DEVELOPING BOTTOM TRAWLS TO IMPROVE SIZE AND SPECIES SELECTIVITY IN NORTH ATLANTIC FISHERIES

by

© Vang Y. Nguyen

A thesis submitted to the

School of Graduate Studies in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy in Fisheries Science

Centre for Sustainable Aquatic Resources, School of Fisheries
Fisheries and Marine Institute
Memorial University of Newfoundland

October 2023

St. John's, Newfoundland and Labrador

ABSTRACT

Bottom trawling is an important and principal capture technique in groundfish fisheries, providing a high proportion of fisheries production to the Northern Atlantic. However, bottom trawling is associated with the bycatch of undersized fish and unwanted species, a large concern from a marine ecosystem perspective. Thus, developing gear designs to improve trawl selectivity (reduce the capture of non-target species and juveniles of target species) is necessary. This thesis has focused on developing trawl designs for an emerging redfish (*Sebastes* spp.) fishery in Canada and understanding the groundgear selectivity of an Icelandic commercial bottom trawl. Firstly, I developed a shaking codend by attaching an elliptical-shaped canvas at the posterior of a T90 codend (codend mesh rotated 90° in the transversal direction) to reduce the capture of undersized redfish in the catch. The results showed that the shaking codend had a higher amplitude ratio, period, and total acceleration and captured less redfish < 22 cm than the T90 codend without canvas. Secondly, I developed a semi-pelagic trawl to capture redfish using the French rigging technique. Semi-pelagic trawls are effective at capturing redfish off the seabed and potentially reduce bycatch of unwanted species. Next, I quantified the length-dependent escape of fish under a commercial bottom trawl in Iceland. The results showed length-dependent escape for roundfish, where more small fish escaped under the groundgear than did large fish, compared with flatfish, whose escape varied among species. Finally, I quantified fish behavior at the mouth of a bottom trawl. Small roundfish (Atlantic cod (*Gadus morhua*) < 20 cm and haddock (*Melanogrammus aeglefinus*) < 11 cm) tend to escape under the trawl at the center area of the groundgear, while larger individuals with greater swimming capacity seek escape openings under the fishing line at the wing areas. For flatfish and monkfish, the results varied. These length-dependent behaviors are related to fish response behavior, escape behavior, size, and likely swimming capacity. The findings of this thesis can have potential implications for the development of the emerging redfish fishery in Canada and for developing groundgear to improve bottom trawl selectivity in North Atlantic fisheries.

GENERAL SUMMARY

Bottom trawling (towing a net along the ocean floor to capture fish on or near the seabed) is an important and principal capture technique in groundfish fisheries, providing a high proportion of fisheries production in the Northern Atlantic. However, bottom trawling retains a large number of undersized fish and unwanted species in its codend (i.e., the ended section of the trawl net, where fish are collected until the net is hauled), involving a reduction in the population productivity of some fisheries. These bycatch issues have been happening for both single and multi-species bottom trawl fisheries in the North Atlantic. As a part of many attempts to improve the trawl selectivity (i.e. reduce the bycatch of undersized fish and unwanted species) in North Atlantic fisheries, I developed a shaking codend for the upcoming redfish (*Sebastes* spp.) fishery in the Gulf of St. Lawrence, Canada (Chapter 2). Findings showed that the shaking codend could reduce the capture of small redfish (< 22 cm). Secondly, I developed a semi-pelagic trawl (the trawl can fish off the seabed while maintaining the trawl doors in contact with the seabed), which is effective at catching redfish and offers potential for reducing the capture of main bycatch species in the redfish fishery (Chapter 3). Thirdly, I examined fish escapement under a typical commercial bottom trawl (Chapter 4). Findings showed that more small roundfish (fish that have a round shape in the cross-section and a body which tapers to a tail) escaped under the groundgear compared to large roundfish, and flatfish (fish that have oval, bony, and flattened bodies, swim on its side, and have both eyes on one side of the head) escape varied among species. Finally, I investigated fish behavior in response to an approaching trawl (Chapter 5) and found that small roundfish preferred to escape under the trawl at the center area of the trawl opening, while large fish escaped more often at the side areas of the trawl opening; flatfish behavior varied among species. This thesis provides important advancements regarding the

development of an emerging redfish fishery in Canada and groundgear to improve bottom trawl selectivity for Northern Atlantic fisheries.

ACKNOWLEDGEMENTS AND AUTHORSHIP

Acknowledgements

Firstly, I would like to express my special thanks to my supervisors: Drs. Shannon Bayse and Paul Winger, for their incredible supervision, excellent guidance, and scholarly support throughout my research at the Fisheries and Marine Institute of Memorial University for almost the last five years. Dr. Shannon Bayse has supported me at the beginning of my study, always behind me with very thorough teaching and guidance in every step of research. I do believe that I have learned a lot from him. I cannot imagine how my thesis could have been possible without his kind help. Dr. Paul Winger supported me with an opportunity to extend my study at Fisheries and Marine Institute since I was in my master's program at Nha Trang University, Vietnam. I will never forget this excellent opportunity that made me much stronger in my favorite field, fisheries research. I am also highly grateful to Dr. Paul Winger's supervision for the first year and mentorship as co-supervisor and committee member in the remaining times of my research.

I would like to thank the members of my supervisory committee: Drs. Paul Winger and Pingguo He, for their valuable guidance and advice during my thesis. There were a lot of things I have learned from my supervisory committee members; those will be of great use for my upcoming career. I am also grateful to Drs. Brett Favaro, Paul Winger, Arnault Le Bris, Scott Grant, Johnathan Fisher, and Sherrylynn Rowe for their great lectures; they were very helpful during my thesis. Many thanks to Drs. Haraldur Arnar Einarsson and Ólafur Arnar Ingólfsson for providing valuable data for two chapters of the thesis and reviewing the manuscripts.

I have loved being a member of the Centre for Sustainable Aquatic Resources' (CSAR) team. My research was completed with a lot of help from CSAR staff, including Harold

DeLouche, Craig Hollett, George Legge, Mark Santos, Kelly Moret, Meghan Donovan, and lab-mates Zhaohai Cheng, Gebremeskel Kebede and other grad students at CSAR. I would also like to extend my many thanks to my colleague, Dr. Khanh Nguyen, and his family, for their kind welcome and help when I first arrived at St. John's and at CSAR.

I also wish to acknowledge fisher partners Captains Rodney and Les Dredge and the crew of the F/V *Lisa M,* and the research vessel "Árni Friðriksson" crew for their assistance during the field experiments.

Financial support for this thesis was provided by The Canada First Research Excellence Fund (CFREF) through the Ocean Frontier Institute (Module H), the Canadian Centre for Fisheries Innovation (CCFI), the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant (awarded to Shannon Bayse), the Government of Newfoundland and Labrador through the Department of Industry, Energy and Technology, Northern Coalition, Fisheries and Marine Institute Startup Grant, Fisheries and Oceans Canada (DFO), and Iceland Marine and Freshwater Research Institute.

Finally, I am extremely grateful for the constant support and encouragement from my wife, Thuy Tran, throughout these years for everything she has done for me. This would have never been possible without her willingness and courage to start life in a new place. She gave up her academic work in high school and her best friends in Vietnam. She always felt very happy taking care of children and working hard to support our family and finances during my studies; all too just let me be comfortable during my studies.

Co-Authorship Statements

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

Chapters 1 and 6

Vang Y. Nguyen: Writing - original draft, Writing - review & editing, Visualization. **Shannon M. Bayse**: Writing – review & editing, Supervision. **Paul D. Winger**: Writing - review & editing, supervision. **Pingguo He**: Writing - review & editing, supervision.

Chapter 2

Published in PLoS ONE 18(1): e0280751; https://doi.org/10.1371/journal.pone.0280751

Vang Y. Nguyen: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Shannon M. Bayse**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Zhaohai Cheng**: Data curation, Investigation, Writing – review & editing. **Paul D. Winger**: Data curation, Funding acquisition, Investigation, Writing – review & editing. **Harold DeLouche**: Investigation, Writing – review & editing. **Gebremeskel Eshetu Kebede**: Investigation, Writing – review & editing. **George Legge**: Investigation, Writing – review & editing.

Chapter 3

Published in PeerJ 11:e16244; https://peerj.com/articles/16244/**Vang Y. Nguyen:** Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Shannon M. Bayse**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Paul D. Winger**: Data curation, Funding acquisition, Investigation, Writing – review & editing. **Harold DeLouche**: Data curation, Investigation, Writing – review & editing. **George Legge**: Data curation, Investigation, Writing – review & editing.

Chapter 4

Published in Fisheries Research; https://doi.org/10.1016/j.fishres.2023.106796

Vang Y Nguyen: Validation, Formal analysis, Writing - original draft, Writing – review and editing, Visualization. **Shannon M Bayse:** Validation, Formal analysis, Writing – review and editing, Visualization. **Haraldur Arnar Einarsson:** Conceptualization, Method, Validation, Investigation, Resources, Data curation, Writing – review and editing, Supervision, Project administration, Funding acquisition. **Ólafur Arnar Ingólfsson:** Conceptualization, Method, Validation, Investigation, Data curation, Writing – review and editing.

Chapter 5

Published in PeerJ 11: e14746; https://doi.org/10.1371/journal.pone.0280751

Vang Y Nguyen: Validation, Formal analysis, Writing - original draft, Writing – review and editing, Visualization. **Shannon M Bayse:** Validation, Formal analysis, Writing – review and editing, Visualization. **Haraldur Arnar Einarsson:** Conceptualization, Method, Validation, Investigation, Resources, Data curation, Writing – review and editing, Supervision, Project administration, Funding acquisition. **Ólafur Arnar Ingólfsson:** Conceptualization, Method, Validation, Investigation, Data curation, Writing – review and editing.

TABLE OF CONTENTS

ABSTRACT ii

GENERAL SUMMARY iv

ACKNOWLEDGEMENTS AND AUTHORSHIP vi

TABLE OF CONTENTS x

LIST OF TABLES xv

LIST OF FIGURES xviii

LIST OF ABBREVIATIONS AND SYMBOLS xx

CHAPTER 1: Introduction and Overview 1

1.1 Bottom trawl and selectivity of bottom trawls 1

1.2 Fish behavior and factors influencing fish behavior near trawls 4

1.2.1 Fish behavior near trawls 4

1.2.2 Factors influencing fish behavior near trawls 7

1.3 Gear modifications to improve the selectivity of bottom trawls 9

1.4 Methods to evaluate size selectivity 12

1.4.1 Absolute size selectivity 13

1.4.2 Relative size selectivity 17

1.4.3 Underwater observations 18

1.5 Redfish fishery in Canada 19

1.6 Icelandic groundfish fisheries 24

1.7 Research objectives and chapter outlines 28

1.8 References 29

1.9 Figures 52

CHAPTER 2. Developing a full-scale shaking codend to reduce the capture of small fish 56

2.1 Abstract 56

2.2 Introduction 57

2.3 Materials and Methods 60

2.3.1 Flume tank experiment 60

2.3.2 Flume tank experiment analysis 63

2.3.3 Sea trials 64

2.3.4 Sea trials analysis 67

2.4 Results 70

2.4.1 Flume tank experiment 70

2.4.2 Sea trials experiment 72

2.5 Discussion 74

2.6 Acknowledgements 80

2.7 References 80

2.8 Tables 89

2.9 Figures....100

CHAPTER 3. Developing a semi-pelagic trawl to capture redfish in the Gulf of St. Lawrence, Canada....107

3.1 Abstract....107

3.2 Introduction....108

3.3. Materials and Methods....111

3.3.1. Model construction, flume tank test, and full-scale modifications....111

3.3.2. Field tests....113

3.4 Results....117

3.4.1. Flume tank test and full-scale modifications....117

3.4.2 Field experiment No. 1....118

3.4.3 Field experiment No. 2....121

3.5 Discussion....123

3.6 Acknowledgements....128

3.7 References....129

3.8 Tables....137

3.9 Figures....143

CHAPTER 4. Quantifying fish escape under a bottom trawl....148

4.1 Abstract....148

4.2 Introduction....149

4.3 Materials and Methods 153

4.3.1 Sea trials 153

4.3.3 Catch sampling 154

4.3.4 Data analysis 154

4.4 Results 159

4.4.1 Length-dependent escape 160

4.4.2 Diurnal and depth variations in length-dependent escape 164

4.5 Discussion 166

4.6 Acknowledgements 171

4.7 References 171

4.8 Tables 180

4.9 Figures 190

CHAPTER 5. Inferring fish behavior at the trawl mouth from escape location 198

5.1 Abstract 198

5.2 Introduction 198

5.3 Materials and Methods 202

5.3.1 Sea trials 202

5.4 Results 206

5.5 Discussion 209

5.6 Acknowledgements 217

5.7 References 217

5.8 Tables 223

5.9 Figures 226

CHAPTER 6. General conclusions 232

LIST OF TABLES

Table 2.1. The mean moving angle of a shaking codend at each flow velocity and linear regression summary tested in a flume tank. 89

Table 2.2. The mean values for total acceleration (TA), amplitude ratio, and period of a shaking and T90 codend tested in five different flow velocities during a flume tank test. 90

Table 2.3. Flume tank experiment analyses comparing the total acceleration, drag forces, amplitude ratio, and period between a shaking codend and T90 codend. 91

Table 2.4. Summary of total acceleration linear regression, drag force linear regression, amplitude ratio linear regression, and period generalized linear model comparing total acceleration, amplitude ratio, and period between a shaking and T90 codend during a flume tank test. 93

Table 2.5. Operational conditions for sea trials testing the size selectivity of shaking and T90 codends. 96

Table 2.6. Subsample number, amplitude ratio, and period of the shaking codend when tested during sea trials. 98

Table 2.7. AIC values for fit size selectivity models. 98

Table 2.8. Results from the best fit size selectivity models. 99

Table 3.1. The geometry of a scaled semi-pelagic trawl comparing rigging scenarios tested in a flume tank. 137

Table 3.2. Detailed description of each variable used to describe the behavioral sequence of redfish at the trawl mouth of semi-pelagic trawl..137

Table 3.3. Trawl system performance observed for each haul during field experiment No. 1....138

Table 3.4. Observed behavior of redfish at the trawl mouth in relation to capture outcome (enter the trawl or escape under the groundgear). 139

Table 3.5. Fish behavior when on-bottom trawling. 140

Table 3.6. Fish behavior when off-bottom trawling..140

Table 3.7. BICc values were estimated for two best models 141

Table 3.8. Observed behavior of escaping redfish at the trawl mouth...142

Table 4.1. Operational conditions for valid hauls during sea trials...180

Table 4.2. Overview of collected data...181

Table 4.3. AIC estimated for each candidate model by species..182

Table 4.4. Parameters of selected models estimated for each species. 183

Table 4.5. AICc values were estimated for several models applied to examine the light effect on the escape of several species 184

Table 4.6. Akaike’s information criterion (AIC) estimated for each candidate model for haddock between day and night...186

Table 4.7. Parameters of selected models estimated for roundfish between day and night.........187

Table 4.8. Parameters of selected models estimated for flatfish and monkfish between day and night...188

Table 5.1. Overview of valid tows observed for each species 223

Table 5.2. AICc values were estimated for each candidate model for each species 224

Table 5.3. GLMM parameters for catch-at-length comparison. 225

LIST OF FIGURES

Figure 1.1. The basic components of a typical commercial bottom trawl (Adapted from Montgomerie, 2015) ... 52

Figure 1.2. Schematic drawing of capture process of bottom trawl (Winger et al., 2010) ... 53

Figure 1.3. Redfish stock management areas in Canada include Unit 1 (the Gulf of St. Lawrence), Unit 2, and 3 (DFO, 2016). ... 54

Figure 1.4. Icelandic jurisdictional boundaries and area around Iceland water closed to trawling by the late 1970s (Halliday and Pinhorn, 1996). ... 55

Figure 2.1. Canvas specification and location on codend. ... 100

Figure 2.2. Map of fishing trials in the Gulf of St. Lawrence, Canada.. ... 101

Figure 2.4. Examples of shaking codend acceleration and depth change in flume tank tests. ... 103

Figure 2.5. Boxplots of total acceleration, amplitude ratio, and period for codends evaluated in a flume tank test. ... 104

Figure 2.6. Size selectivity plots for the shaking and T90 codends. ... 105

Figure 2.7. Selectivity comparison between the shaking and T90 codend. ... 106

Figure 3.1. A 1:10 scale model was evaluated in the flume tank located at the Fisheries and Marine Institute of Memorial University of Newfoundland, Canada. ... 143

Figure 3.2. Side profile schematic of the semi-pelagic trawl system. ... 143

Figure 3.3. Location of field experiments (red rectangle) in the Gulf of St. Lawrence, Canada. 144

Figure 3.4. Camera placement and view at the trawl mouth. ... 145

Figure 3.5. Screen capture of video frames illustrates redfish behavior at the center of trawl mouth...146

Figure 3.6. Screen capture of video frames illustrates redfish behavior under the groundgear...147

Figure 4.1. Map of the study area off western Iceland...190

Figure 4.2. Net plan of the Gulltoppur trawl..191

Figure 4.3. The net plan of the collecting bags used to capture fish that escaped under the trawl. (1) illustrates the wing bags, and (2) illustrates the bosom bag. 192

Figure 4.4. Size selection curves of roundfish. 193

Figure 4.5. Size selection curve of flatfish and demersal fish..194

Figure 4.6. The selectivity curves of Atlantic cod, haddock, and dab during the day (left column) and the night (middle column) and delta curves (right column). 195

Figure 4.7. The selectivity curves of flatfish (European plaice, dab, and American plaice) and monkfish during the day (left column) and the night (middle column) and delta curves (right column)...196

