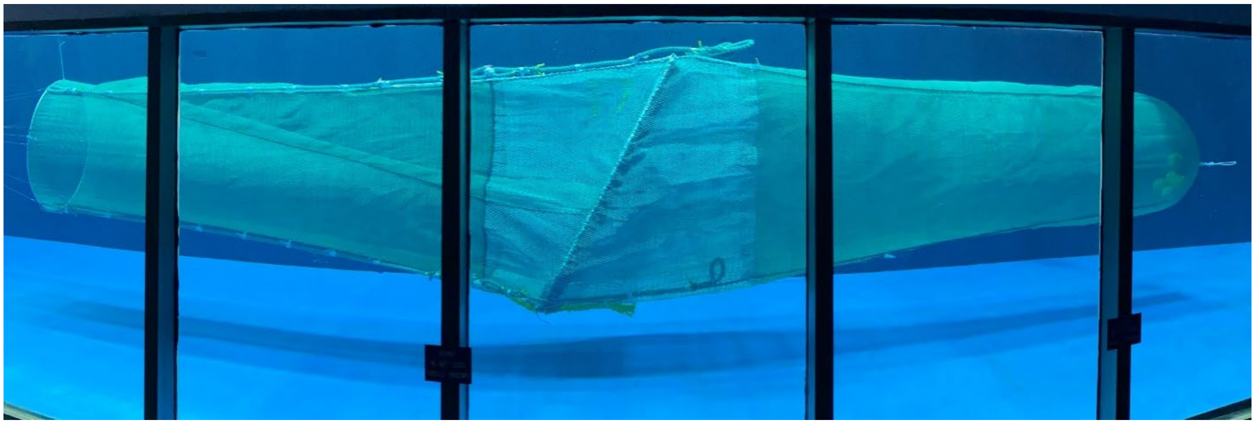


Figure 5.1. Traditional 22 mm bar spacing Nordmøre grid section during flume tank testing.

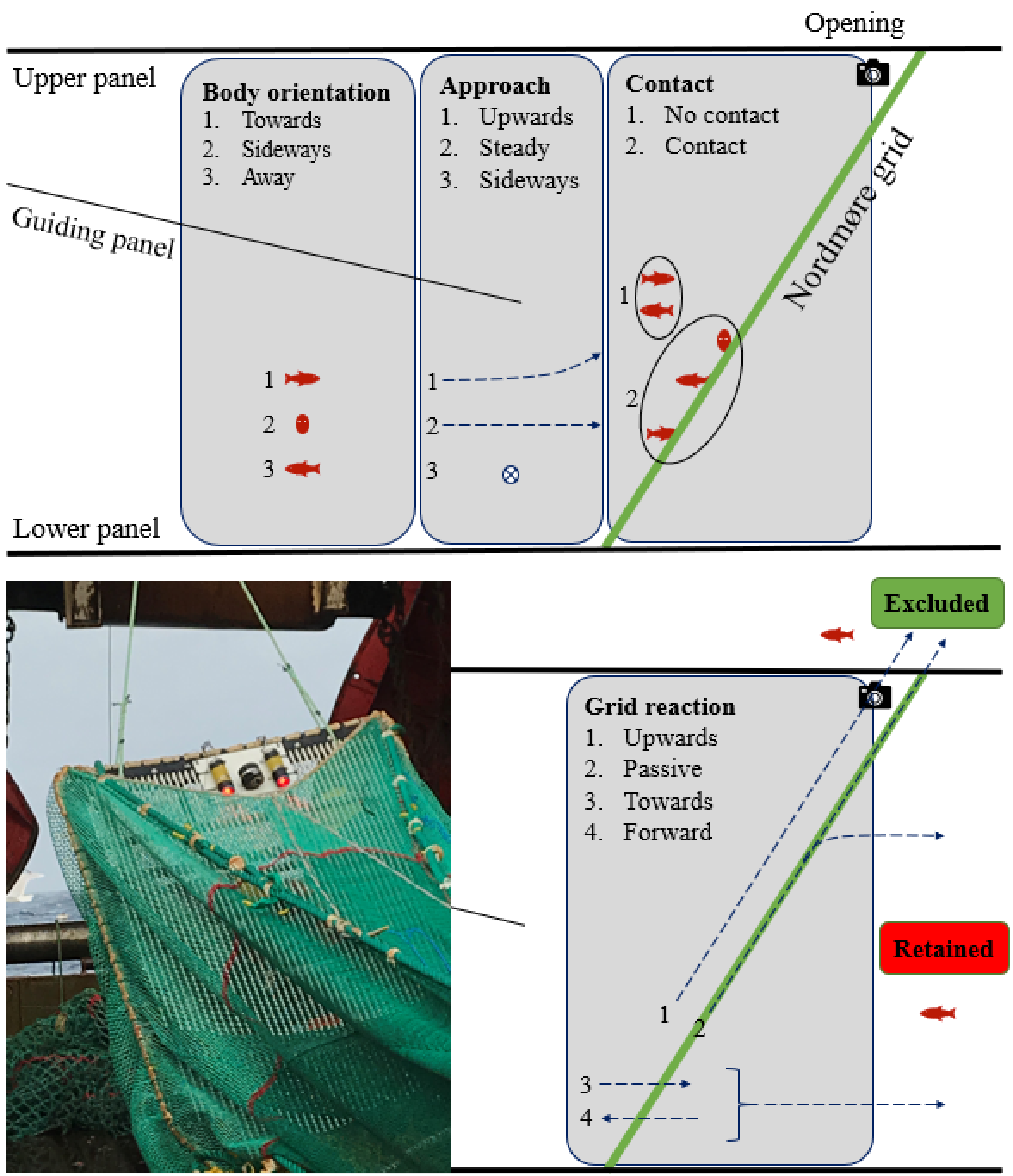


Figure 5.2. Juvenile redfish behavioural stages in a Nordmøre grid system. An image of the underwater camera mounted on the 19 mm Nordmøre grid during sea trials is shown.

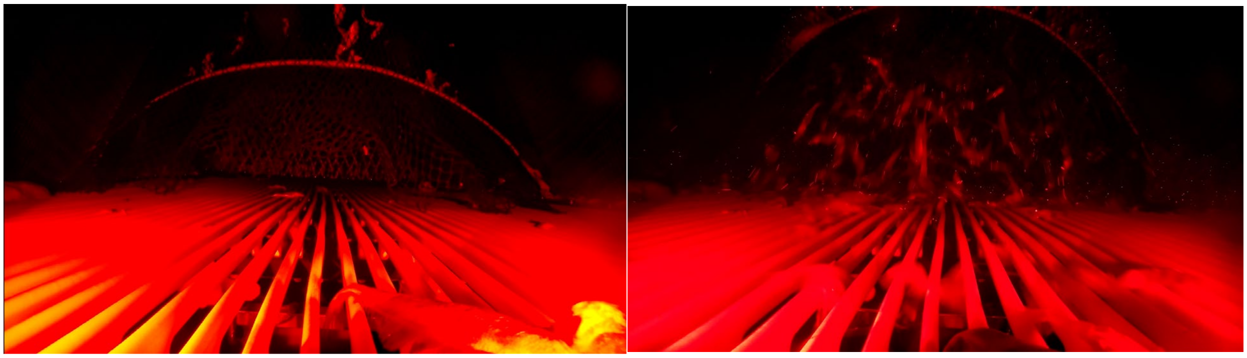


Figure 5.3. Underwater video screenshots of the 19 mm bar spacing Nordmøre grid during fishing. On the left, at the beginning of the tow, the guiding panel exit opening on its starting position. On the right, five minutes into the tow, the guiding panel exit has opened.