Figure 5.1. Map of the study area off western Iceland..226

Figure 5.2. Net plan of the Gulltoppur trawl..227

Figure 5.3. The net plan of the collecting bags used to capture fish that escaped under the trawl. (1) illustrates the wing bags, and (2) illustrates the bosom bag. 228

Figure 5.4. The length frequency and escape-at-length curves of roundfish. 229

Figure 5.5. The length frequency and escape-at-length curves of flatfish. 230

LIST OF ABBREVIATIONS AND SYMBOLS

AIC: Akaike information criterion

AICc: Akaike information criterion with a correction for small sample sizes

ASDs: Active Simulating Devices

BRD: Bycatch Reduction Device

CA: Canada

CI: Confidence Interval

DFO: Fisheries and Oceans Canada

FAO: Food and Agriculture Organization of the United Nations

FRCC: Fisheries Resource Conservation Council

GLM: Generalized Linear Model

GLMM: Generalized Linear Mixed Models

GRT: Gross Registered Tonnage

GSL: Gulf of St. Lawrence

Hz: one event (or cycle) per second

ICES: International Council for the Exploration of the Sea

IQs: Individual Vessel Quota system

ITQs: Individual Transferable Quotas system

L50: Length at 50% Retention

MLL: Fish Length

MRL: Minimum Reference Length

t: Metric Ton

REML: Restricted Maximum Likelihood

SD: Standard Deviation

SE: Standard Error

SEM: Standard Error of the Mean

SR: Selection Range

TA: Total Acceleration

TAC: Total Allowable Catch

CHAPTER 1: Introduction and Overview

1.1 Bottom trawl and selectivity of bottom trawls

Bottom trawling (also known as otter trawling) is one of the most important fish capture techniques, known as a versatile fishing practice which captures target and non-target species living on or near the seabed by towing a net along the ocean floor (Graham, 2006; FAO, 2022; Montgomerie, 2022). A typical commercial bottom trawl comprises a trawl net, pair of doors, and bridles that connect the doors and wings (He et al., 2015; 2021) (Fig. 1.1). The trawl net is a cone-shaped net typically made by two or four netting panels, which is wide at the trawl's mouth and narrow toward the trawl's codend (He et al., 2021; Montgomerie, 2022; Araya-Schmidt, 2022). The trawl net is horizontally opened by two doors, which are made of steel or wood, attached to the fishing vessel by wires called "trawl warps" (Winger et al., 2010). Trawl doors are towed through the water at an angle to spread them from each other, opening the trawl net in a horizontal direction. The vertical opening of the trawl net is performed using floats attached to the headrope and weighted groundgear or footgear (i.e., bobbin or rockhopper groundgear) attached to the footrope (Winger et al., 2010; Montgomerie, 2022). The use of weighted groundgear also keeps the bottom trawl in contact with the seabed, protecting the netting from damage (He et al., 2021; Montgomerie, 2022). The trawl codend is at the end of the trawl net, where fish are collected until the net is hauled (Graham, 2006; FAO, 2022; Montgomerie, 2022).

Bottom trawls capture demersal fish by herding them from ahead of the trawl to the trawl mouth, where fish either enter the trawl net or escape over the headline or under the fishing line (Walsh, 1996; He et al., 2021). The initial response of fish to an approaching trawl occurs ahead of the vessel (Zone 1, Fig. 1.2), where in many cases, fish swim toward the seabed in response to vessel noise, thereby increasing their availability to capture (Godø, 1994; Winger et al., 2010). Compared to zone 1, fish in zone 2 (between the trawl doors and trawl opening) are herded into the trawl path, where they become vulnerable to capture. In this zone, the trawl doors, bridles, and groundgear present a combination of visual stimuli to herd fish toward the trawl mouth (Godø, 1994; Walsh, 1996; Winger et al., 2010). In this area, fish either escape under the fishing line or enter the trawl and swim toward the codend (zone 3) (Winger et al., 2010).

Bottom trawls capture demersal fish and shrimp economically bottom trawl has become the preferred fishing method for many fishers worldwide, providing a high proportion of the fisheries production. Global bottom trawl fisheries annually contribute around 19 million t of demersal fish and invertebrates, accounting for almost 23% of total landings (Kumar and Deepthi, 2006; Amoroso et al., 2018; Pérez Roda et al., 2019). However, bottom trawls have been identified to be the most important contributors to bycatch and habitat impacts.

The impacts of bottom trawling on benthic communities have been a matter of great concern regarding sustainable fisheries management (de Groot, 1984; Jennings and Kaiser, 1998; Kvamme and Frøysa, 2004; Hiddink et al., 2006; 2011). The use of weighted groundgear in bottom trawls to increase contact with the seabed and capture fish close to the seabed leads to a substantial amount of bycatch of undersized fish and unwanted species which are discarded at sea (Main and Sangster, 1985a; Engås and Godø, 1989; Kelleher, 2005; Victorero et al., 2018). Overall, bottom trawls produce over 50 percent of the total fisheries discard (Kelleher, 2005; Kumar and Deepthi, 2006). The amount of discard varies according to different fishing regions. For example, in the North Atlantic and Northwest Pacific, the annual discards represented 39% of annual totals. Of those, bottom trawl fisheries contributed about 33% (Clark et al., 2015; Pérez Roda et al., 2019). These discard issues are expected to threaten sustainable fisheries by inducing unnecessary fishing mortality, which is considered a waste of natural resources and makes fisheries management designs difficult (Kelleher, 2005; Pérez Roda et al., 2019). Reducing these discards has been the cause for development of selective fishing gears in the North Atlantic in the last decades (Kelleher, 2005; Kumar and Deepthi, 2006; Pérez Roda et al., 2019; Barnes et al., 2022).

The estimation of bottom trawl selectivity is one of the most important tools available for fisheries management (Ramakrishnan, 2018). The parameters of selectivity can be used in estimating the length frequency of the stock, catch quotas, and minimum landing size for bottom trawl fisheries (Sparre et al., 1989; Millar and Fryer, 1999)C. This is important for managing the catchability and the fishing mortality of a fishery (Wileman et al., 1996; Kvamme and Frøysa, 2004), assessing the effect of mesh size on yield (Millar and Fryer, 1999; Broadhurst et al., 2006), formulating management targets and evaluating harvest control rules (Scott and Sampson, 2011; Sampson, 2014).

Improving trawl selectivity (i.e., reducing the capture of juveniles of target species and discard of non-target species) is performed based on selective processes, which take place during trawling (Wileman et al., 1996; Grimaldo et al., 2016; Lucchetti et al., 2021). Selective processes can occur at all sections of the trawl net, where fish exhibit different reactions, which are length-dependent and species-specific (Winger et al., 2010; Hendrickson, 2011; Tokaç et al., 2014). These differences are fundamental for developing selective fishing gear methods to target fish by size, species, or both (Grimaldo et al., 2016). In general, size-selective fishing involves avoiding the capture of undersized individuals while maintaining the high probability of large individuals of target species. These size-selective processes are mainly focused on the codend, where fish are small enough to escape from the codend meshes (i.e., changes in the codend mesh size and configuration, etc.) (Broadhurst et al., 2004; He, 2007; Herrmann et al., 2007; Tokaç et al., 2014). Species selective fishing, by comparison, involves targeting certain species, while preventing the bycatch of unwanted species (Graham, 2006; Breen et al., 2016). Species selectivity research has focused on developing selective fishing gear to separate bycatch species from the target catch (i.e., using separator panels, bycatch reduction devices, groundgear modification, etc.) based on morphological and behavioral differences between species (e.g., Gabr et al., 2007; He and Balzano, 2013; Bayse et al., 2014; Brinkhof et al., 2020). Overall, size and species selection works are directly based on how fish react to behavior the trawl components during the capture process (Winger et al., 2010).

1.2 Fish behavior and factors influencing fish behavior near trawls

1.2.1 Fish behavior near trawls

Like all animals, marine fish exhibit a wide variety of behaviors, ranging from behavioral genetics to motivational behaviors (Keenleyside, 1979; Colgan, 1986; Pitcher 2012). These fish behaviors are involved in solving critical needs, including finding and ingesting appropriate food, avoiding predation, and reproducing (Keenleyside, 1979). Generally, fish behaviors involve locomotor capacity that fish utilize in either moving forward, holding station in flowing water, or slowing movement, turning, rising, and sinking (Keenleyside, 1979). Recent studies have clustered these behaviors into meaningful behavior groups to make interpretation easier, such as feeding behavior, anti-predator behavior, social behavior, and others, which often play a vital role in the catchability of fishing gears (Keenleyside, 1979; Videler and He, 2010; Pitcher, 2012).

The response behavior of marine fish to bottom trawls varies with different trawl components (Winger et al., 2010). The complex sequence of fish behavior is due to alternative reactions of fish at each of the positions in trawls from the herding process to herd fish into the trawl path to being retained in the codend. Recent studies have separated fish behavior near bottom trawls into three specific zones, based on three zones of the capture process (Walsh, 1996; Winger et al., 2010). These specific zones are illustrated in Figure 1.2. Zone 1 illustrates the area in which fish respond to the low-frequency noise generated by the fishing vessel and trawl warps. Zone 2 illustrates the area in which fish respond to the doors, sweeps, and groundgear. Zone 3 illustrates the area in which fish respond inside the trawl net.

Fish response to trawl components during herding could alter escape and capture patterns, directly affecting trawl efficiency. Most fish in front of the trawl typically use cues to keep their station with trawl components (doors, bridles, and groundgear) at a safe distance, leading to them being herded into the trawl path, and becoming available for capture (Ryer, 2008; Wardle, 1993; Winger et al., 2010). These reactions depend on several intrinsic factors, including swimming capacity and endurance, visual range, and physiological conditions, which can vary among species and differ according to fish size (Beamish, 1966; He, 1991; Winger et al., 1999). Roundfish (fish that have a round shape in the cross-section and a body which tapers to a tail) generally use their swimming and visual capacity to maintain a safe distance in response to the advancing trawl net system, which is known as the "fountain maneuver" (Winger et al., 2010). The fountain maneuver behavior is length-dependent. Large individuals with better swimming capacity, can keep their station for a long period, leading them into the center of the trawl mouth, becoming available for capture, compared with smaller individuals (Wardle, 1993; Winger et al., 2010).

Compared to roundfish, flatfish (fish that have oval, bony, and flattened bodies, swim on their side, and have both eyes on one side of the head) are usually positioned close to the seabed and respond to the advancing groundgear and sweeps at short distances (Ryer, 2008; Winger et al., 2010). This is related to an anti-predator strategy and can be different within and between flatfish species (Ryer, 2008; Winger et al., 2010). Herding flatfish from the two sweep zones (see hatched areas in Figure 1.2) is key to the successful capture of flatfish. If individuals swim perpendicular (90º) in response to the sweeps, they will unknowingly be herded into the net path, becoming available for capture (Winger et al., 2010). Choosing a different swimming trajectory (i.e., swimming in the tow direction) will not necessarily guide them into the trawl path (Winger et al., 2010). The effectiveness of the herding process depends on the swimming capacity of the fish (i.e., speed and endurance), which is known to be both temperature and size dependent (e.g., Winger et al., 1999).

Once the fish arrive in the net mouth, most species and sizes of fish will turn and swim in the direction of tow and maintain station with the advancing trawl. The duration spent in this location depends largely on the endurance of the individual fish, which can vary with several extrinsic and intrinsic factors (see next section). Towing speeds of trawls are typically chosen so as to slowly exhaust fish (anaerobic swimming). As exhaustion sets in, fish commonly rise and turn, unknowingly entering the net. Unlike roundfish, the heights at which flatfish rise above the fishing line to enter the trawl are typically less than 1 m from the seabed (Main and Sangster, 1981; Bublitz, 1996; King et al., 2004; Ryer, 2008).

Fish aggregated in the trawl codend are now considered in the last step of the capture process. How fish respond inside the codend depends in large part on their available energy reserves. Some individuals may arrive in the codend quickly, while others may delay their arrival by swimming with the towing direction inside the trawl for various periods of time. Bycatch reduction devices (e.g., square mesh panels, fish-eyes, grids, etc.) are commonly used prior to the codend to encourage the escape of non-targeted species and sizes of fish (e.g., Larsen, 2016; Grimaldo et al., 2018). Eventually, the remaining fish which have not escaped, arrive exhausted and trapped in the codend (O'Neill et al., 2003; Winger et al., 2010). Smaller fish typically show an erratic or panic response that changes their swimming speed and direction, leading to fish escaping through the codend meshes (Kim et al., 2008). The size, shape, and orientation of mesh can largely determine escape success (e.g., Pol et al., 2016; Cheng et al., 2020). See more in Section 1.2.3.

1.2.2 Factors influencing fish behavior near trawls

During the last few decades, investigations on factors influencing fish behavior in the trawls have been conducted in different fisheries worldwide (e.g., Walsh and Hickey, 1993; Godø, 1999; He and Pol, 2010; Harding et al., 2020). Many factors have been observed to influence fish behavior during the capture process, and they involve biological (intrinsic factors) and environmental (extrinsic factors) conditions (Beamish, 1966; Winger et al., 2010). The best understood of these factors are light intensity, fish density, and fish size. In general, these factors govern fish behavior along the fishing zones of the trawl, particularly from herding to the codend (Hemmings, 1973; Keenleyside, 1979; He, 2010a).

Light intensities underwater differ according to the time of day and are negatively correlated with increases in depth (Bradburn and Keller, 2015). The visual capacity of fish to recognize underwater objects (i.e., the advancing trawl's components) is based on visual acuity, separable angle, and maximum sighting distance (Arimoto et al., 2010). These visual conditions differ at varying ambient light conditions, leading to variations in fish response to the gear (Glass and Wardle, 1989; Ryer, 2008; Wardle, 1993; Winger et al., 2010). Several observations on fish behavior during the herding process have revealed that fish actively react to the advancing trawl components earlier under high light conditions. This active response is represented by swimming to keep the advancing trawl out of the visual range (the distances that fish can see underwater objects), resulting in fish swimming to keep a safe distance in front of the trawl components in the trawl mouth (Olla et al., 2000; Kim and Wardle 2003; Winger et al., 2010). In contrast, fish respond erratically to the oncoming trawl at a shorter distance during low light conditions, represented by a short reaction distance, swimming in different directions, and colliding with gear components and other fish (Walsh and Hickey, 1993; Olla et al., 2000).

Variations in fish densities likely influence fish response during the capture process (Winger et al., 2010). Fish density is related to aggregation behavior (i.e., shoaling) that in fish is a response to other motivations, such as feeding and the risk of predators (i.e., anti-predator defence) (Pitcher and Parrish, 1993; Ioannou et al., 2011). Fish density at the trawl mouth varies among species. Some species maintain their aggregations continuously, while others are shoaling occasionally (Winger et al., 2010). These variations lead to differences in fish reactions to the upcoming trawl, particularly under the trawl's groundgear. Fish that aggregate at low densities (i.e., loner behavior), show kick-and-glide swimming behavior, which is characterized by zigzag behavior, increasing escape under the groundgear (Godø et al., 1999). In contrast, when fish are schooling at the trawl mouth (i.e., high densities), their zigzag behavior is disrupted, they collide with others and groundgear, leading to more fish entering the trawl rather than escaping under the fishing line (Walsh, 1996; Godø et al., 1999). Compared with fish densities at the trawl mouth, the degree of accumulated catch in the codend alters the contact likelihood of fish (i.e., contact probability that fish can make contact with the codend meshes to provide a chance of escape) to the codend meshes. For instance, haddock in the codend have been observed to increase their contact with the codend meshes during low catch accumulation, increasing the escape rate compared with those at high catch accumulation (Jones et al., 2008).

Fish size has been considered the most important intrinsic factor which directly influences the swimming behavior of fish during the capture process. The swimming speed and endurance of fish are closely related to the individual's body length, represented as length-dependent swimming capacity (Keenleyside, 1979; Videler and He, 2010; Winger et al., 2010). Variation in swimming capacity within species has been observed at the trawl mouth and in the codend. During the herding process, fish of different sizes swim at varying tail-beat frequencies (Winger et al., 2010). Small fish swim with higher tail-beat frequencies, reaching the upper end of their performance range, while larger individuals swim with lower tail-beat frequencies (Winger et al., 2010). For example, Atlantic cod (*Gadus morhua*) 1 m long were observed to show only 2.9 Hz of tailbeat frequencies to maintain its position, compared with 10 cm cod using 28.6 Hz for the same mechanical work (Wardle, 1986). This leads to the differences in swimming capacity of fish, which drives the capture efficiency of the trawl. Generally, large fish with greater swimming capacity prefer cruising (fish swim continuously over long distance at a fair speed) and falling back into the trawl above the fishing line, while small fish with poor swimming capacity tend to be positioned close to the seabed and seek to escape under the footgear, likely due to fatigue (Winger et al., 2004; Ingólfsson and Jørgensen, 2006; Ryer, 2008).

1.3 Gear modifications to improve the selectivity of bottom trawls

Complex fish behaviors near the trawl play a vital role in improving the catch efficiency of bottom trawls (Albert et al., 2003; Oostenbrugge et al., 2008; He, 2010b). Over the last few decades, many studies have developed technical measures to enhance size and species selectivity

(Walsh, 1992; Wardle, 1993; Broadhurst et al., 2004; Jørgensen et al., 2006; He, 2010b). These studies have focused on specific aspects of fish behavior during the capture process (Walsh, 1992; Broadhurst et al., 2004; Jørgensen et al., 2006; He, 2007; Krag et al., 2010). While mesh selectivity modifications have focused on the codend to release small fish through the codend meshes (Garcia et al., 2006; He, 2010b), species-selective modifications can also take place in sections before the codend, such as extension (Krag et al., 2009; Bayse et al., 2016c) and trawl mouth area to separate unwanted species from the catch of target species (He et al., 2007; Krag et al., 2010; Larsen et al., 2018a).

Changing the codend mesh size and mesh configuration to increase juvenile fish escape from the codend has been tested in different fisheries worldwide. Underwater observations demonstrated that small fish escaped from the codend rather than other sections during the capture process (Engås et al., 1989; O'Neill et al., 2003). These studies showed that the accumulated catch in the codend could open the meshes in front of the catch, where fish, particularly small fish were able to escape through. These findings allowed the hypothesis that increasing opened meshes of codend panels can increase the escape probability of small individuals. A large number of follow-up studies showed that using larger meshes can improve the codend size-selectivity (Broadhurst et al., 2004; Herrmann et al., 2007; Hendrickson, 2011; Tokaç et al., 2014; Pol et al., 2016; Cheng et al., 2020; Yang and Herrmann, 2022).

Changes in mesh orientation have also shown the potential to increase fish escape probability. Tokaç et al. (2014) and Bayse et al. (2016a) showed that rotating a diamond mesh to 90° in the transversal direction (i.e., T90 codend) can increase the escape rate of small roundfish from the codend. More recently, applying T90 codends in the Canadian redfish (*Sebastes* spp.) fishery has shown reductions in the capture of small redfish (Cheng et al., 2020). Alternatively, adding a so-called bycatch reduction device (BRD, is the addition of a device to a fishing gear, such as a grid or large-mesh panel that is added to a fishing gear to reduce the capture of unwanted animals or animal sizes) to the codend or front of the codend can reduce the capture of both unwanted species and undersized target species (Isaksen et al., 1992; Alverson et al., 1994; Winger et al., 2010). Active simulating devices (ASDs), such as conical rope array, fluttering net panel, etc., are placed inside the codend to generate visual stimuli for juvenile fish. Such an application has shown potential to induce escape behaviors of fish inside the codend (Kim and Whang, 2010; Herrmann et al., 2015; Grimaldo et al., 2018). Herrmann et al. (2015) and Cuende et al. (2020) revealed that mounting fluttering ropes with floats to the bottom panel of the codend could increase the escape ability of Atlantic cod through a square mesh panel of bottom trawl in the Baltic Sea. Grimaldo et al. (2018) also showed that mechanical stimulation could trigger escape behaviors for haddock (*Melanogrammus aeglefinus*) in the Barents Sea demersal trawl fishery.

Research into reducing bycatch of unwanted species at the earliest stages of the fishing process (i.e., the herding process) has been effective. Several studies have developed novel technology to separate the bycatch species from the catch of target species at the trawl mouth area using behavioral differences among species (e.g., Engås et al., 1988; Main and Sangster, 1985b; He et al., 2007; Krag et al., 2010; He et al., 2015; Grimaldo et al., 2018). A particular trawl design without a square (an overhung netting panel right after the headline), the so-called "topless trawl" can reduce the bycatch of finfish and groundfish from the catch of shrimp (*Pandalus borealis*) (He et al., 2007; Graham, 2010; Krag et al., 2015). The topless trawl is designed to move the groundgear forward more than the headline, allowing fish to escape over the headline more easily before entering the trawl (He et al., 2007; Krag et al., 2015). Another technique uses a horizontal separator panel to vertically separate species distributed at different heights within the trawl mouth (Main and Sangster, 1985b; Ferro et al., 2007; Krag et al., 2010). Krag et al. (2010) reported that increasing spaces under the trawl by raising the fishing line ~ 60 cm above the seabed can increase the escape of Atlantic cod under the trawl, reducing bycatch of this species from haddock-directed fisheries. These studies were successful at eliminating unwanted species that enter the trawl close to the seabed such as cod and flatfish species from the catch of haddock and other gadoid fish.

1.4 Methods to evaluate size selectivity

Evaluating the size selectivity of a bottom trawl has been standardized by measuring the probability of a given species being captured by the trawl at different sizes that are available in the sampled population (Wileman et al., 1996). Estimations of trawl size selectivity can take place at any part through the capture process but typically focus on the trawl netting (i.e., the trawl's body and codend) where fish are retained as opposed to escaping through the meshes. In principle, selectivity measurements of several sections of the trawl are possible. However, most experiments have been focused on the codend, where all fish that entered the trawl were assumed to enter into the codend (Wileman et al., 1996). This method has been the subject of numerous studies on evaluating trawl selectivity in the last few decades. Recently, attempts to evaluate trawl selectivity have extended to other sections of the trawl in early stages of the capture process (i.e., trawl mouth, extension). Because of differences in structures, conducting experiments and selectivity methods to obtain the selectivity functions for each section of the trawl can be varied.

1.4.1 Absolute size selectivity

If the trawl selection experiment is conducted to retain all size composition of target species in the sampled population, the absolute size selectivity is known (Wileman et al., 1996). The absolute size selectivity method estimates the size selection parameters of the trawl based on the length frequency distributions of fish in the experimental (selective) and the control gear (non-selective) (Wileman et al., 1996). The length distribution in non-selective gear is used to estimate the size distribution of fish escaping from the meshes (i.e., meshes of trawl body or codend), while the selective gear provides the size distribution of fish being retained in the trawl codend (Rudders et al., 2000). These size distributions are collected using two methods: the covered codend and paired-gear.

Traditionally, the selection process of a trawl mainly occurs in the codend, where large amounts of fish are observed to escape through codend meshes, and thus the covered codend method is required. This method uses a small mesh net cover over the codend to retain all fish escaping from the codend (e.g., Madsen and Holst, 2002; Cheng et al., 2020). These captures, combined with the length frequency of fish retained in the codend of the selective gear, represent all sizes of fish in the sampled population, thus allowing one to generate the selection curve (Pope et al., 1975; Wileman et al., 1996). Selection curves can be produced for each haul, accurately estimating the population entering the codend. This leads to a consideration that this method gives a true measure of selectivity (Pope et al., 1975). However, given the potential for physical masking between the covered codend and the trawl codend, effort must be taken to ensure fish are able to properly escape. One approach is the hooped cover method. However, this method is restricted in handling large catches in both the codend and covered codend (Grimaldo et al., 2009). This idea has been further developed by using plastic kites. A number of kites are mounted around the circumference of the cover net to lift the small mesh netting off of the inner codend. This method reduces physical masking, and promotes easier handling of the gear (e.g., He, 2007; Grimaldo et al., 2009; Cheng et al., 2020).

Compared with the covered codend method, the paired-gear technique can be applied for estimating codend selectivity and whole trawl selectivity. Paired-gear methods include the alternate, parallel, twin, and trouser haul. These methods use two gears: the selective and control (non-selective) gears, which are towed alternately or alongside each other (Wileman et al., 1996). The non-selective gear is constructed with a small mesh size in order to retain all fish entering the trawl mouth. Relative to the covered codend, the paired-gear techniques do not suffer from physical masking (see above). However, these paired-gear methods need a larger number of hauls to generate the selection curve (i.e., alternate haul and twin trawl method), more fishing capacity (i.e., two vessels for parallel haul method) and may cause differences in fish behavior (i.e., trouser trawl method) along with and variation in fishing conditions (Kotwicki et al., 2017).

The traditional size selection of the trawl codend described above is characterized by two parameters: the 50% retention length (L50) and selection range (SR) (Wileman et al., 1996). The 50% retention length is the length of fish with a 50% probability of being retained or escaping after entering the trawl codend. The SR is the difference in length between L75 (the length of fish that had a 75% probability of being retained in the codend) and L25 (the length of fish that had a 25% probability of being retained in the codend). The parameter L50 demonstrates the efficiency of the codend that if the selection curve has a shorter tail to the right of the L50, the codend captures most large fish. If the selection curve has a longer tail to the left of the L50, some small fish may be retained in the codend. The parameter SR is a measure of the sharpness of the selection curve. A large SR value illustrates that the codend starts to retain small fish and fails to retain large fish compared with the codend with the same L50, but smaller SR.

Four basic selection models have been traditionally used to fit selection curves and estimate L50 and SR parameters, which include Logit, Probit, Gompertz, and Richard (Eqs. 1.1-1.4) (Wileman et al., 1996) . Logit and Probit curve are symmetric around the L50, whereas Gompertz curve has a long tail to the right of L50. The Richard model has an additional parameter δ, which gives additional information about the selection curve. If $\delta > 1$, the curve has a longer tail to the left; if $0 < \delta < 1$, the curve has a longer tail to the right. If $\delta = 1$, the selection curve is the logistic curve. The estimated values of L50 and SR varied among these traditional models and are detailed in Eqs. 1.5-1.8 based on Wileman et al. (1996).

$$Logit\left(l, L50_{Logit}, SR\right) = \left(\frac{\exp\,(a+bl)}{1+\exp\,(a+l)}\right) \tag{1.1}$$

$$Probit(l, L50_{Probit}, SR) = \Phi(a+bl) \tag{1.2}$$

$$Gompertz\left(l, L50_{Gompertz}, SR\right) = \exp\,(-\exp\,(-(a+bl))) \tag{1.3}$$

$$Richard\left(l, L50_{Richard}, SR, \frac{1}{\delta}\right) = \left(\frac{\exp\,(a+bl)}{1+\exp\,(a+l)}\right)^{\frac{1}{\delta}} \tag{1.4}$$

$$L50_{Logit} = -\frac{a}{b}; \qquad \mathrm{SR}_{Logit} = \left(\frac{2log_e(3)}{b}\right) = \frac{2.197}{b} \tag{1.5}$$

$$L50_{Probit} = -\frac{a}{b}; \qquad \mathrm{SR}_{Probit} = \left(\frac{2probit(0.75)}{b}\right) = \frac{1.349}{b} \tag{1.6}$$

$$\mathrm{L50}_{Gompertz} = \left(\frac{-log_e\left(-log_e(0.5)\right)-a}{b}\right) = \frac{3.0665-a}{b}; \qquad \mathrm{SR}_{Gompertz} = \frac{log_e\left(\frac{log_e(0.25)}{log_e(0.75)}\right)}{b} = \frac{1.573}{b} \tag{1.7}$$

$$\mathrm{L50}_{Richard} = \frac{logit\left(0.5^{\delta}\right)-a}{b}; \quad \mathrm{SR}_{Richard} = \frac{logit\left(0.75^{\delta}\right)-logit\left(0.25^{\delta}\right)}{b} \tag{1.8}$$

These traditional models are based on the assumption that all fish entering into the codend come into contact with the codend meshes, having a chance to escape through them and thus are subjected to the same size selection process. However, as discussed above, some factors may influence fish behavior in the codend, such as visual stimuli that are created by the color and contrast of netting, the influence of temperature on swimming behavior, and other fishing conditions. These may lead to differences in the contact likelihood of fish to the codend meshes, providing a size-dependent chance of escape (e.g., Bayse et al., 2016a). This contact probability has been quantified by a contact parameter (*C*) in four contact models in Eqs. 1.9-1.12.

$$CLogit(l,\ C,\ \mathrm{L50}_c, \mathrm{SR}_c) = 1.0 - C + C \times Logit(l,\ \mathrm{L50}_c, \mathrm{SR}_c) \qquad (1.9)$$

$$CProbit(l,\ C,\ \mathrm{L50}_c, \mathrm{SR}_c) = 1.0 - C + C \times Probit(l,\ \mathrm{L50}_c, \mathrm{SR}_c) \qquad (1.10)$$

$$CGompertz(l,\ C,\ \mathrm{L50}_c, \mathrm{SR}_c) = 1.0 - C + C \times Gompertz(l,\ \mathrm{L50}_c, \mathrm{SR}_c) \qquad (1.11)$$

$$CRichard\left(l,\ C,\ \mathrm{L50}_c, \mathrm{SR}_c, 1/\delta_c\right) = 1.0 - C + C \times Richard\left(l,\ \mathrm{L50}_c, \mathrm{SR}_c, 1/\delta_c\right) \qquad (1.12)$$

As such, the factor's influence may differ according to the size, likely leading to differences in the selection process of fish of different sizes. Thus, the number of selection processes and the fraction of fish in each process have been addressed by Double logistic (DLogit) and Triple Logistic (TLogit) models (Eq. 1.13-1.14). These models estimate the fraction *C* of fish for several selection processes corresponding with parameter v (i.e., L50 and SR). For example, $\mathrm{L50}_1$ and SR_1 are the selection parameters estimated for the fraction of C_1 fish to be subjected to the first selection process; $\mathrm{L50}_2$ and SR_2 are the selection parameters estimated for the fraction of C_2 fish to be subjected to the second selection process.

$$DLogit(l, C_1, v) = C_1 \times Logit(l, v_1) + (1.0 - C_1) \times Logit(l, v_2) \qquad (1.13)$$

$$TLogit(l, C, v) = C_1 \times Logit(l, v_1) + C_2 \times Logit(l, v_2) + (1.0 - C_1 - C_2) \times Logit(l, v_3) \qquad (1.14)$$

Further, the Polynomial model can be used to fit complex size selectivity scenarios. The polynomial model was a group of highly flexible models up to a quartic polynomial (Poly4, Eq. 1.15).

$$Poly4(l,v) = \frac{exp\left(v_0 + v_1 \times \frac{l}{100} + v_2 \times \frac{l^2}{100^2} + v_3 \times \frac{l^3}{100^3} + v_4 \times \frac{l^4}{100^4}\right)}{1.0 + exp\left(v_0 + v_1 \times \frac{l}{100} + v_2 \times \frac{l^2}{100^2} + v_3 \times \frac{l^3}{100^3} + v_4 \times \frac{l^4}{100^4}\right)} \qquad (1.15)$$

1.4.2 Relative size selectivity

The absolute size selectivity discussed above is obtained with different degrees of bias suffered from experimental designs. These are often the case due to the limitations in time and space as well as estimating the effect of fishing conditions (Wileman et al., 1996). In particular, in some paired-gear experiments, the control gear may not meet the non-selective assumption, leading to a bias in estimating the size selectivity of the test gear (e.g., Kotwicki et al., 2017). Since obtaining the absolute size selectivity for some test gears is difficult, many studies use the catch comparison method to evaluate the catch efficiency of the test gear relative to the conventional gear, where both gears are selective (Wileman et al., 1996; Kotwicki et al., 2017). Experimental designs for catch comparison between two gears are carried out without the ability to measure the population of fish not captured by gears (escaped through meshes, etc.), therefore, relative size selectivity (Halliday, 2002).

Measuring relative selectivity can be undertaken using a wide variety of methods (e.g., Reid et al., 2012; Sistiaga et al., 2015; Kotwicki et al., 2017). These methods include the catch comparison rate (Reid et al., 2012; Krag et al., 2014; Sistiaga et al., 2015), catch ratio (Santos et al., 2016), relative efficiency (Cadigan and Dowden, 2010; Miller, 2013), selectivity ratios (Kotwicki et al., 2017), and others. Most of these methods have focused on statistically comparing the catch efficiencies or catch rates between the test and conventional gear (Engås and Godø, 1989; Munro and Somerton, 2002; Ingólfsson and Jørgensen, 2006).

The approach for analyzing catch comparison has been developed. Most catch comparison studies initially used Paired t-tests, and then Wilcoxon tests (Holst and Revill, 2009); however, these tests require many assumptions (i.e., selected data are not discrete and non-symmetric for Paired t-tests) and less power (Wilcoxon). Many approaches have been implemented to advance catch comparison analyses. The ideal situation is to use continuous curves along the length scale to describe the differences in catch efficiency between the test and conventional trawl. The curve illustrates the proportion of fish at length in the catch of each trawl (Kotwicki et al., 2017). This approach has been developed for catch comparison using generalized linear mixed models (GLMM) and statistical software, which provides several tools for performing these models (Holst and Revill, 2009; Kotwicki et al., 2017). For example, Holst and Revill (2009) developed a simple statistical method for catch comparison studies using GLMM using low-order polynomials to fit the proportion curve with a realistic confidence band. This approach is adequate to account for overdispersion in proportion data and simply applies to catch data using R packages (R Development Core Team, 2020). More recently, studies have implemented polynomial GLMMs using the glmer function in the lme4 package (Bates et al., 2015) and used the minimum Akaike information criterion (Akaike, 1974) with a correction for small sample sizes (AICc) for model selection (e.g., Eighani et al., 2020; Santos et al., 2020; Araya-Schmidt et al., 2023).

1.4.3 Underwater observations

Both absolute and relative selectivity methods evaluate the efficiency of gear designs based on the catch data, where results rely on what makes it to the back deck (Bayse, 2015).

These methods are not focused on fish responses to the gear design, which have a vital role in determining the effectiveness of the test gear (Underwood et al., 2012). Further, study types (collection bags, covered codends, etc.) may increase bias by the mechanism that measures escaping fish itself (Kotwicki et al., 2017). In these cases, some selectivity studies have combined the catch data with underwater observations to evaluate the efficiency of test gears (e.g., Bayse et al., 2016a; Grimaldo et al., 2018; Larsen et al., 2018b) or using the underwater observations alone to quantify the interaction between fish and the gear designs (Bayse et al., 2014; Underwood et al., 2015; Bayse et al., 2016b).

Starting in the 1980s, underwater camera technology has been used to describe fish behavior qualitatively at the trawl mouth (Main and Sangster, 1981; Wardle, 1983). These studies initially documented how fish respond to the gear, which directly influences the catch efficiency of the trawl. Qualitative descriptions of fish behavior have been developed since the 1990s with improved underwater camera technologies (Walsh and Hickey, 1993; Godø, 1999). Recently, underwater video technologies have allowed fishing gear technologists to quantify fish behavior and selectivity of the whole gear or bycatch reduction devices. For example, He et al. (2008) documented the behavior of various groundfish species in response to a rope separator panel. Underwood et al. (2015) and Bayse et al. (2016a) described how fish swimming behavior at the center part of the trawl mouth drives the catch efficiency of a trawl. These observations, combined with catch comparison data, provide insights into evaluating the efficiency of trawl designs. Bayse et al. (2014; 2016c) and Grimaldo et al. (2018) used underwater videos to observe fish response to the BRD in evaluating the effectiveness of the BRD.