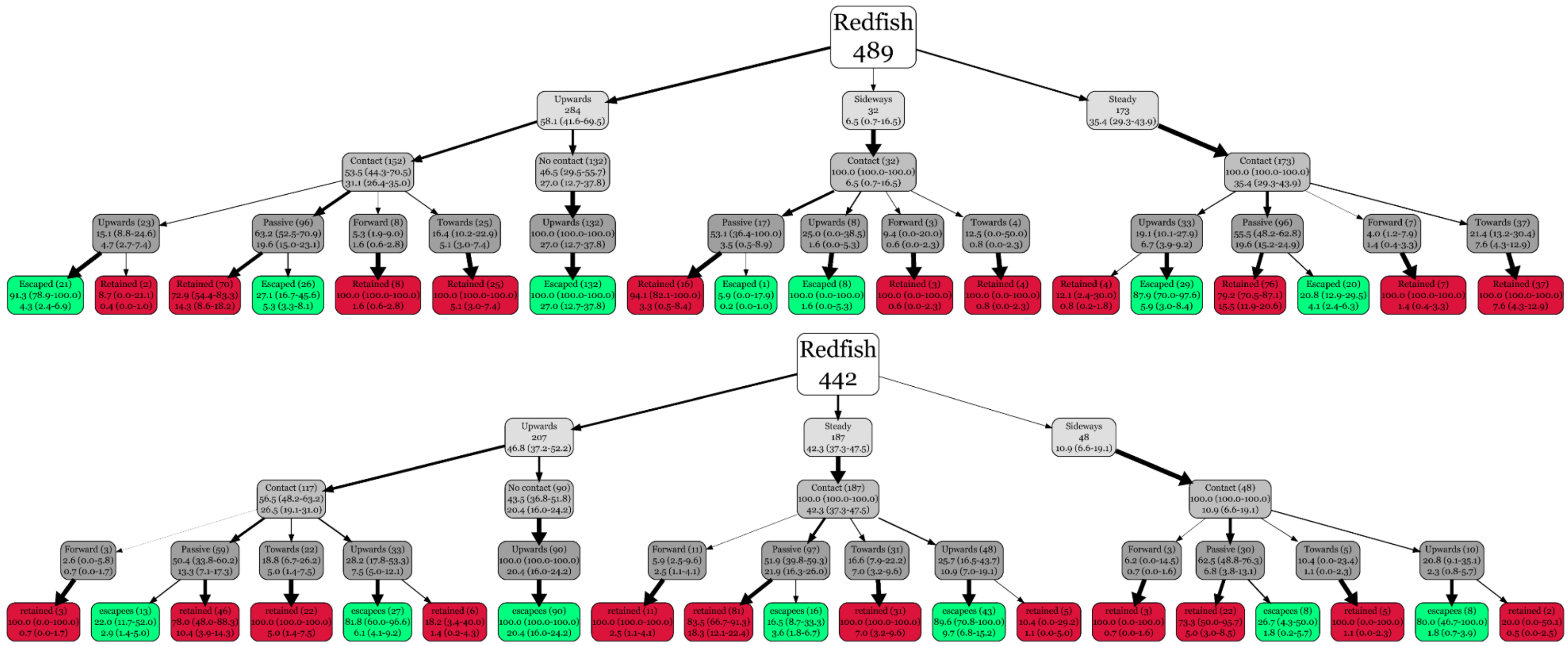
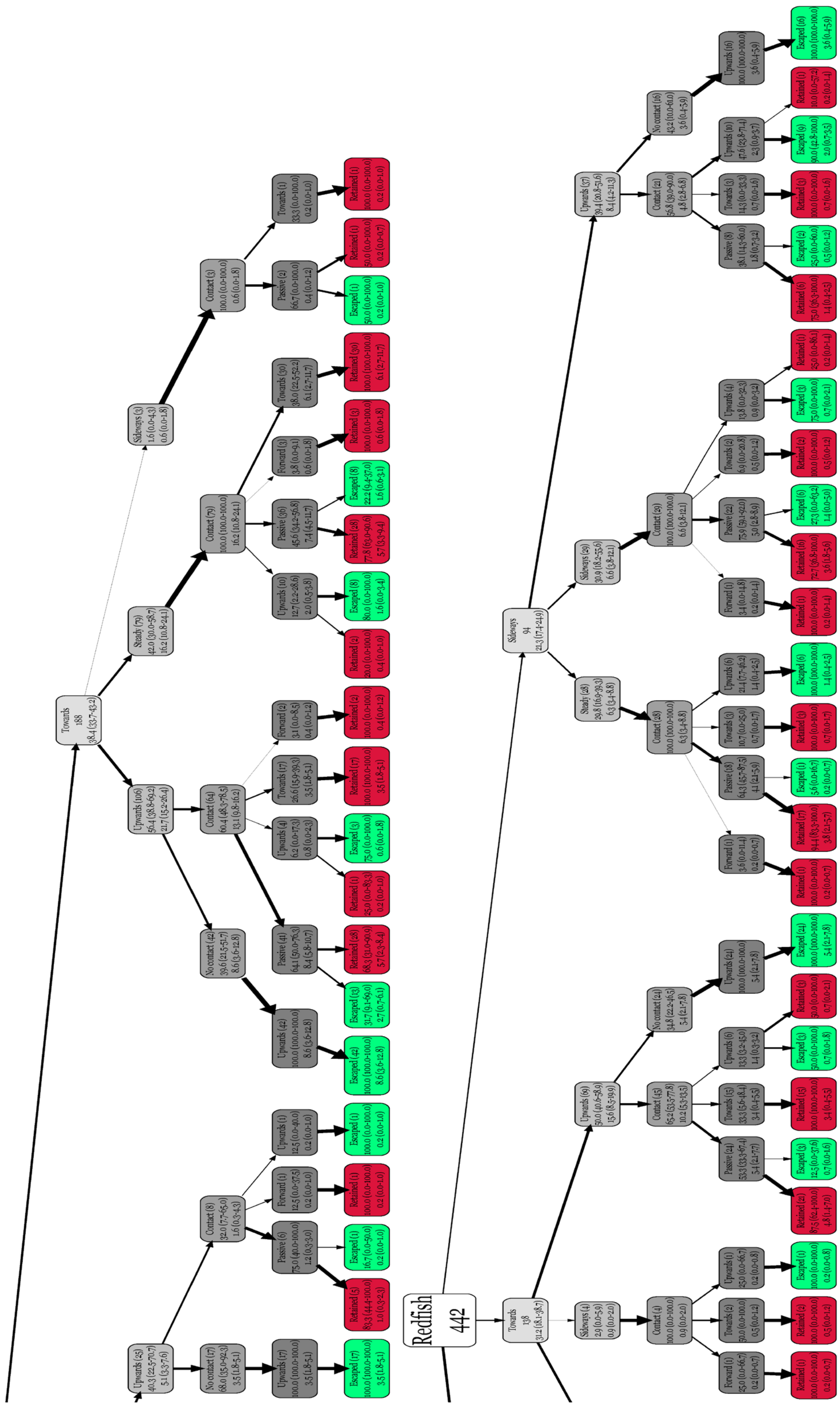
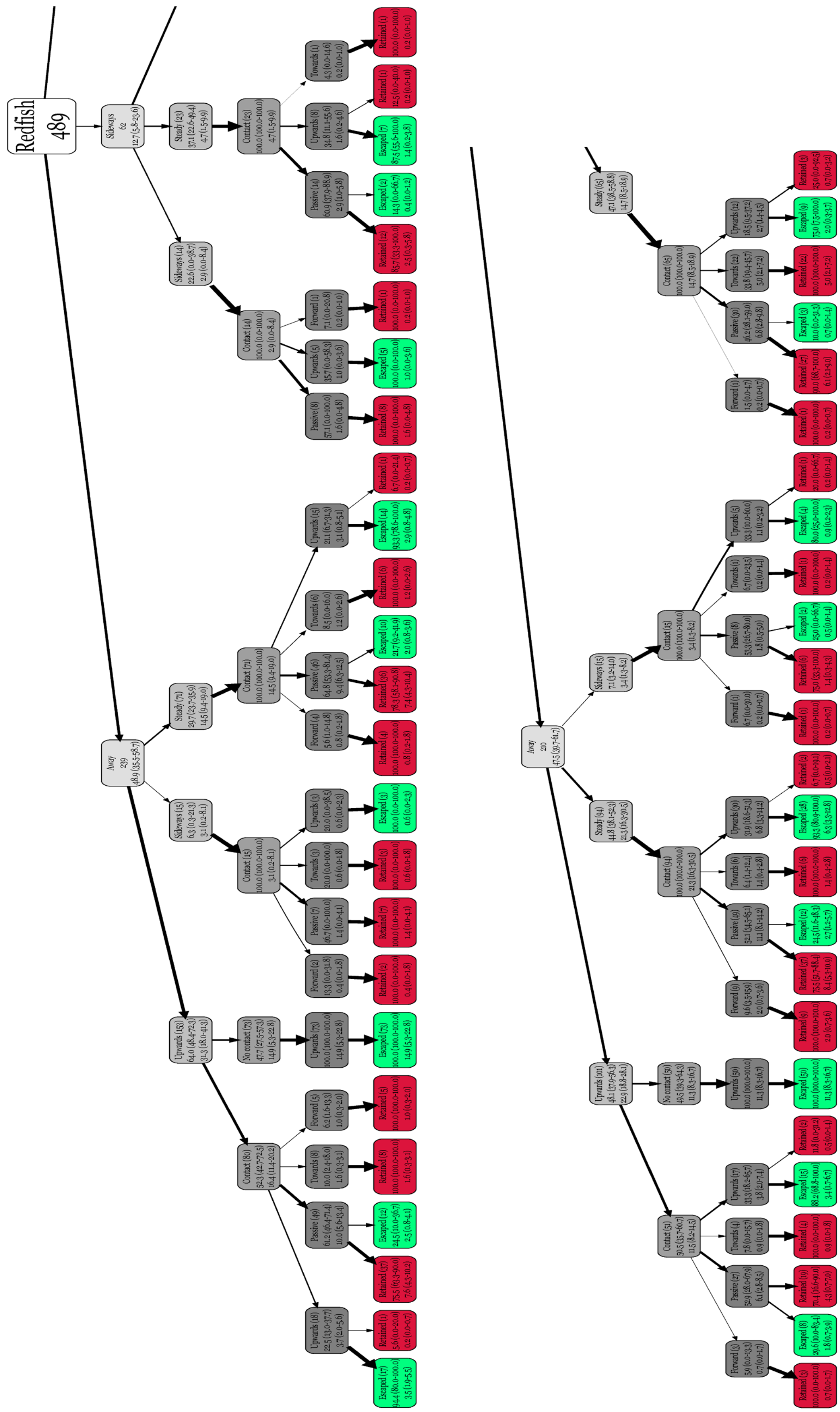