1.5 Redfish fishery in Canada

Groundfish is one of three major species groups in the fishing industry that has been harvested in North America for centuries (DFO, 2017). Groundfish includes Atlantic cod, haddock, redfish, saithe (pollock; *Pollachius virens*), and various flatfish (e.g., Atlantic halibut (*Hippoglossus hippoglossus*), American plaice (*Hippoglossoides platessoides*), winter flounder (*Pseudopleuronectes americanus*), yellowtail flounder (*Limanda ferruginea*), and witch flounder (*Glyptocephalus cynoglossus*)). These groundfish species provide about two-thirds of the total landings in Canada (Charles, 1997; DFO, 2018). Groundfish fisheries in Canada are currently managed by Fisheries and Oceans Canada (DFO) through the Sustainable Fisheries Conservation Council . DFO manages groundfish fisheries using a combination of quota management (i.e., TACs), limited entry licensing (i.e., number of participants), gear restrictions (i.e., mesh size), and closed areas and seasons (Charles, 1997; Halliday and Fanning, 2006). Vessel sizes range between 35 feet (10.7 m) to over 100 feet (30.5 m), depending on gear types and fishing grounds (Charles, 1997). Fishing gear types include fixed (i.e., longline and gillnet) and mobile gear (i.e., bottom trawl, midwater trawl, and Danish and Scottish seines) (DFO, 2018). During the last few decades, Canadian groundfish fisheries have experienced two major fish stock collapse events: the first collapse happened in the early and mid-1970s due largely to environmental conditions and fishing pressure by foreign vessels, and the second collapse occurred in the late 1980s and early 1990s due to high levels of domestic fishing mortality (Charles, 1997; Doubleday et al., 1997). These collapses led to a moratorium in some fisheries, such as Northern cod in 1992 and redfish in 1995 (Charles, 1997; Duplisea, 2018).

There are three redfish species that inhabit cool waters in the Northwest Atlantic off the east coast of Canada, including deepwater redfish (*S. mentella*), Acadian redfish (*S. fasciatus*), and golden redfish (*S. norvegicus*) (Gauthier and Rose, 2002; DFO, 2016). However, two of those redfish species (deepwater redfish and Acadian redfish) dominate the catch in the commercial redfish fishery in the Gulf of St. Lawrence, Canada (DFO, 2020; Cadigan et al., 2022). They have the same small anterior protuberance on their lower jaw and are typically considered as redfish (Rubec et al., 1991; Gauthier and Rose, 2002). As a semi-demersal species, redfish typically aggregate in small or large shoals, which may perform extensive vertical movements due to the amount of light intensity (Templeman, 1959) while pursuing their prey (Atkinson, 1989). Gauthier and Rose (2002; 2005) suggested that redfish aggregated close to the seabed during the day but moved off the seabed at night. Additionally, redfish species are slow-growing, late-maturing, and long-lived (Cadigan et al., 2022) and thus, are susceptible to overfishing (Koslow et al., 2000).

The redfish fishery in the Gulf of St. Lawrence (Unit 1; Fig. 1.3) developed in the late 1950s, had a high annual landing of 46,000 t on average during the 1960s and then increased to 82,000 t on average during the 1970s, with the highest annual landing on average of 136,000 t in 1973 (DFO, 2016). This fishery was managed by DFO using the TAC system according to the 1993 management structure (DFO, 2016). The redfish stock was abundant through the early 1990s before a decline in biomass and catch in 1995 (Duplisea, 2018). The first major reason for the decline was related to an increase in fishing effort due to fishers switching their target species from Atlantic cod, which had declined between 1985 and 1993 (Goetting, 2008; Duplisea, 2018). A second reason was the unsustainable fishing practices associated with catching small non-marketable fish using a 90 mm diamond codend (Duplisea, 2018; DFO, 2020). Ultimately, the decline in stock biomass led to a moratorium in the Gulf of St. Lawrence (GSL) redfish fishery in 1995, resulting in only a small (2,000 t year $^{-1}$) index fishery since 1999 (Duplisea, 2018; DFO, 2020). However, due to recent strong recruitment events, a large redfish biomass is now found in the GSL (DFO, 2016). Redfish, particularly large individuals > 25 cm have been observed to be a predator of Northern shrimp, which is the main prey of some groundfish (Cadigan et al., 2022). Thus, the arrival of a large redfish biomass is expected to reduce food resources (i.e., Northern shrimp) for other competitor species, such as Greenland halibut (*Reinhardtius hippoglossoides*), likely considering a reason for a reduction in growth rates of those species (Cadigan et al., 2022). This significant impact leads to conservation measures for an emerging commercial redfish fishery (DFO, 2020).

The Northwest Atlantic Redfish Symposium was recently held to improve the scientific basis for developing a sustainable redfish fishery in the GSL (Cadigan et al., 2022). The Symposium focused on issues of ecology, stock dynamics, and capture technologies. Several projects were subsequently initiated and focused on reducing the capture of undersized redfish and bycatch species from the catch of bottom trawls. A study by Cheng et al. (2020) showed that T90 netting in the codend (i.e., rotating diamond mesh codend to 90˚ in the transversal direction) reduced over 30% of the capture of small redfish, compared with the traditional diamond mesh codend (i.e., T0 codend) currently used in the small index redfish fishery in the GSL. Ongoing studies are also currently investigating the feasibility of mechanical sorting devices (grids) to improve size selectivity of redfish (Grelon et al., 2020), the ability for semi-pelagic trawling (doors off bottom) and midwater trawling to catch commercial quantities of redfish (E.H. Carruthers, unpublished data; Grelon et al., 2020), and the feasibility of reducing bycatch of nontargeted groundfish using horizontal separator panels (E.H. Carruthers, unpublished data).

A new and novel approach uses codend movement (i.e., moving up and down) to increase the escape rate of undersized fish in the codend (Kim, 2013; 2015). Attaching a circular piece of canvas at the posterior of the codend can form a cap that generates lifting force with respect to drag (Kim, 2013; 2015). This force induces a “shaking” movement of the codend, which can reduce the distance between fish in the codend and netting panels. This leads to an increase in the contact likelihood with codend meshes, resulting in an increased escape rate of small fish through the codend meshes. Kim (2015) reported that a shaking codend increased 22 – 30% escape rates of juvenile fish relative to the codend without canvas. To our knowledge, this technology has not been tested for redfish, particularly in combination with T90 netting, which earlier work has shown to be effective at reducing the capture of small redfish (Cheng et al., 2020).

Another important challenge when developing a sustainable redfish fishery (e.g., harvesting fish stocks in a way that meets our needs without compromising the ability to meet future needs; defined by DFO (https://www.dfo-mpo.gc.ca/fisheries-peches/sustainable-durable/fisheries-peches/index-eng.html)) is the need to reduce the capture of bycatch species (Duplisea, 2018; DFO, 2021; Cadigan et al., 2022). Many groundfish in the Northwest Atlantic, such as Atlantic cod, white hake (*Urophycis tenuis*), and flatfish, have been observed to co-occur with redfish (Gomes et al., 1992). These species are associated with the seabed and overlap in distribution with redfish, and thus, they are captured as bycatch in the redfish fishery (DFO, 2021). Atlantic cod and flatfish (such as Greenland halibut and Atlantic halibut) can be captured along with redfish as they enter the trawl at heights close to the seabed (Ryer, 2008; Winger et al., 2010; Pol and Eayrs, 2021). The distribution of white hake has shifted to deeper waters, which now overlap with redfish in the GSL and other areas of Canada (Simpson et al., 2018; DFO, 2021). These are the most common bycatch species and contribute a considerable proportion (i.e., Greenland halibut, white hake, and Atlantic cod made up 9% of the total landings in Unit 1 between 2000-2019) in the landings of the redfish index fishery in the GSL (DFO, 2020; 2021).

Semi-pelagic trawling is designed as a hybrid technique that can capture fish distributed on- and off-seabed (Garner, 1978; Montgomerie, 2015; He et al., 2021). There are two common forms: 1) doors are fished off-seabed and the trawl is on-seabed, or 2) trawl is off-seabed and the doors are on-seabed. Vessels should they choose, may also alternate their fishing situation where either doors or trawl are moved on- or off-seabed as fishing conditions or motivations change. Semi-pelagic trawling has been used to skim the trawl just clear of the seabed to target the groundfish species distributed off the seabed (Montgomerie, 2022). This method was developed in the 1990s to capture redfish in the GSL. This rigging technique connects the upper bridles to the warps anterior to the doors, allowing the trawl to fish dynamically at different water levels from the seabed (Garner, 1978; He and Winger, 2010). Thus, this technique is effective at targeting redfish as they move to heights clear of the seabed and avoid net damage from a rough seabed (Garner, 1978; He and Winger, 2010). Further, increasing the distance between the seabed and groundgear by lifting the trawl net off the seabed may increase escape openings under the trawl for bycatch species related to the seabed. However, the technique fell into disuse, and its effectiveness was not documented once the GSL redfish fishery went into moratorium.

1.6 Icelandic groundfish fisheries

Groundfish fisheries in Iceland are one of four main fisheries, playing the most important role in Icelandic fisheries, contributing 75-80% of the total catch value (Arnason, 1996; Halliday and Pinhorn, 1996; Nielsen et al., 2018). Iceland groundfish fisheries mainly target mixed-species, including roundfish species (Atlantic cod, haddock, redfish, and saithe), Greenland halibut, and other flatfish (Halliday and Pinhorn, 1996). These mixed-species were initially harvested mostly by sidewinder trawlers (the trawl is deployed over the side with the trawl warps passed through blocks suspended from two gallows located on the starboard side) between 1950 and 1970, with an annual catch of 770,000 t on average. This sidewinder fleet was then replaced by stern trawlers (trawlers that can haul heavier catches up the stern onto the working deck). By 1985, 100 trawlers were participating in the fishery, these vessels ranged between 40 and 75 m, and had a large capacity above 10 Gross Registered Tonnage (GRT) (Halliday and Pinhorn, 1996; Gunnlaugsson et al., 2020). This led to an annual catch of over 50% increase before remaining at around 450,000 t in recent decades (Nielsen et al., 2018; Gunnlaugsson et al., 2020).

The groundfish fisheries are managed by a Minister for Fisheries through the Directorate of Fisheries and Marine Research Institute (Halliday and Pinhorn, 1996). Iceland is one of the first countries in the North Atlantic that applied the Individual Transferable Quotas system (ITQs) to manage fishing industries (Agnarsson et al., 2016). This was initially known as the Individual Vessel Quota system (IQs), established by the Directorate of Fisheries since the groundfish stock was overfished in 1977 (Agnarsson et al., 2016; Gunnlaugsson et al., 2020). This management system allocated demersal quotas to the fishing vessels over 10 GRT (Gunnlaugsson et al., 2020). This system was then replaced by a comprehensive ITQ system in 1990, based on recommendations from the Marine Research Institute. The ITQ system enables the transfer of quotas between individual vessels in every fishery (Halliday and Pinhorn, 1996). The quota shares were initially based on the percentage of each year's total catches (total allowable catch, TAC), which was annually issued by the Minister of Fisheries through the regulations formed by the Fisheries Management Act (Arnason, 1996; Matthíasson, 2003; Agnarsson et al., 2016; Gunnlaugsson et al., 2020). In 1998, regulations on maximum quota share were applied to prevent a handful of firms from possessing the majority of the quota, and this quota share differed according to the species (Gunnlaugsson et al., 2020).

Like most groundfish fisheries in the North Atlantic, capturing small fish in the catch is the largest concern in the groundfish fisheries in Iceland, although many regulatory actions have been implemented to solve this issue (Pálsson, 2003; Woods et al., 2015). Since the 1970s, Icelandic groundfish fisheries within 12 nm (22 km) of the coast have been under exclusive Icelandic control to prevent the capture of small fish from trawling (Halliday and Pinhorn, 1996). Since then, several critical mesh sizes have been established to address the capture of small groundfish in the catch of bottom trawls. These included increasing the size of the diamond mesh codend of bottom trawls from 130 mm to 135 mm in 1976 and to 155 mm in 1977 (Halliday and Pinhorn, 1996; Thorsteinsson, 1980). Additionally, minimum fish sizes at this time were also increased to be consistent with increases in the mesh sizes. For example, for Atlantic cod and saithe, the minimum landing size increased from 34 and 35 cm, respectively to 50 cm in 1977, whereas those for haddock increased from 31 cm to 45 cm (Halliday and Pinhorn, 1996).

Fisheries management regulations have focused on reducing the capture of small fish by increasing their escape from the trawl's codend meshes. However, mixed species captured by multi-species bottom trawls have different body shapes, leading to differences in escape and size selectivity. This is the most important reason for high catch rates of bycatch in the capture of Icelandic groundfish fisheries, challenging Icelandic fisheries managers and fishers (Halliday and Pinhorn, 1996). This led to some closed areas to trawling around Iceland due to bycatch (Fig. 1.4).

The rockhopper groundgear has been widely used in commercial bottom trawls worldwide and in particular in Iceland since the mid-1980s (Ingólfsson and Jørgensen, 2006; Garcia et al., 2006). Trawls equipped with rockhopper groundgear can fish on rougher seabed efficiently and reduce net damage caused by the seabed (Engås and Godø, 1989; Ingólfsson and

Jørgensen, 2006; He et al., 2021; Montgomerie, 2022). Additionally, rockhopper groundgear has been shown to be effective at reducing the capture of undersized fish of target species and invertebrates compared with traditional steel bobbins groundgear (Engås and Godø, 1989; Ingólfsson and Jørgensen, 2006; Garcia et al., 2006). In particular, increasing the spaces between the rockhopper discs by using bigger rubber spacers can facilitate the escape of fish under the fishing line of a trawl, and this escape pattern has been shown to be size-dependent (Engås and Godø, 1989; Walsh, 1992; Ingólfsson and Jørgensen, 2006; Larsen et al., 2018a). Thus, observations have considered the size-dependent escape under the groundgear as a part of the overall trawl selectivity (Walsh, 1992; Ingólfsson and Jørgensen, 2006). However, these studies only focused on gadoid species and were conducted in specific fisheries (i.e., Atlantic Canada and Barents Seas). Less quantitative work has focused on the wide assortment of species observed in the mixed-species nature of a typical commercial bottom trawl in Iceland. Further, observations revealed that fish behavior at the trawl mouth, which drives the length-based escape under the trawl may differ at particular locations (i.e., center and wing locations) along the fishing line (Engås and Godø, 1989; Walsh, 1992). However, most research on fish behavior at the trawl mouth have focused on the center area, while fish behavior on the wings are still not fully understood. Therefore, more investigations are required on the escape of multiple species under the bottom trawl in Icelandic waters (i.e., length-dependent escape under the fishing line of the trawl). Additionally, further work is necessary on fish behavior at the trawl mouth along the groundgear to provide additional insights into improving and understanding trawl selectivity and fish behavior.

1.7 Research objectives and chapter outlines

This thesis aims to develop gear designs to improve the selectivity of bottom trawls in North Atlantic fisheries. Research areas focused on developing trawl designs for the emerging redfish fishery in Canada and evaluating the groundgear selectivity of a bottom trawl, which is currently used to capture groundfish species in Iceland groundfish fisheries. For the Canadian redfish fishery, I developed a shaking codend to reduce the bycatch of undersized redfish and modify a semi-pelagic trawl from an existing groundfish trawl to capture redfish when they move off the seabed and potentially reduce bycatch of unwanted species. For Icelandic groundfish fisheries, I investigated the length-dependent escape of a wide variety of fish species under a trawl equipped with a rockhopper groundgear and consider fish behavior at the trawl mouth at particular locations, which drives the escape patterns of fish under the groundgear. These research findings will contribute to the development and application of effective techniques to reduce bycatch in the emerging redfish fishery in Canada and will have potential implications for the development of groundgear to improve bottom trawl selectivity in Icelandic groundfish fisheries and other fisheries. This thesis is comprised of six chapters:

Chapter 1 (this chapter) provides an introduction and overview of the thesis, including bottom trawl and its selectivity, an introduction to fish behavior near the trawls and factors affecting fish behavior, an introduction to gear modifications to improve the selectivity of bottom trawls, and an overview of the history of Canadian redfish fishery and Icelandic groundfish fisheries.

Chapter 2 describes a flume tank experiment to develop a full-scale shaking codend using a T90 codend and an experiment at sea to evaluate and compare the size selectivity of the shaking and non-shaking codend for the emerging redfish fishery in the Gulf of St. Lawrence, Canada.

Chapter 3 describes a flume tank experiment to construct a full-scale model of a semi-pelagic trawl using the French rigging technique and two at-sea experiments to evaluate the effectiveness of a full-scale semi-pelagic trawl for the emerging redfish fishery in the Gulf of St. Lawrence, Canada.

Chapter 4 demonstrates the length-dependent escape of a wide variety of species under a commercial bottom trawl in Iceland and considers how the fish escape was affected by light and dark conditions.

Chapter 5 quantifies fish response behavior, herding behavior, and swimming capacity at the mouth of a bottom trawl at particular locations using the escape-at-length captured by the collection bags mounted under the trawl.

Chapter 6 synthesizes the main conclusions obtained from several experiments and discusses the potential applications of the trawl innovations for the emerging redfish fishery in the Gulf of St. Lawrence, Canada and Icelandic groundfish fisheries. In this chapter, the limitations that were challenging my approaches are also described clearly, and recommended directions for future research are proposed.