Figure 5.4. Behavioural trees for the 19 (top) and 22 (bottom) mm bar spacing Nordmøre grids. White boxes represent the tree root with the number of redfish observed, grey boxes represent the behaviours at the different behavioural stages (approach, grid contact and grid behaviour), red boxes represent redfish that were retained and green boxes redfish that escaped. On each box the number of redfish, conditional probability and marginal probability, with their respective 95% confidence intervals are

5.10. Appendices




Redfish
489

Supplemental figure 5.1. Raw behavioural trees for the 19 (left) and 22 (right) mm bar spacing Nordmøre grid. White boxes represent the tree root with the number of redfish observed, grey boxes represent the behaviours at the different behavioural stages (approach, grid contact and grid behaviour), red boxes represent redfish that were retained and green boxes redfish that escaped. On each box the number of redfish, conditional probability and marginal probability, with their respective 95% confidence intervals are shown.

CHAPTER 6. Summary and Conclusions

The purpose of this thesis was to develop bottom trawls with reduced seabed impact and reduced bycatch of juvenile redfish, which are important issues in the Eastern Canada offshore Northern shrimp (*Pandalus borealis*) and striped shrimp (*Pandalus montagui*) fishery and other bottom trawl fisheries worldwide. In the first study and as a steppingstone for the development of innovative footgear with reduced seabed impact, I investigated the performance of the traditional roller footgear technology used in the fishery using underwater video observations (Chapter 2). In my second study, I conducted a flume tank experiment to compare the performance of model scale footgears, both a traditional roller footgear and a new aligned-rolling footgear under different simulated seabed scenarios. Both footgear types were evaluated in terms of total drag (warp loads) and qualitatively validated visually as they contacted the simulated seabed rocks (Chapter 3). The next section focused on a different topic and evaluated the selectivity of reduced bar spacing Nordmøre grids during commercial fishing experiments at-sea. In my third study, I investigated the effectiveness of reduced bar spacing Nordmøre grids at decreasing juvenile redfish bycatch and maintaining shrimp catches (Chapter 4). I finally conducted underwater video observations to investigate juvenile redfish behaviour in response to the Nordmøre grid system during commercial fishing (Chapter 5). This final chapter (Chapter 6), presents and discusses the major findings of each study. I discussed the limitations of the approaches used in the studies and recommended future research directions.