1.8 References

Agnarsson, S., Matthiasson, T., Giry, F., 2016. Consolidation and distribution of quota holdings in the Icelandic fisheries. Marine Policy 72, 263–270. https://doi.org/10.1016/j.marpol.2016.04.037

Akaike, H., 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control 19, 716–723. https://doi.org/10.1109/TAC.1974.1100705

Albert, O.T., Harbitz, A., Høines, Å.S., 2003. Greenland halibut observed by video in front of survey trawl: behavior, escapement, and spatial pattern. Journal of Sea Research 50, 117–127. https://doi.org/10.1016/S1385-1101(03)00063-7

Alverson, D.L., Food and Agriculture Organization, Freeberg, M.H., Murawski, S.A., Pope, J.G., 1994. A Global Assessment of Fisheries Bycatch and Discards. FAO Fisheries Technical Paper 339, 233.

Amoroso, R.O., Pitcher, C.R., Rijnsdorp, A.D., McConnaughey, R.A., Parma, A.M., Suuronen, P., Eigaard, O.R., Bastardie, F., Hintzen, N.T., Althaus, F., Baird, S.J., Black, J., Buhl-Mortensen, L., Campbell, A.B., Catarino, R., Collie, J., Cowan, J.H., Durholtz, D., Engstrom, N., Fairweather, T.P., Fock, H.O., Ford, R., Gálvez, P.A., Gerritsen, H., Góngora, M.E., González, J.A., Hiddink, J.G., Hughes, K.M., Intelmann, S.S., Jenkins, C., Jonsson, P., Kainge, P., Kangas, M., Kathena, J.N., Kavadas, S., Leslie, R.W., Lewis, S.G., Lundy, M., Makin, D., Martin, J., Mazor, T., Gonzalez-Mirelis, G., Newman, S.J., Papadopoulou, N., Posen, P.E., Rochester, W., Russo, T., Sala, A., Semmens, J.M., Silva, C., Tsolos, A., Vanelslander, B., Wakefield, C.B., Wood, B.A., Hilborn, R., Kaiser, M.J., Jennings, S., 2018. Bottom trawl fishing footprints on the world's continental shelves. Proceedings of the National Academy of Sciences of the United States of America. 115. https://doi.org/10.1073/pnas.1802379115

Araya-Schmidt, T., 2022. Reducing bottom trawl seabed impacts and bycatch in the Eastern Canada offshore Northern shrimp (*Pandalus borealis*) fishery. Memorial University of Newfoundland. PhD Thesis, 193p.

Araya-Schmidt, T., Bayse, S.M., Winger, P.D., Frank, C.H., 2023. 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. Aquaculture and Fisheries 8, 661–671. https://doi.org/10.1016/j.aaf.2023.01.009

Arimoto, T., Glass, C.W., Zhang, X., 2010. Fish vision and its role in fish capture, In: He, P. (Ed.), Behavior of Marine Fishes: Capture Processes and Conservation Challenges. Blackwell Publishing, Ames, Iowa, USA, pp. 25–44.

Arnason, R., 1996. On the ITQ fisheries management system in Iceland. Reviews in Fish Biology and Fisheries 6, 63–90. https://doi.org/10.1007/BF00058520

Atkinson, D.B., 1989. Diel movements of beaked redfish and the implications of these for stratified random bottom trawl estimates of biomass and abundance. North American Journal of Fisheries Management 9, 163–170.

Barnes, T.C., Candy, S.G., Morris, S., Johnson, D.D., 2022. Understanding discarding in trawl fisheries: A model based demersal case study with implications for mitigating and assessing impacts. PLoS ONE 17, e0264055. https://doi.org/10.1371/journal.pone.0264055

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software 67, 1-48. https://doi.org/10.18637/jss.v067.i01

Bayse, S.M., He, P., Pol, M.V., Chosid, D.M., 2014. Quantitative analysis of the behavior of longfin inshore squid (*Doryteuthis pealeii*) in reaction to a species separation grid of an otter trawl. Fisheries Research 152, 55–61. https://doi.org/10.1016/j.fishres.2013.03.018

Bayse, S.M., Herrmann, B., Lenoir, H., Depestele, J., Polet, H., Vanderperren, E., Verschueren, B., 2016a. Could a T90 mesh codend improve selectivity in the Belgian beam trawl fishery? Fisheries Research 174, 201–209. https://doi.org/10.1016/j.fishres.2015.10.012

Bayse, S.M., Pol, M.V., He, P., 2016b. Fish and squid behavior at the mouth of a drop-chain trawl: factors contributing to capture or escape. ICES Journal of Marine Science 73, 1545–1556. https://doi.org/10.1093/icesjms/fsw007

Bayse, S.M., Rillahan, C.B., Jones, N.F., Balzano, V., He, P., 2016c. Evaluating a large-mesh belly window to reduce bycatch in silver hake (*Merluccius bilinearis*) trawls. Fisheries Research 174, 1–9. https://doi.org/10.1016/j.fishres.2015.08.022

Beamish, F.W.H., 1966. Swimming endurance of some Northwest Atlantic fishes. Journal of the Fisheries Board of Canada 23, 319–340.

Bradburn, M.J., Keller, A.A., 2015. Impact of light on catch rate of four demersal fish species during the 2009–2010 U.S. west coast groundfish bottom trawl survey. Fisheries Research 164, 193–200. https://doi.org/10.1016/j.fishres.2014.11.010

Breen, M., Graham, N., Pol, M., He, P., Reid, D., Suuronen, P., 2016. Selective fishing and balanced harvesting. Fisheries Research 184, 2–8. https://doi.org/10.1016/j.fishres.2016.03.014

Brinkhof, J., Larsen, R.B., Herrmann, B., Sistiaga, M., 2020. Size selectivity and catch efficiency of bottom trawl with a double sorting grid and diamond mesh codend in the North-east Atlantic gadoid fishery. Fisheries Research 231, 105647. https://doi.org/10.1016/j.fishres.2020.105647

Broadhurst, M.K., Millar, R.B., Kennelly, S.J., Macbeth, W.G., Young, D.J., Gray, C.A., 2004. Selectivity of conventional diamond- and novel square-mesh codends in an Australian estuarine penaeid-trawl fishery. Fisheries Research 67, 183–194. https://doi.org/10.1016/j.fishres.2003.09.043

Broadhurst, M.K., Millar, R.B., Wooden, M.E.L., Macbeth, W.G., 2006. Optimising codend configuration in a multispecies demersal trawl fishery. Fisheries Manage 13, 81–92. https://doi.org/10.1111/j.1365-2400.2006.00479.x

Bublitz, C.G., 1996. Quantitative evaluation of flatfish behavior during capture by trawl gear. Fisheries Research 25, 293–304. https://doi.org/10.1016/0165-7836(95)00431-9

Cadigan, N. G, Dowden, J., 2010. Statistical inference about the relative efficiency of a new survey protocol, based on paired-tow survey calibration data. Fishery Bulletin 108, 15–29.

Cadigan, N. G., Duplisea, D.E., Senay, C., Parent, G.J., Winger, P.D., Linton, B., Kristinsson, K., 2022. Northwest Atlantic redfish science priorities for managing an enigmatic species complex. Canadian Journal of Fisheries and Aquatic Sciences 79, 1572–1589. https://doi.org/10.1139/cjfas-2021-0266

Charles, A.T., 1997. Fisheries management in Atlantic Canada. Ocean & Coastal Management 35, 101–119. https://doi.org/10.1016/S0964-5691(97)00028-8

Cheng, Z., Winger, P.D., Bayse, S.M., Kebede, G.E., DeLouche, H., Einarsson, H.A., Pol, M.V., Kelly, D., Walsh, S.J., 2020. Out with the old and in with the new: T90 codends improve size selectivity in the Canadian redfish (*Sebastes mentella*) trawl fishery. Canadian Journal of Fisheries and Aquatic Sciences 77, 1711–1720. https://doi.org/10.1139/cjfas-2020-0063

Clark, K.J., Hansen, S.C., Gale, J., 2015. Overview of Discards from Canadian Commercial Groundfish Fisheries in Northwest Atlantic Fisheries Organization (NAFO) Divisions 4X5Yb for 2007-2011.

Colgan, P., 1986. The Motivational Basis of Fish Behavior, in: Pitcher, T.J. (Ed.), The Behavior of Teleost Fishes. Springer US, Boston, MA, pp. 23–46. https://doi.org/10.1007/978-1-4684-8261-4_2

Cuende, E., Arregi, L., Herrmann, B., Sistiaga, M., Onandia, I., 2020. Stimulating release of undersized fish through a square mesh panel in the Basque otter trawl fishery. Fisheries Research 224, 105431. https://doi.org/10.1016/j.fishres.2019.105431

de Groot, S.J., 1984. The impact of bottom trawling on benthic fauna of the North Sea. Ocean Management 9, 177–190. https://doi.org/10.1016/0302-184X(84)90002-7

DFO, 2021. Impact of an expanding Redfish (*Sebastes spp.*) fishery on southern Gulf of St. Lawrence White Hake (*Urophycis tenuis*). DFO Canadian Science Advisory Secretariat Science Advisory Report 2021/033, 25.

DFO, 2020. Redfish (*Sebastes mentella* and *S. fasciatus*) stocks assessment in Unit 1 and 2 in 2019. DFO Canadian Science Advisory Secretariat Science Advisory Report 019.

DFO, 2018. Integrated Fisheries Management Plan (IFMP). 4VWX5 groundfish - Maritimes Region.

DFO, 2017. Gulf of St. Lawrence Groundfish (NAFO Subdivisions 3Pn, 4Vn and Divisions 4RST). Integrated Fisheries Management Plan EKME 3363587, 29.

DFO, 2016. Assessment of Redfish Stocks (*Sebastes fasciatus* and *S. mentella*) in Units 1 and 2 in 2015. DFO Canadian Science Advisory Secretariat Science Advisory Report 047.

Doubleday, W., Atkinson, D., Baird, J., 1997. Comment: Scientific inquiry and fish stock assessment in the Canadian Department of Fisheries and Oceans. Canadian Journal of Fisheries and Aquatic Sciences 54: 1422–1426. https://doi.org/10.1139/cjfas-54-6-1422

Duplisea, D.E., 2018. Fishermen’s historical knowledge leads to a re-evaluation of redfish catch. Marine and Coastal Fisheries 10, 3–11. https://doi.org/10.1002/mcf2.10006

Eighani, M., Bayse, S.M., Paighambari, S.Y., Broadhurst, M.K., 2020. Mono- *vs* multifilament gillnets: effects on selectivity of narrow-barred Spanish mackerel *Scomberomorus commerson* in the Persian Gulf. Journal of the Marine Biological Association of the United Kingdom 100, 285–290. https://doi.org/10.1017/S0025315419001243

Engås, A., Godø, O.R., 1989. Escape of fish under the fishing line of a Norwegian sampling trawl and its influence on survey results. ICES Journal of Marine Science 45, 269–276. https://doi.org/10.1093/icesjms/45.3.269

Engås, A., Isaksen, B., Valdemarsen, J., 1989. Escape behavior of fish in codends of trawl, In: Square Mesh Workshop. St. John’s, Newfoundland: Marine Institute, pp. 72–76.

Engås, A., Jacobsen, J.A., Soldal, A.V., 1988. Catch comparison between rockhoppers and bobbins ground gear on the Norwegian bottom sampling trawl, in: ICES C.M. 1988/B: 31. Presented at the Fish Capture Committee, International Council for the Exploration of the Sea, p. 12.

FAO, 2022. Fishing Gear types. Bottom trawls (nei). Technology Fact Sheets (Technology Fact Sheets). Fisheries and Aquaculture Division [online], Rome. Updated 2008-10-21. Accessed January 10, 2022.

FAO, 2012. The state of world fisheries and aquaculture 2012. Food and Agriculture Organization of the United Nations; Eurospan [distributor], Rome, London.

Ferro, R.S.T., Jones, E.G., Kynoch, R.J., Fryer, R.J., Buckett, B.-E., 2007. Separating species using a horizontal panel in the Scottish North Sea whitefish trawl fishery. ICES Journal of Marine Science 64, 1543–1550. https://doi.org/10.1093/icesjms/fsm099

Gabr, M., Fujimori, Y., Shimizu, S., Miura, T., 2007. Behavior analysis of undersized fish escaping through square meshes and separating grids in simulated trawling experiment. Fisheries Research 85, 112–121. https://doi.org/10.1016/j.fishres.2007.01.006.

Garcia, E.G., Ragnarsson, S.A., Steingrimsson, S., Naevestad, D., Haraldsson, H., Fossaa, J., Tendal, O., Eiriksson, H., 2006. Bottom Trawling and Scallop Dredging in the Arctic: impacts of fishing on non-target species, vulnerable habitats and cultural heritage. TemaNord 2006:529.

Garner, J., 1978. Pelagic and semi-pelagic trawling gear, in: Fishing News Books Ltd., Surrey. England, p. 59.

Gauthier, S., Rose, G.A., 2002. Acoustic observation of diel vertical migration and shoaling behavior in Atlantic redfish. Journal of Fish Biology 61, 1135–1153. https://doi.org/10.1111/j.1095-8649.2002.tb02461.x

Gauthier, S., Rose, G.A., 2005. Diel vertical migration and shoaling heterogeneity in Atlantic redfish: effects on acoustic and bottom-trawl surveys. ICES Journal of Marine Science 62, 75–85. https://doi.org/10.1016/j.icesjms.2004.10.001

Glass, C.W., Wardle, C.S., 1989. Comparison of the reactions of fish to a trawl gear, at high and low light intensities. Fisheries Research 7, 249–266.

Godø, O., 1999. Investigating density-dependent catchability in bottom-trawl surveys. ICES Journal of Marine Science 56, 292–298. https://doi.org/10.1006/jmsc.1999.0444

Godø, O.R., 1994. Factors affecting the reliability of groundfish abundance estimates from bottom trawl surveys. In Marine Fish Behavior in Capture and Abundance Estimation, pp. 166–199. Ed. by A. Fernö and S. Olsen. Fishing News Books, Oxford.

Godø, O.R., Walsh, S.J., Engås, A., 1999. Investigating density-dependent catchability in bottom-trawl surveys. ICES Journal of Marine Science 56, 292–298. https://doi.org/10.1006/jmsc.1999.0444

Goetting, K., 2008. Is fisheries diversification a sustainable strategy?: the case of the Newfoundland redfish fishery (Master thesis). Memorial University of Newfoundland, Canada.

Gomes, M.C., Haedrich, R.L., Rice, J.C., 1992. Biogeography of Groundfish Assemblages on the Grand Bank. Journal of Northwest Atlantic Fishery Science 14, 13–27. https://doi.org/10.2960/j.v14.a1

Graham, N., 2010. Technical measures to reduce bycatch and discards in trawl fisheries, in: Behavior of Marine Fishes. pp. 237–264. https://doi.org/10.1002/9780813810966.ch10

Graham, N., 2006. Trawling: historic development, current status and future challenges. Marine Technology Society Journal 40(3), 20–24. https://doi.org/10.4031/002533206787353231

Grelon, D., Cote-Laurin, M.-C., Coulombe, F., Montagnac, V., 2020. Developpement d'un chalut pelagique selectif et performant pour une peche responsable au sebaste dans le golfe du Saint-Laurent., Rapport final 2017–2020.

Grimaldo, E., Larsen, R.B., Sistiaga, M., Madsen, N., Breen, M., 2009. Selectivity and escape percentages during three phases of the towing process for codends fitted with different selection systems. Fisheries Research 95, 198–205. https://doi.org/10.1016/j.fishres.2008.08.019

Grimaldo, E., Sistiaga, M., Herrmann, B., Larsen, R.B., 2016. Trawl selectivity in the Barents Sea demersal fishery, In: Mikkola, H. (Ed.), Fisheries and Aquaculture in the Modern World. InTech. https://doi.org/10.5772/63019

Grimaldo, E., Sistiaga, M., Herrmann, B., Larsen, R.B., Brinkhof, J., Tatone, I., 2018. Improving release efficiency of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea demersal trawl fishery by stimulating escape behavior. Canadian Journal of Fisheries and Aquatic Sciences 75, 402–416. https://doi.org/10.1139/cjfas-2017-0002

Gunnlaugsson, S.B., Saevaldsson, H., Kristofersson, D.M., Agnarsson, S., 2020. Resource rent and its distribution in Iceland’s fisheries. Marine Resource Economics 35, 113–135. https://doi.org/10.1086/708507

Halliday, R.G., 2002. A comparison of size selection of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglenus*) by bottom longlines and otter trawls. Fisheries Research 57, 63–73.

Halliday, R.G., Fanning, L.P., 2006. A history of marine fisheries science in the Atlantic Canada and its role in the management of fisheries. Proc NSIS 43. https://doi.org/10.15273/pnsis.v43i2.3641

Halliday, R.G., Pinhorn, A.T., 1996. North Atlantic fishery management systems: A comparison of management methods and resource trends. Journal of Northwest Atlantic Fishery Science 21, 3–135. https://doi.org/10.2960/j.v20.a1

Harding, H.R., Gordon, T.A.C., Wong, K., McCormick, M.I., Simpson, S.D., Radford, A.N., 2020. Condition-dependent responses of fish to motorboats. Biology Letters. 16, 20200401. https://doi.org/10.1098/rsbl.2020.0401

He, P., 2010a. Swimming capacity of marine fishes and its role in capture by fishing gear, In: Fish Locomotion. Cambridge UP, Print., Cambridge ; New York.

He, P. (Ed.), 2010b. Behavior of Marine Fishes: Capture Processes and Conservation Challenges. Wiley-Blackwell, Oxford, UK. https://doi.org/10.1002/9780813810966

He, P., 2007. Selectivity of large mesh trawl codends in the Gulf of Maine: I. Comparison of square and diamond mesh. Fisheries Research 83, 44–59. https://doi.org/10.1016/j.fishres.2006.08.019

He, P., 1993. Swimming speeds of marine fish in relation to fishing gears. ICES Journal of Marine Science 196, 183–189.