6.1. Roller footgear performance in Newfoundland and Labrador's shrimp fishery

The Eastern Canada offshore Northern shrimp and striped shrimp bottom trawl fishery, as well as other inshore bottom trawl fisheries in the region, remain the only economically viable manner to efficiently capture shrimp. They are a key component of Newfoundland and Labrador's fishing industry and economy. However, ecological impacts associated with bottom trawling (locally and worldwide) have been often questioned by NGOs and the public, who demand more environmentally friendly fishing practices. Specifically, topics such as seabed impact, bycatch and fuel consumption (i.e., carbon dioxide emission) are of high interest.

The investigation of the traditional roller footgear used in the Northern shrimp fishery (i.e., Chapter 2) provided evidence that the technology is not performing as expected by the fishing industry. As its name indicates, the footgear is designed to roll over the seabed. However, findings suggested that the footgear sections are rotating at very low levels. Surprisingly, the bosom section located in the center of the footgear, where the section axis is oriented ~90% relative to the direction of tow, also produced low rotation rates. The footgear had reduced rolling forces, which translates into higher sliding friction and digging forces (Fridman, 1986). Therefore, we speculate that the roller footgear under study behaved in a similar way to a rockhopper footgear, which uses similar components but does not roll. This investigation not only provided useful information on the current technology but also documented a novel technique for quantitatively analyzing footgear performance using underwater video observations.

The use of such footgear in the fishery has many implications. Since the footgear is one of the main bottom trawl components in contact with the seabed, a footgear that poorly performs can greatly contribute to the overall seabed impact and drag of the bottom trawl. We hypothesize that a non-rolling footgear, with most of the rubber discs misaligned with respect to the towing direction, could produce a higher seabed impact and drag when compared to wheeled footgears (Ball et al., 2003; He and Balzano, 2010; Murphy, 2014), aligned footgears (Winger et al., 2018, Munden, 2013) or footgears that have reduced weight or area of contact with the seabed (Sterling 2008; Broadhurst et al., 2015; Nguyen et al., 2015; Brinkhof et al., 2017; McHugh et al., 2017; Larsen et al., 2018).

Despite the many efforts to develop footgears with reduced seabed impact, to our knowledge, there has not been an adoption of these technologies in commercial fisheries. Perhaps studies like the one presented in Chapter 2 can provide valuable information to the fishing industry so they can realize to what extent their current technology is achieving the desired performance. With empirical evidence that a footgear is underperforming, users are more likely prone to modifying, testing and up-taking footgear technologies that can reduce seabed impacts, drag, and fuel consumption.

6.2. Development of footgear with reduced seabed impact

Building on previous roller footgear concepts (Ball et al., 2003; Zachariassen, 2004; He and Balzano, 2010; Winger et al., 2018) and with the evidence of current footgear poor performance found in Chapter 2, my next study (Chapter 3) designed and evaluated an innovative aligned-rolling footgear. Using a model scale bottom trawl commonly used in the fishery, traditional roller footgear and aligned-rolling footgear were exposed to various simulated seabed types of different roughness in the Marine Institute's flume tank in St. John's, Newfoundland and Labrador. While the flume tank has a flat moving belt, we used simulated seabed scenarios with rocks to observe the new footgear's behaviour when encountering rocks and validate the prototype before future sea trials.

Findings suggested a reduction in warp load and a substantial reduction in the width of contact for the bottom trawl, simply by aligning footgear rubber discs with the towing direction. Reduced drag was attributed to a reduction in contact points, alignment with towing direction, and rotation of the footgear components, replacing most of the sliding friction by rolling friction forces. Results were encouraging and demonstrate the potential of the invention to reduce seabed impact and drag in the Northern shrimp fishery locally and in other bottom trawl fisheries around the world.

6.3. Juvenile redfish bycatch reduction with smaller Nordmøre grid bar spacings

With the introduction of the Nordmøre grid in the 1990s in the Northern shrimp fishery, bycatch levels were reduced drastically and remained at low levels for the last three decades. However, a recent increase in juvenile redfish abundance off the coast of eastern Canada has increased bycatch levels creating a new challenge for the fishery. Redfish was considered threatened in 2010 (Government of Canada, 2021). It is a slow-growing and long-lived species, suggesting that mortality of juvenile redfish could have a negative impact on the recruitment, biomass and recovery of the stock, as well as an impact on the trophic structures of communities, affecting other important commercial fisheries (Dayton et al., 1995; Devine and Haedrich, 2011). This issue has impacted the fishery in many ways. When bycatch levels exceed 2.5% or 100 kg of the total catch, the "move away protocol" is triggered, and fishing vessels must change their fishing area by a minimum of 10 NM (DFO, 2018). This increases time at sea, fuel consumption, and represents a safety issue when ice conditions are poor. Furthermore, increased amounts of redfish in the catch can reduce shrimp quality.

To address the environmental and operational concerns produced by juvenile redfish bycatch, the Nordmøre grids with reduced bar spacings were tested in Chapter 4. Findings suggested that reducing bar spacing from 22 mm to 17 and 15 mm significantly reduced juvenile redfish bycatch and maintained shrimp catches. However, there is a proportion of redfish that are as small as shrimp (i.e., their body width is equal to shrimp carapace width) and fit through the reduced bar spacing grids. Furthermore, larger shrimp are just small enough to pass through the 15 mm grid, if further bar spacing reductions are tested (i.e., 14 or 13 mm) it is likely that the larger and most valuable shrimp will be lost. To achieve smaller redfish exclusion, we recommend further research on behavioural BRDs to separate redfish and shrimp based on their differences in behaviour and not based on size.

Results are encouraging and multiple fishing vessels have adopted the smaller bar spacing grids after this research was completed. This has enabled the continuity of the fishing activity. However, bycatch remains above historical levels, hence further BRDs need to be developed and implemented to ensure the sustainability of the fishery.

6.4. Understanding redfish behaviour to aid in the development of BRDs to increase escapement

Direct observation of species behaviour using underwater video observations is an extremely powerful tool to assess, develop and improve BRDs or fishing gear in general (Bayse et al., 2014, 2016; Underwood et al., 2015; Queirolo et al., 2010, 2019; Santos et al., 2020;

Ahumada et al., 2021; Chladek et al., 2021ab). With catch comparison data alone, we can only guess what processes are occurring behind the selection of a certain device. Where possible, it is always recommended to incorporate underwater video observations during at-sea trials. For Chapter 3 we used underwater footage of the Nordmøre grids under operation to interpret the size selectivity results and observe Nordmøre grid system performance. Furthermore, during sea trials presented in Chapter 5 we were performing both, a selectivity experiment and underwater video observations, nevertheless only underwater video data was used for the study, as catch comparison data was affected due to alternate haul methodology and high variability in species abundance between areas, proving the value of including underwater video, using relatively simple equipment.

Main findings from Chapter 5 suggests that the 19 mm bar spacing Nordmøre grid slightly reduced the number of redfish that were retained. However, the proportion of redfish captured by the traditional and experimental gear for the different size classes is not known, as this can only be estimated in a size selectivity experiment where redfish are measured. Chapter 5 revealed why vessels in the fishery are encountering high amounts of redfish bycatch on many tows - over half of the redfish that entered the bottom trawl were retained.

Interestingly, a fair proportion of redfish reacted when approaching the grid (62.85%) and one-fourth of these redfish escaped through the bycatch outlet without contacting the grid. These results suggest that despite the small size of redfish, limited swimming capabilities and energy spent in the trawl while transiting to the grid section, a proportion are still able to swim and react to the grid system components. Quantifying these behaviours and understanding how redfish react to the grid system is extremely useful to enhance its escapement (Winger et al., 2010). In this case, modifying the Nordmøre grid system or designing a new behavioural BRD that triggers an upwards swimming behaviour could be more effective and could greatly reduce redfish bycatch in the fishery.

6.5. Limitations of my approach

Underwater video of the current footgear technology used in the fishery (Chapter 2) provided important results. However, I recognize that results need to be interpreted with caution as the observations were performed aboard one vessel with one bottom trawl. This was a major limitation of the study. Ideally, the experiment would have included several vessels in the fleet with varying versions of the roller footgear and for different seabed types, as they might perform differently. I also acknowledge that sample sizes were small due to 1) low visibility that resulted in discarded video and 2) the challenges associated with performing such experiments during commercial fishing operations (i.e., slowing down fishing operations which sometime is not supported by the vessels).