He, P., 1991. Swimming endurance of the Atlantic cod, *Gadus morhua L*., at low temperatures. Fisheries Research 12, 65–73. https://doi.org/10.1016/0165-7836(91)90050-P

He, P., Balzano, V., 2013. A new shrimp trawl combination grid system that reduces small shrimp and finfish bycatch. Fisheries Research 140, 20–27. https://doi.org/10.1016/j.fishres.2012.11.009

He, P., Chopin, F., Suuronen, P., Ferro, R.S.T., Lansley, J., 2021. Classification and illustrated definition of fishing gears, FAO Fisheries and Aquaculture Technical Paper. FAO, Rome. 94p. https://doi.org/10.4060/cb4966en

He, P., Goethel, D., Smith, T., 2007. Design and test of a topless shrimp trawl to reduce pelagic fish bycatch in the Gulf of Maine pink shrimp fishery. Journal of Northwest Atlantic Fishery Science 38, 13–21. https://doi.org/10.2960/J.v38.m591

He, P. (Ed.), Pol, M., 2010. Fish behavior near gillnets: Capture processes, and influencing factors, In: Behavior of Marine Fishes: Capture Processes and Conservation Challenges. Wiley-Blackwell, Oxford, UK, pp. 183–203. https://doi.org/10.1002/9780813810966.ch8

He, P., Rillahan, C., Balzano, V., 2015. Reduced herding of flounders by floating bridles: application in Gulf of Maine Northern shrimp trawls to reduce bycatch. ICES Journal of Marine Science 72, 1514–1524. https://doi.org/10.1093/icesjms/fsu235

He, P. (Ed.), Winger, P., 2010. Effect of trawling on the seabed and mitigation measures to reduce impact, In: Behavior of Marine Fishes: Capture Processes and Conservation Challenges. pp. 295–314. https://doi.org/10.1002/9780813810966.ch12

Hemmings, C.C., 1973. Direct observation of the behavior of fish in relation to fishing gear. Helgolander Wiss. Meeresunters 24, 348–360. https://doi.org/10.1007/BF01609525

Hendrickson, L.C., 2011. Effects of a codend mesh size increase on size selectivity and catch rates in a small-mesh bottom trawl fishery for longfin inshore squid, *Loligo pealeii*. Fisheries Research 108, 42–51. https://doi.org/10.1016/j.fishres.2010.11.019

Herrmann, B., Priour, D., Krag, L.A., 2007. Simulation-based study of the combined effect on cod-end size selection of turning meshes by 90° and reducing the number of meshes in the circumference for round fish. Fisheries Research 84, 222–232. https://doi.org/10.1016/j.fishres.2006.10.020

Herrmann, B., Wienbeck, H., Karlsen, J.D., Stepputtis, D., Dahm, E., Moderhak, W., 2015. Understanding the release efficiency of Atlantic cod (*Gadus morhua*) from trawls with a square mesh panel: effects of panel area, panel position, and stimulation of escape response. ICES Journal of Marine Science 72, 686–696. https://doi.org/10.1093/icesjms/fsu124

Hiddink, J.G., Jennings, S., Kaiser, M.J., 2006. Indicators of the ecological impact of bottom-trawl disturbance on seabed communities. Ecosystems 9, 1190–1199. https://doi.org/10.1007/s10021-005-0164-9

Hiddink, J.G., Johnson, A.F., Kingham, R., Hinz, H., 2011. Could our fisheries be more productive? Indirect negative effects of bottom trawl fisheries on fish condition: Effects of bottom trawls on fish condition. Journal of Applied Ecology 48, 1441–1449. https://doi.org/10.1111/j.1365-2664.2011.02036.x

Holst, R., Revill, A., 2009. A simple statistical method for catch comparison studies. Fisheries Research 95, 254–259. https://doi.org/10.1016/j.fishres.2008.09.027

Ingólfsson, Ó.A., Jørgensen, T., 2006. Escapement of gadoid fish beneath a commercial bottom trawl: Relevance to the overall trawl selectivity. Fisheries Research 79, 303–312. https://doi.org/10.1016/j.fishres.2005.12.017

Ioannou, C.C., Bartumeus, F., Krause, J., Ruxton, G.D., 2011. Unified effects of aggregation reveal larger prey groups take longer to find. Proceedings Biological science. 278, 2985–2990. https://doi.org/10.1098/rspb.2011.0003

Isaksen, B., Valdermarsen, J.W., Larsen, R.B., 1992. Reduction of fish by-catch in shrimp trawl using a rigid Separator grid in the aft belly. Fisheries Research. 13.3 (1992): 335-352.

Jennings, S., Kaiser, M.J., 1998. The effects of fishing on marine ecosystems, In: Blaxter, J.H.S., Southward, A.J., Tyler, P.A. (Eds.), Advances in Marine Biology. Academic Press, pp. 201–352. https://doi.org/10.1016/S0065-2881(08)60212-6

Jones, E.G., Summerbell, K., O'Neill, F., 2008. The influence of towing speed and fish density on the behavior of haddock in a trawl cod-end. Fisheries Research 94, 166–174. https://doi.org/10.1016/j.fishres.2008.06.010

Jørgensen, T., Ingólfsson, Ó.A., Graham, N., Isaksen, B., 2006. Size selection of cod by rigid grids - Is anything gained compared to diamond mesh codends only? Fisheries Research 79, 337–348. https://doi.org/10.1016/j.fishres.2006.01.017

Keenleyside, M.H.A., 1979. Diversity and Adaptation in Fish Behavior. Springer-Verlag, Berlin. 210p.

Kelleher, K., 2005. Discards in the World's Marine Fisheries. An Update. FAO Fisheries Technical Paper 470. 150p.

Kim, Y.-H., 2015. Escape response of juvenile fish in a shaking codend determined from tank experiments. Fisheries Research 161, 273–279. https://doi.org/10.1016/j.fishres.2014.08.012

Kim, Y.-H., 2013. Shaking motion characteristics of a cod-end caused by an attached circular canvas during tank experiments and sea trials. Fisheries and Aquatic Sciences 16, 211–220. https://doi.org/10.5657/FAS.2013.0211

Kim, Y.-H., Wardle, C.S., 2003. Optomotor response and erratic response: quantitative analysis of fish reaction to towed fishing gears. Fisheries Research 60, 455–470. https://doi.org/10.1016/S0165-7836(02)00114-5

Kim, Y.-H., Wardle, C.S., An, Y.-S., 2008. Herding and escaping responses of juvenile roundfish to square mesh window in a trawl cod end. Fisheries Science 74, 1–7. https://doi.org/10.1111/j.1444-2906.2007.01490.x

Kim, Y.-H., Whang, D.-S., 2010. An actively stimulating net panel and rope array inside a model cod-end to increase juvenile red seabream escapement. Fisheries Research 106, 71–75. https://doi.org/10.1016/j.fishres.2010.07.005

King, S.E., Hannah, R.W., Parker, S.J., Matteson, K.M., Berkeley, S.A., 2004. Protecting rockfish through gear design: development of a selective flatfish trawl for the U.S. west coast bottom trawl fishery. Canadian Journal of Fisheries and Aquatic Sciences 61, 487–496. https://doi.org/10.1139/f03-153

Koslow, J., Boehlert, G.W., Gordon, J.D.M., Haedrich, R.L., Lorance, P., Parin, N., 2000. Continental slope and deep-sea fisheries: implications for a fragile ecosystem. ICES Journal of Marine Science 57, 548–557. https://doi.org/10.1006/jmsc.2000.0722

Kotwicki, S., Lauth, R.R., Williams, K., Goodman, S.E., 2017. Selectivity ratio: A useful tool for comparing size selectivity of multiple survey gears. Fisheries Research 191, 76–86. https://doi.org/10.1016/j.fishres.2017.02.012

Krag, L.A., Herrmann, B., Karlsen, J.D., 2014. Inferring fish escape behavior in trawls based on catch comparison data: Model development and evaluation based on data from Skagerrak, Denmark. PLoS ONE 9, e88819. https://doi.org/10.1371/journal.pone.0088819

Krag, L.A., Herrmann, B., Karlsen, J.D., Mieske, B., 2015. Species selectivity in different sized topless trawl designs: Does size matter? Fisheries Research 172, 243–249. https://doi.org/10.1016/j.fishres.2015.07.010

Krag, L.A., Holst, R., Madsen, N., Hansen, K., Frandsen, R.P., 2010. Selective haddock (*Melanogrammus aeglefinus*) trawling: Avoiding cod (*Gadus morhua*) bycatch. Fisheries Research 101, 20–26. https://doi.org/10.1016/j.fishres.2009.09.001

Krag, L.A., Madsen, N., Karlsen, J.D., 2009. A study of fish behavior in the extension of a demersal trawl using a multi-compartment separator frame and SIT camera system. Fisheries Research 98, 62–66. https://doi.org/10.1016/j.fishres.2009.03.012

Kumar, A.B., Deepthi, G.R., 2006. Trawling and by-catch: Implications on marine ecosystem. CURRENT SCIENCE 90, 11.

Kvamme, C., Frøysa, K.G., 2004. Assessing the effects on stocks of selectivity changes in a fishery. Fisheries Research 69, 283–292. https://doi.org/10.1016/j.fishres.2004.02.010

Larsen, R.B., Herrmann, B., Brinkhof, J., Grimaldo, E., Sistiaga, M., Tatone, I., 2018a. Catch efficiency of groundgears in a bottom trawl fishery: A case study of the Barents Sea haddock. Marine and Coastal Fisheries 10, 493–507. https://doi.org/10.1002/mcf2.10048

Larsen, R.B., Herrmann, B., Sistiaga, M., Grimaldo, E., Tatone, I., Brinkhof, J., 2018b. Size selection of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Northeast Atlantic bottom trawl fishery with a newly developed double steel grid system. Fisheries Research 201, 120–130. https://doi.org/10.1016/j.fishres.2018.01.021

Lucchetti, A., Virgili, M., Vasapollo, C., Petetta, A., Bargione, G., Li Veli, D., Brĉic, J., Sala, A., 2021. An overview of bottom trawl selectivity in the Mediterranean Sea. Mediterranean Marine Science. 22, 566. https://doi.org/10.12681/mms.26969

Main, J., Sangster, G., 1981. A study of the fish capture process in a bottom trawl by direct observation from a towed underwater vehicle. Scottish Fisheries Research Report 23, 1–23.

Main, J., Sangster, G.I., 1985a. Report on the direct observation experiments with the chalut 28.90/37.1m JCB trawl during July 3–23, 1984. ICES CM 1985/B: 9/Ref K 19.

Main, J., Sangster, G.I., 1985b. Trawling experiments with as two-level net to minimize the undersized gadoid by-catch in a Nephrops fishery 15.

Madsen, N., Holst, R., 2002. Assessment of the cover effect in trawl codend selectivity experiments. Fisheries Research 56, 289–301. https://doi.org/10.1016/S0165-7836(01)00330-7

Matthíasson, T., 2003. Closing the open sea: Development of fishery management in four Icelandic fisheries. Natural Resources Forum 27, 1–18. https://doi.org/10.1111/1469-8219.00065-i1

Millar, R. B., Fryer, R.J., 1999. Estimating the size-selection curves of towed gears, traps, nets and hooks. Reviews in Fish Biology and Fisheries 9, 89–116. https://doi.org/10.1023/A:1008838220001

Miller, T.J., 2013. A comparison of hierarchical models for relative catch efficiency based on paired-gear data for US Northwest Atlantic fish stocks. Canadian Journal of Fisheries and Aquatic Sciences. 70, 1306–1316. https://doi.org/10.1139/cjfas-2013-0136

Montgomerie, M., 2015. Basic fishing methods. A comprehensive guide to commercial fishing methods. SEAFISH, 103p.

Munro, P.T., Somerton, D.A., 2002. Estimating net efficiency of a survey trawl for flatfish. Fisheries Research 55, 267–279.

Nielsen, M., Asche, F., Bergesen, O., Blomquist, J., Henriksen, E., Hoff, A., Nielsen, R., Viðarsson, J.R., Waldo, S., 2018. The myth of the poor fisher: Evidence from the Nordic countries. Marine Policy 93, 186–194. https://doi.org/10.1016/j.marpol.2018.04.003

Olla, B.L, Davis, M.W., Rose, C., 2000. Differences in orientation and swimming of walleye pollock *Theragra chalcogramma* in a trawl net under light and dark conditions: concordance between field and laboratory observations. Fisheries Research 44, 261–266. https://doi.org/10.1016/S0165-7836(99)00093-4

O'Neill, F G, McKay, S.J., Ward, J.N., Strickland, A., Kynoch, R.J., Zuur, A.F., 2003. An investigation of the relationship between sea state induced vessel motion and cod-end selection. Fisheries Research 60, 107–130. https://doi.org/10.1016/S0165-7836(02)00056-5.

Oostenbrugge, H.J.A.E., Powell, J.P., Smit, J.P.G., Poos, J.-J., Kraak, S.B.M., Buisman, E.F.C., 2008. Linking catchability and fisher behavior under effort management. Aquatic Living Resources. 21, 265–273. https://doi.org/10.1051/alr:2008035

Pálsson, Ó.K., 2003. A length-based analysis of haddock discards in Icelandic fisheries. Fisheries Research 59, 437–446. https://doi.org/10.1016/S0165-7836(02)00017-6

Pérez Roda, M.A, Gilman, E., Huntington, T., Kennelly, S.J., Suuronen, P., Chaloupka, M., Medley, P.A.H., Food and Agriculture Organization of the United Nations, 2019. A third assessment of global marine fisheries discards. FAO Fisheries and Aquaculture Technical Paper No. 633. Rome, FAO. 78 pp.

Pitcher, T., Parrish, J., 1993. Function of shoaling behavior in teleosts, In: Pitcher, T. (Ed.), Behavior of Teleost Fishes, 2nd Ed. Croom helm, London, pp. 365–439.

Pitcher, T.J., 2012. The behavior of teleost fishes. Springer Science & Business Media.

Pol, M., Eayrs, S., 2021. Behavior in a bottom trawl: moving forward to limit catches of Atlantic cod. ICES Journal of Marine Science 78, 2317–2324. https://doi.org/10.1093/icesjms/fsab106

Pol, M.V., Herrmann, B., Rillahan, C., He, P., 2016. Impact of codend mesh sizes on selectivity and retention of Acadian redfish Sebastes fasciatus in the Gulf of Maine trawl fishery. Fisheries Research 184, 54–63. https://doi.org/10.1016/j.fishres.2016.06.013

Pope, J.A., Margetts, A.R., Hamley, J.M., Akyuz, F., 1975. Manual of methods for fish stock assessment. Pan 111. Selectivity of fishing gear. FAO Fisheries Technical Paper 41, 65p.

R Development Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ramakrishnan, M., 2018. A review of trawl selectivity studies carried out along Indian Coast. Fishery Technology 55, 1–18.

Reid, D.G., Kynoch, R.J., Penny, I., Summerbell, K., Edridge, A., O’Neill, F.G., 2012. A comparison of the GOV survey trawl with a commercial whitefish trawl. Fisheries Research 121–122, 136–143. https://doi.org/10.1016/j.fishres.2012.01.021

Rubec, P.J., McGlade, J.M., Trottier, B.L., Ferron, A., 1991. Evaluation of methods for separation of Gulf of St. Lawrence Beaked Redfishes, *Sebastes fasciatus* and *S. mentella*: Malate dehydrogenase mobility patterns compared with extrinsic gasbladder muscle passages and anal fin ray counts. Canadian Journal of Fisheries and Aquatic Sciences 48, 640–660. https://doi.org/10.1139/f91-082

Rudders, D., Dupaul, W., Kirkley, J., 2000. A comparison of size selectivity and relative efficiency of sea scallop, *Placopecten Magellanicus* (Gmelin, 1791), trawls and dredges. Journal Of Shellfish Research 19, 757–764.

Ryer, C.H., 2008. A review of flatfish behavior relative to trawls. Fisheries Research 90, 138–146. https://doi.org/10.1016/j.fishres.2007.10.005

Sampson, D.B., 2014. Fishery selection and its relevance to stock assessment and fishery management. Fisheries Research 158, 5–14. https://doi.org/10.1016/j.fishres.2013.10.004

Santos, J., Herrmann, B., Mieske, B., Stepputtis, D., Krumme, U., Nilsson, H., 2016. Reducing flatfish bycatch in roundfish fisheries. Fisheries Research 184, 64–73. https://doi.org/10.1016/j.fishres.2015.08.025

Santos, J., Herrmann, B., Stepputtis, D., Kraak, S.B.M., Gökçe, G., Mieske, B., 2020. Quantifying the performance of selective devices by combining analysis of catch data and fish behavior observations: methodology and case study on a flatfish excluder. ICES Journal of Marine Science 77, 2840–2856. https://doi.org/10.1093/icesjms/fsaa155

Scott, R.D., Sampson, D.B., 2011. The sensitivity of long-term yield targets to changes in fishery age-selectivity. Marine Policy 35, 79–84. https://doi.org/10.1016/j.marpol.2010.08.005

Simpson, M.R., Miri, C.M., Mello, L.G.S., Colbourne, E., H Rockwood, 2018. Assessment update of White Hake (*Urophycis tenuis*, Mitchill 1815) in NAFO Division 3P. Canadian Science Advisory Secretariat (CSAS) Research Document 2018/060, 29.

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R.B., Tatone, I., 2015. Effect of lifting the sweeps on bottom trawling catch efficiency: A study based on the Northeast arctic cod (*Gadus morhua*) trawl fishery. Fisheries Research 167, 164–173. https://doi.org/10.1016/j.fishres.2015.01.015

Sparre, P., Ursin, E., Venema, S.C., 1989. Introduction to tropical fish stock assessment. FAO Fisheries Technical Paper 306, 337.

Templeman, W., 1959. Redfish distribution in the North Atlantic. Bulletin (Fisheries Research Board of Canada) 120, 168–173.

Thorsteinsson, G., 1980. Iceland bottom trawl and Danish seine codend selection experiments on cod, haddock, redfish and plaice in 1972-1976. ICES Fish Capture Committee. C.M. 1980/B3, 14.

Tokaç, A., Herrmann, B., Aydın, C., Kaykaç, H., Ünlüler, A., Gökçe, G., 2014. Predictive models and comparison of the selectivity of standard (T0) and turned mesh (T90) codends for three species in the Eastern Mediterranean. Fisheries Research 150, 76–88. https://doi.org/10.1016/j.fishres.2013.10.015

Underwood, M., Winger, P., Legge, G., 2012. Development and evaluation of a new high definition self-contained underwater camera system to observe fish and fishing gears in situ. The Journal of Ocean Technology 7, 60–70.

Underwood, M.J., Winger, P.D., Fernö, A., Engås, A., 2015. Behavior-dependent selectivity of yellowtail flounder (*Limanda ferruginea*) in the mouth of a commercial bottom trawl. Fishery Bulletin 113, 430–441. https://doi.org/10.7755/FB.113.4.6

Victorero, L., Watling, L., Deng Palomares, M.L., Nouvian, C., 2018. Out of sight, but within reach: A global history of bottom-trawled deep-sea fisheries from >400 m depth. Frontiers in Marine Science 5, 98. https://doi.org/10.3389/fmars.2018.00098

Videler, J.J., He, P., 2010. Swimming in Marine Fish, in: He, P. (Ed.), Behavior of Marine Fishes. Wiley-Blackwell, Oxford, UK, pp. 3–24. https://doi.org/10.1002/9780813810966.ch1

Walsh, S.J., 1996. Efficiency of bottom sampling trawls in deriving survey abundance indices. NAFO Scientific Council Studies 28, 9–24.

Walsh, S.J., 1992. Size-dependent selection at the footgear of a groundfish survey trawl. North American Journal of Fisheries Management 12, 625–633.

Walsh, S.J., Hickey, W.M., 1993. Behavioral reactions of demersal fish to bottom trawls at various light conditions. ICES Marine Science Symposia 196, 68–76.

Wardle, C.S., 1983. Fish reactions to towed fishing gear, in: Experimental Biology Sea. pp. 168–193.

Wardle, C.S., 1993. Fish behavior and fishing gear, in: Pitcher, T.J. (Ed.), Behavior of Teleost Fishes. Chapman & Hall, London, pp. 609–643.

Wardle, C.S., 1986. Fish Behavior and Fishing Gear, in: Pitcher, T.J. (Ed.), The Behavior of Teleost Fishes. Springer US, Boston, MA, pp. 463–495. https://doi.org/10.1007/978-1-4684-8261-4_18

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Cooperative Research Report 215.

Winger, P., Eayrs, S., Glass, C., 2010. Fish behavior near bottom trawls, In He, P (Ed.), Behavior of Marine Fishes: Capture Processes and Conservation Challenges. Wiley-Blackwell, Oxford, UK, pp. 65–103. https://doi.org/10.1002/9780813810966.ch4

Winger, P., He, P., Walsh, S.J., 1999. Swimming endurance of American plaice (*Hippoglossoides platessoides*) and its role in fish capture. ICES Journal of Marine Science 56, 252–265. https://doi.org/10.1006/jmsc.1999.0441

Winger, P.D., Walsh, S.J., He, P., Brown, J.A., 2004. Simulating trawl herding in flatfish: the role of fish length in behavior and swimming characteristics. ICES Journal of Marine Science 61, 1179–1185. https://doi.org/10.1016/j.icesjms.2004.07.015

Woods, P.J., Bouchard, C., Holland, D.S., Punt, A.E., Marteinsdóttir, G., 2015. Catch-quota balancing mechanisms in the Icelandic multi-species demersal fishery: Are all species equal? Marine Policy 55, 1–10. https://doi.org/10.1016/j.marpol.2015.01.004

Yang, B., Herrmann, B., 2022. Effect of codend mesh sizes on the size selectivity and exploitation pattern of cocktail shrimp (*Trachypenaeus curvirostris*) in shrimp trawl fishery of the South China Sea. Frontiers in Marine Science 9, 928906. https://doi.org/10.3389/fmars.2022.928906

1.9 Figures

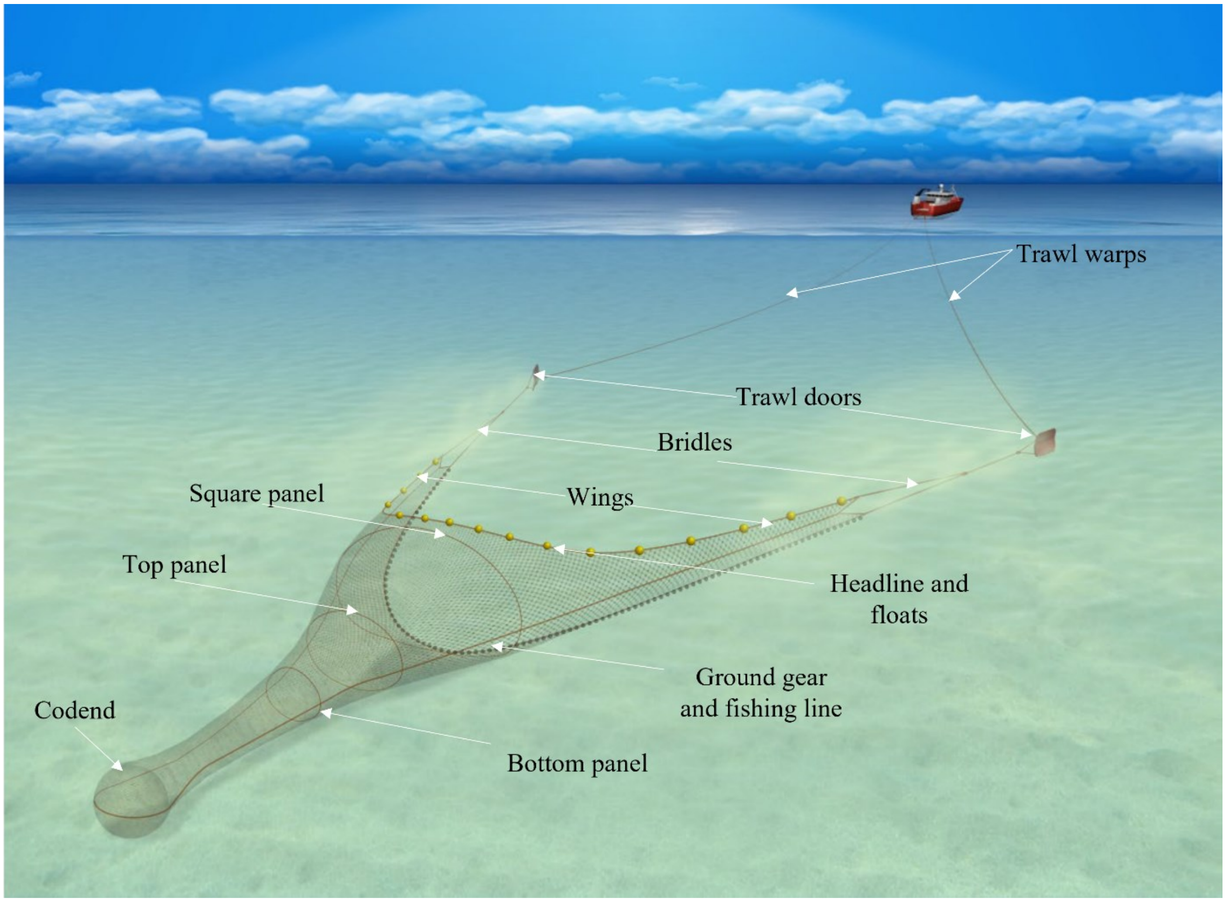


Figure 1.1. The basic components of a typical commercial bottom trawl (Adapted from Montgomerie, 2015)

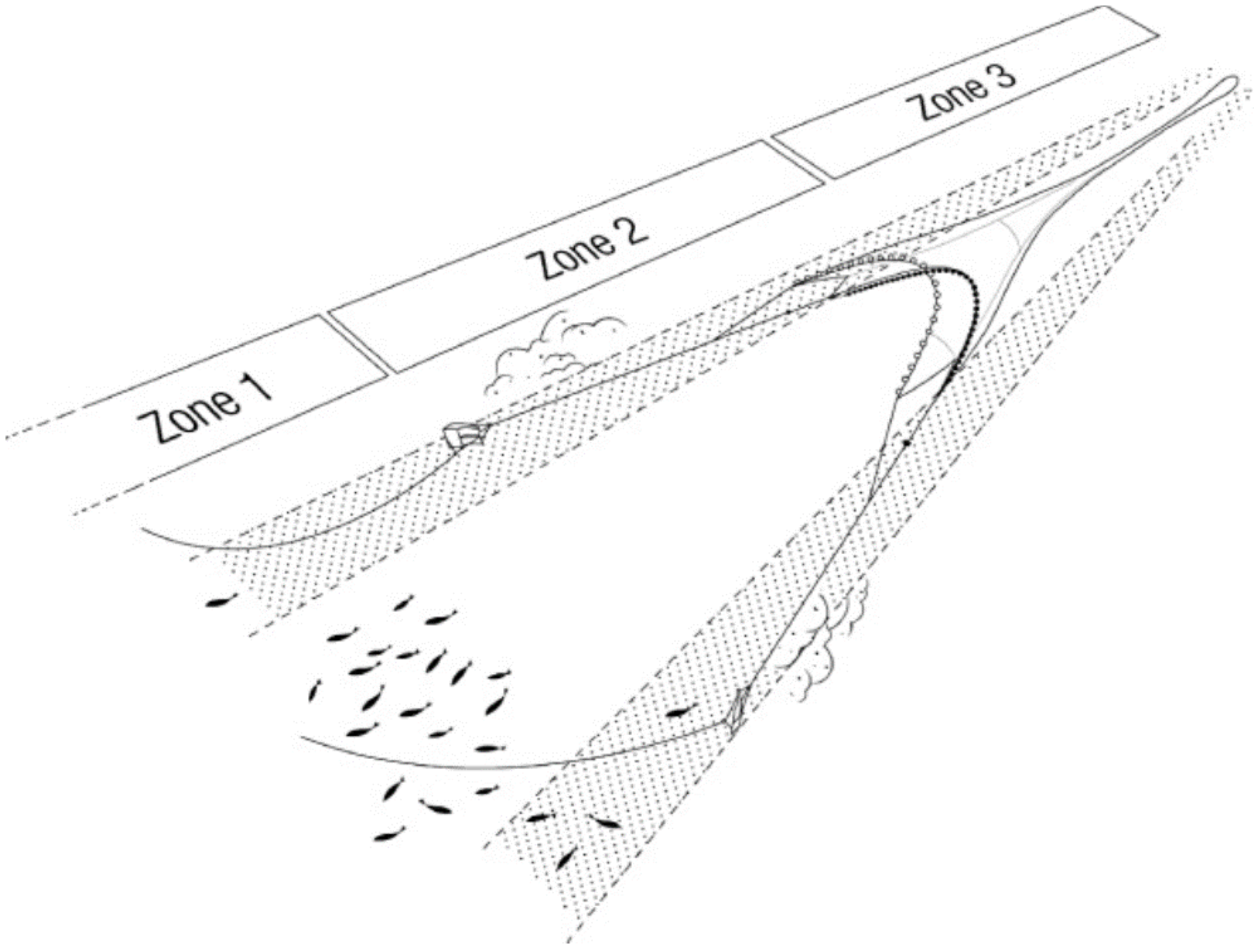


Figure 1.2. Schematic drawing of capture process of bottom trawl (Winger et al., 2010)

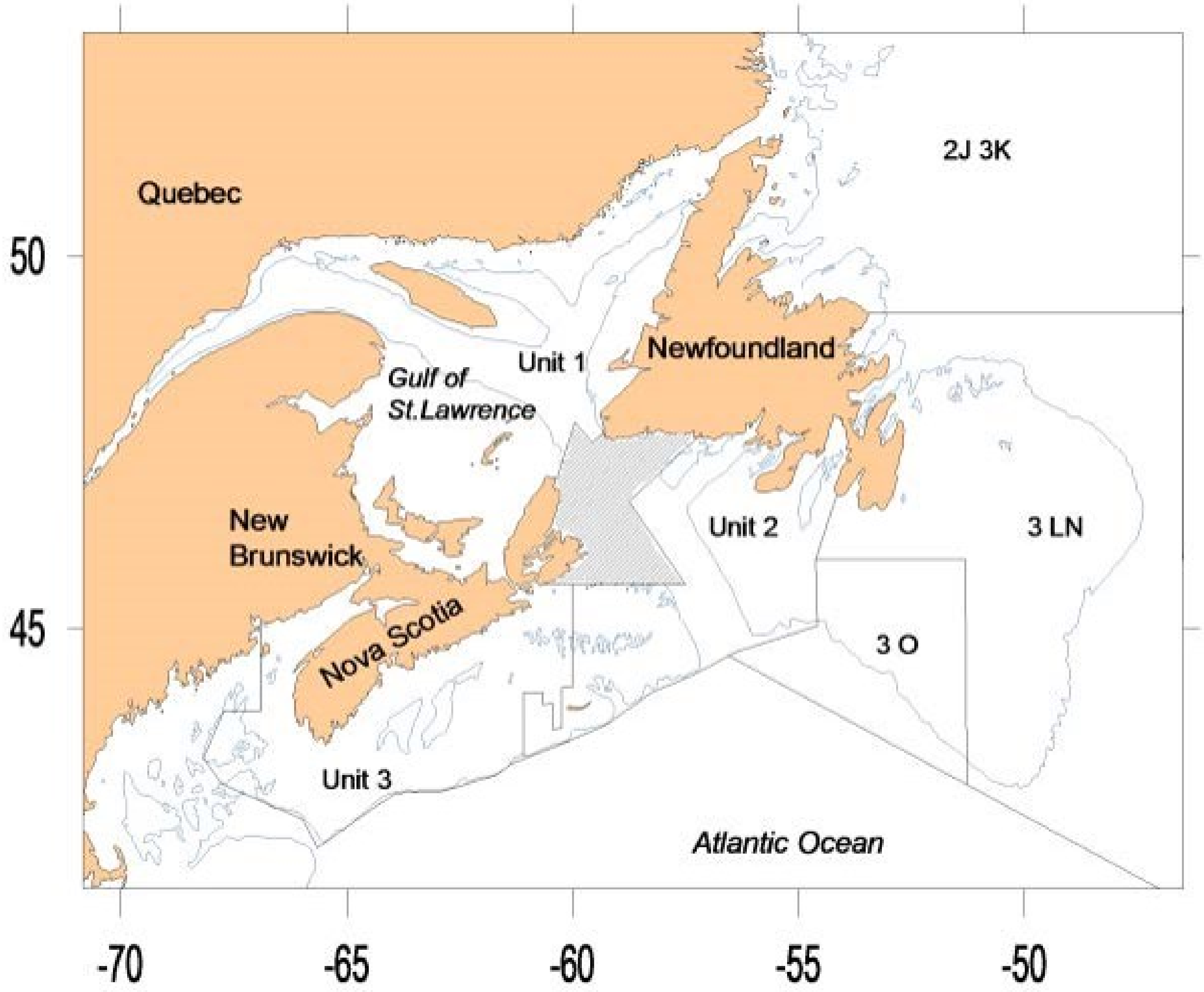


Figure 1.3. Redfish stock management areas in Canada include Unit 1 (the Gulf of St. Lawrence), Unit 2, and 3 (DFO, 2016).

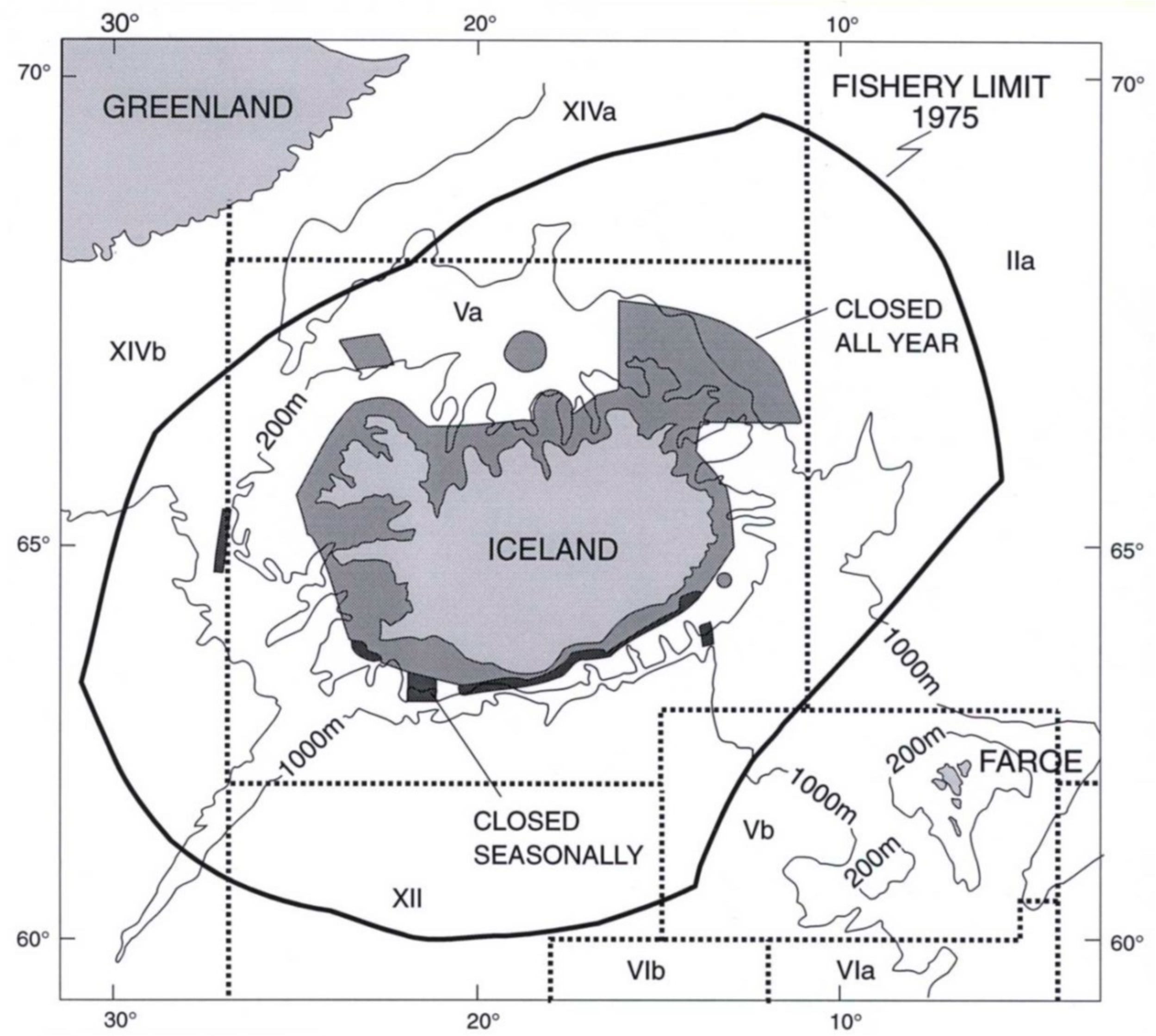


Figure 1.4. Icelandic jurisdictional boundaries and area around Iceland water closed to trawling by the late 1970s (Halliday and Pinhorn, 1996).