Regarding the flume tank testing study (Chapter 3), the main limitations of my approach were the size of the plates used for the simulated seabed and the fact that the rocks were fixed to the plates when in reality bottom trawl footgear is capable of moving and displacing rocks (Freese et al., 1999). Regarding the first limitation, I feel that larger simulated seabed plates across the whole tank width would have better mimicked the bottom trawl being towed over the rocky seabed. Instead, the plates used my study only covered part of the trawl path, leaving the remaining sections in contact the flat moving belt. Regarding the second limitation, rocks were glued (i.e., fixed) to the plates, which did not permit the displacement of rocks and its effects on warp tension. This was a purely practical requirement as loose rocks in the flume tank would have been unacceptable. Finally, I recognize that the study could have included different towing speeds to estimate its effect on warp tension. However, this would have considerably increased flume tank time and costs.

The size selectivity experiment with reduced bar spacings (Chapter 4) used a twin-trawling catch comparison method. However traditional and experimental grids were installed in starboard and port bottom trawls, respectively, and remained in that position during the trials. Even though I carefully inspected the trawls to ensure they were equal, swapping the grids would have improved the certainty of the results obtained. Furthermore, due to the large catches during commercial fishing, the resultant sub-sampling ratios for redfish and shrimp were small. Shorter tows and smaller catches would have allowed me to increase the sub-sampling ratio or even weigh and measure all catch, increasing the robustness of the results. Limitations were due to the commercial nature of the fishing trip and trade-offs needed to be made to continue fishing efficiently while the experiments were being performed.

Finally, the major limitation for the redfish behaviour study (Chapter 5) was that I was only able to compare the performance of the grids based on the number of redfish that were retained or excluded. Therefore, the information on which size redfish were present in each tow and the size selectivity of the grids remains unknown. Furthermore, videos were obtained from different tows in different areas (i.e., not using twin-trawling method video recording the two grids at the same time), therefore redfish size, shrimp abundance, water current, and other factors could have affected redfish behaviours and outcome. In the future, I recommend using the twin-trawling method and recording traditional and experimental BRDs simultaneously or controlling for other variables in the experiment by estimating total catch, measuring redfish size, among others.

6.6. Recommendation for future research

The reduction of seabed impacts and bycatch in bottom trawls are extremely important topics and extensive research efforts are needed to continue developing environmentally friendly fishing gears that can meet the sustainability standards expected by the many stakeholders involved in such fisheries. In the following section, I provide a list of recommendations for future research that could help achieve these goals, as well as solve some of the limitations of the approaches presented in this thesis.

Regarding seabed impact reduction technologies:

1) Further investigate current roller footgears used in the fishery, including more vessels and different types of roller footgears on different fishing grounds.
2) Perform at-sea trials for the aligned-rolling footgear to validate the full-scale prototype, add several wheeled components and use underwater video observations to assess their performance.
3) Perform a catch comparison study between the traditional and aligned-rolling footgear to understand its effect on shrimp catches and bycatch of other species.
4) Study trawl geometry between traditional and aligned-rolling footgear.
5) Measuring drag of traditional and experimental bottom trawls to validate the hypothesis of reduced drag force of the new footgear.

6) If this footgear is implemented in the fishery, I recommend quantifying the benefits of this new footgear technology by measuring and comparing the impacts on the benthic habitat compared to the traditional roller footgear (Løkkeborg, 2005). Alternatively, benthic impacts could be modeled to assess the new technology and its seabed impact reduction (Smeltz et al., 2019).

Regarding the reduction of juvenile redfish bycatch:

1) Develop a behavioural BRD and perform a size selectivity experiment to increase juvenile redfish exclusion in the fishery.
2) Collect further underwater video of redfish behaviour at different locations on the bottom trawl (i.e., footgear, headline, wings, belly and others) to inform the process of developing behavioural BRDs that could solve juvenile redfish bycatch issue.
3) Investigate biological aspects of redfish, such as their sensory system, visual acuity and swimming endurance that could provide information to enhance exclusion.
4) Evaluate and document redfish survival (or behavioural impairment) after being excluded from the bottom trawl.
5) Further develop or improve the guiding panel used in the grid system to reduce shrimp exclusion, as seen throughout this research in multiple underwater videos during high catch rates.
6) Test Nordmøre grids with lower angles (Isaksen et al., 1992) and their effectiveness at reducing juvenile redfish bycatch and maintaining shrimp catch.

6.7. References

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