CHAPTER 2. Developing a full-scale shaking codend to reduce the capture of small fish

2.1 Abstract

To reduce the retention of undersized fish in the redfish (*Sebastes* spp.) trawl fishery in the Gulf of St. Lawrence, Canada, we developed a full-scale shaking codend. The shaking codend uses a mechanical stimulating device, an elliptical-shaped piece of polyvinyl chloride canvas, attached to the posterior of a T90 codend that generates a lifting force with respect to drag, causing a 'shaking motion'. A shaking codend could stimulate fish movement and increase contact probability, both of which could increase the escape of small redfish out of a codend, especially when combined with a codend that maintains mesh openings. The movement and fishing characteristics of a shaking codend (T90 codend with canvas) relative to a T90 codend (without canvas) were tested in a flume tank and a field experiment. In the flume tank test, the shaking codend had a peak-to-peak amplitude (i.e., the distance the codend moves from the lowest to highest depth) > 24 cm higher than the T90 codend for each velocity tested (1.0-1.8 kt), higher amplitude ratio, and a higher period (1 revolution) that gradually decreased with increasing velocity. The total acceleration (m s^{-2}) and drag forces (kgf) estimated for the shaking codend were significantly higher than the T90 codend across all flow velocities. The results from the field experiment, considered preliminary due to sample size, showed that the shaking codend significantly reduced the capture of small redfish (< 21 cm) and the best fit model did not need to consider contact probability which was necessary for the non-shaking T90 codend. Overall, the dynamics of the movement of the codend were described and could be potentially used as an

effective technique to reduce the catch of small redfish, and perhaps in other trawl fisheries to reduce the catch of small fish.

2.2 Introduction

Discards are the portion of the catch consisting of unwanted species that are either too small or have no market value and are thrown overboard at sea after capture (Kelleher, 2005; Zeller et al., 2018). Estimating and reducing discards in the catch of marine fisheries, particularly in commercial fishing, has been the subject of much concern by fisheries management, fishers, and researchers in recent decades. Estimated annual discards in global marine fisheries during 2010 – 2014 were around 9.1 million t, occupying approximately 10.8% of the total annual catch (Pérez Roda et al., 2019). The amount of discard varies according to region and gear type. For example, in the Northeast Atlantic and Northwest Pacific, the annual discards occupied 39% of annual totals, with 33% contributed by bottom trawl fisheries (Pérez Roda et al., 2019).

Discarding from commercial fisheries is expected to impact marine ecosystems and stock management globally. High levels of discard in marine fisheries threaten sustainable fisheries (e.g., harvesting fish stocks in a way that meets our needs without compromising the ability to meet future needs; defined by DFO (https://www.dfo-mpo.gc.ca/fisheries-peches/sustainable-durable/fisheries-peches/index-eng.html) by inducing unnecessary fishing mortality, which is considered a waste of natural resources (Kelleher, 2005; World Bank and Food and Agriculture Organization, 2009). Additionally, discard problems make fisheries management designs and execution difficult (Bellido et al., 2011). Thus, in recent years, fisheries have been managed with discard quotas, effort regulation, no-discard regimes, and selective fishing to reduce discards (Kelleher, 2005; Bellido et al., 2011).

In the Gulf of St. Lawrence, CA, two redfish species are commercially harvested, deepwater redfish (*Sebastes mentella*) and Acadian redfish (*S. fasciatus*), and are typically considered together as redfish (*Sebastes* spp.) (DFO, 2020; Cadigan et al., 2022). These species are slow growing, late maturing, and long-lived and thus are susceptible to overfishing (Koslow et al., 2000). In 1995, the Gulf of St. Lawrence (Unit 1) redfish fishery was placed into moratorium, and only a small (2,000 t year^{-1}) index fishery has taken place since 1999 (DFO, 2020). However, due to recent strong recruitment events, there is a large redfish biomass now found in the Gulf of St. Lawrence (estimated over four million t), which will lead to a reopening of the commercial fishery (DFO, 2020).

Current conservation measures for the redfish fishery include a small fish protocol, bycatch protocol, minimum landing size of 22 cm, and the use of a mesh opening of 90 mm (DFO, 2016; 2020). Recent studies have attempted to develop trawls to further reduce the catch of small redfish (Cheng et al., 2019; Cheng et al., 2020) and a T90 codend was shown to effectively reduce the capture of undersized redfish (Cheng et al., 2020). Considering that the high proportion (more than 50% of catch weight) of undersized redfish captured led to the redfish fishery moratorium in the 1990s (Duplisea, 2018), continued research should be applied to further reduce the capture of small redfish in the commercial fishery.

Discards can be reduced by the addition of a so called bycatch reduction device (BRD), where bycatch is the retention or discarding of a non-target species or specific sizes of target species (Alverson et al., 1994). A BRD is the addition of a device to a fishing gear (e.g., grid, large-mesh panel, etc.) that reduces the capture of unwanted animals or animal sizes (Winger et al., 2010). Recently, several studies have investigated the use of active stimulating devices (ASDs) as, or in conjunction with, a BRD to increase the escape of undersized fish in trawls.

ASDs have been developed to encourage fish to approach netting, BRDs (e.g. square mesh panel), or an area of a fishing gear (typically trawl) to increase the likelihood of escape. Thus, an ASD stimulates fish to react to a moving object (e.g., rope, trawl panel) increasing the likelihood of contact and escape through a BRD, mesh, or other opening (Kim and Whang, 2010; Herrmann et al., 2015; Grimaldo et al., 2018).

Past ASD experiments include a tank experiment by Kim and Whang (2010) that found that the retention of juvenile red seabream was reduced below 20% when an array-rope stimulation was introduced in the codend. This type of ASD changed how fish reacted in the codend by increasing an erratic response, which encouraged individuals to approach the netting and escape from the codend. Herrmann et al. (2015) and Cuende et al. (2020) have investigated the increase in escape of cod through a square-mesh panel using fluttering ropes with floats mounted to the bottom panel of the codend in the Baltic Sea. Additionally, Grimaldo et al. (2018) showed that mechanical stimulation can trigger escape behaviors for haddock in the Barents Sea demersal trawl fishery. Kim (2013; 2015) used a circular piece of canvas at the posterior of the codend to form a cap which generates lifting force with respect to drag, inducing a “shaking” movement of the codend. This movement was shown to lead to an increased escape rate for small fish through the codend meshes. Escape rates of juvenile fish were observed to increase by 22 – 30% when compared with a codend without the canvas (Kim, 2013; 2015).

Alternative codend size-selectivity research into increasing mesh size, changing mesh shape, and net construction has been effective, in certain cases, at reducing the capture of small fish in trawls (Reeves et al., 1992; Glass, 2000; Scandol et al., 2006). Several studies have modified diamond mesh codends to improve the size selectivity for groundfish (Bayse et al., 2016b), which includes redfish fisheries (Cheng et al., 2019; Pol et al., 2016). A diamond mesh codend rotated 90° in the transversal direction, called a T90 codend, has been shown to significantly reduce the capture of small roundfish (Herrmann et al., 2007; Tokaç et al., 2014; Bayse et al., 2016a). Cheng et al. (2020) applied three T90 codends with different mesh sizes (i.e., 90 mm, 100 mm, 110 mm) in the Canadian redfish fishery and reduced the capture of small fish.

The objective of this study was to develop a shaking codend to reduce the capture of small redfish. For the first time, a T90 codend was used in conjunction with a shaking codend to potentially aid the escape of small redfish. Since T90 meshes remain open during hauling, as opposed to diamond meshes that close under tension of the catch, they can lead to a reduction in capture of small round fish (Herrmann et al., 2007; Bayse et al., 2016a) and combining bycatch reduction technology has been shown to even further reduce bycatch (Bayse and He, 2017). The moving dynamics of adding a canvas to the posterior of a commercial codend were described and compared to a codend without a canvas in a flume tank test. Additionally, a full-scale sea trial was attempted for the first time using a shaking codend using commercial gear in a commercial fishing scenario, comparing the catches with and without the canvas using a covered codend technique.

2.3 Materials and Methods

2.3.1 Flume tank experiment

A four-panel codend constructed of double-braided polyethylene netting (nominal 4.6 mm Ø) with meshes configured as T90 (nominal stretched inside mesh opening of 90 mm) was used for flume tank tests. The codend was attached to an extension made of the same netting (a total of

211 meshes in length), 3 meshes made up the selvedges, and the riblines were Quicklines (DynIce DuxTM, Dyneema, 18/22 mm Ø) 5% shorter than the selvedges.

For experimental treatments, a black, elliptical-shaped canvas (Polyvinyl chloride, R 62 cm) was attached to the posterior of the codend, positioned slightly over the top of the codend similar to Kim (2015) (Fig. 2.1). The canvas was 1.8 m in length, 1.1 m wide, and had a radius of 0.62 m. For tank tests, two canvases were attached and overlapped to make up these dimensions, for sea trials, one canvas was used; for both cases, the perimeter of the canvas was the same. The final version had a total of 58 grommets of 22 mm dimensions included around the canvas's edge for connecting to the end of the codend, and the distance between consecutive grommets was 6 cm (Fig. 2.1A). The canvas was attached to the codend via plastic ties through the grommets on previously marked meshes for consistency.

Codend movement was quantified in a flume tank located at the Centre for Sustainable Aquatic Resources, Fisheries and Marine Institute of Memorial University of Newfoundland, Canada, between 02 and 27 April 2019. The flume tank test area is 22.3 m long, 8.0 m wide, and 4.0 m deep, and can maintain water velocities up to 1.8 kt, and the side observation window is 20 m long x 3 m in height (Winger et al., 2006).

For testing, the codend was attached to a towing mast by four steel bridles (2 m) and a steel ring (140 cm Ø) at the anterior of the codend extension. Trawl floats (*n* = 80; 20 cm Ø; Pescaflot N-90, Castro, Donostia, Gipuzkoa, Spain) were added to the codend to simulate accumulated catch that weighed approximately 350 kg (estimated by volume) following Cheng et al. (2022). Each float had six holes drilled (2.6 cm Ø) through it to balance its weight and buoyancy. The total weight of floats in water was 0.0 kg. Shaking and T90 codend experiments were tested separately with five flow velocities, from 1.0 to 1.8 kt with a 0.2 kt increment. The duration of each flow velocity tested was performed for 30 min, except for one iteration of the T90 codend, which was tested for 14 min and 45 sec at the flow velocity of 1.0 kt.

The moving angle (°) of the shaking codend for each flow velocity was measured. The moving angle is defined by the angle formed between the vertical axis and the direction that the shaking codend moved in the vertical plane which was perpendicular to the flow direction in the flume tank. The moving direction was determined by tracking the center of the canvas. Thus, a marker (small red ball) was attached to the center of the canvas (Fig. 2.1D), and its movement was recorded using the camera positioned at the end of the flume tank looking toward the posterior of the codend. For the moving angle analysis, a 10 min and 30 sec video recording was made and subsampled at each flow velocity. HITFILM 4 EXPRESS software (FXhome, Norwich, England) was used to track the movement of the red marker. The tracking was performed frame-by-frame until the end of each subsample. The moving angle was measured for every 1 min of tracking using ImageJ software (http://rsb.info.nih.gov/ij).

Codend acceleration (m s^{-2}), the rate of change in the velocity of the codend movement, was measured by an accelerometer (HOBO, UA-004-64 Pendant G Data logger, Bourne, MA, USA). Acceleration was recorded every second in three directions, X- (anterior to posterior), Y- (port to starboard) and Z-direction (top to bottom) (Fig 2.1B). The codend acceleration is represented by the total acceleration (TA (m s^{-2})) (Brownscombe et al., 2014; Richard et al., 2020), which is calculated by square root of summing accelerations from three directions using the Eq. 2.1:

$$TA = \sqrt{}(X)^2 + (Y)^2 + (Z)^2 \qquad (2.1)$$

where X, Y, Z are acceleration values recorded in X, Y, Z-direction, respectively.

Drag (kgf) was measured using a 500 lb load cell (Model-No. 31, Honeywell, USA). The load cell was attached to a connection which consisted of four steel bridles with a towing mast for the purpose of measuring drag forces of each codend separately at flow velocities between 1.0 and 1.8 kt.

The distance (cm) that the codends moved vertically was described using a depth sensor (HOBO, U20L-02 Water Level Data Logger, Bourne, MA, USA). Depth was recorded every second. The logger was attached to the middle of the side panel, right before the front edge of the canvas. The change in depth allowed each codend to be characterized by amplitude ratio and period (Kim, 2013; 2015). The amplitude ratio was defined by the peak-to-peak amplitude divided by the length of the side panel. The peak-to-peak amplitude describes the distance the codend moves from the lowest to highest depth. The lowest and highest depth (peak) was determined using the find_peaks function in the ggpmisc package (Aphalo, 2021) of R Statistical Software (R Development Core Team, 2020)]. The length of the side panel was measured from a side-view video using ImageJ software. A total of 20 frames were randomly chosen for the measurement, and the mean length of the side panel was 99.6 cm (Standard Error of the Mean (SEM) = 0.5 cm). The period was defined as the time of one oscillation, derived from the peak-to-peak analysis.

2.3.2 Flume tank experiment analysis

A simple linear regression was used to determine the relationship between moving angle and flow velocity using the lm function in base R. Total acceleration, drag, and amplitude ratio were analyzed with a multiple regression using the lm function, where independent variables included codend, flow velocity, and their interaction term. The best model was selected based on the minimum Akaike information criterion value (Akaike, 1974) with a correction for small sample sizes (AICc) and was calculated using the AICctab function in the bbmle package (Bolker and R Development Core Team, 2020). A model that had a ΔAICc < 2 was considered the best model. A post hoc test was performed with the TukeyHSD function to compare differences between codends and flow velocities following an analysis of variance (ANOVA; aov function).

Period data were collected every second, thus could be considered count-based (by individual second) and were analyzed initially with a Poisson distributed model using the glm function. The dependent variable was period, independent variables were codend and flow velocity, and their interaction term. Dispersion was estimated with the DHARMa package (Hartig, 2021), which approximates dispersion with simulations. If the resultant model was equidispersed (dispersion ~ 1.0), then the analysis continued with the Poisson distributed model, if overdispersed (dispersion > 1.0) then the model would be fit with a negative binomial distribution, and if underdispersed (dispersion < 1.0) then the model would be fit with a quasi-Poisson model. Model selection followed the AICc methods described above, unless the model was underdispersed. In that case, QAIC was used for model selection following the methods described in Bolker (Bolker, 2021). A post hoc test, general linear hypothesis test–Tukey all-pair comparisons (glht function in the multcomp package; (Hothorn et al., 2008) was used to compare period between codends and flow velocity.

2.3.3 Sea trials

This study did not involve any endangered or protected species. Experimental fishing was performed on a commercial fishing vessel *F/V Lisa M* (overall length 19.8 m; gross tonnage 122.5 t; engine power 700 horse power; 1 hp = 746 W) in accordance with the experimental fishing license granted by Fisheries and Oceans Canada (NL-5596-19). The license required that all redfish catches be landed.

Trials were conducted off the west coast of Newfoundland in the Gulf of St. Lawrence, Canada between 16 July and 02 August 2019 (Fig 2.2). Fishing locations were determined by the captain. Gear performance (towing velocity, duration, warp length, and door spread) was recorded for each haul. All hauls were fished during the day. Haul durations for the experiment were shorter than typical for the fishery. Generally, at high catch rates, a tow of 1-2 hr is typical and longer with lower catch rates (personal observation). Short tow durations can be successful however since redfish can be highly congregated. Our tows were short for a few reasons, high catch volumes in both a codend and cover were difficult to handle at the same time and we had to use caution while fishing on limited quotas. Ultimately, our tow times were based on the goal of having similar catch volumes per tow, which can change throughout the day with redfish diel migration.

The codend described in the tank experiment was attached to a commercial groundfish bottom trawl for sea trials and mesh sizes were measured using an ICES OMEGA mesh gauge; 40 meshes measured per codend while wet (ICES, 2005). The trawl was a high opening balloon trawl described in Cheng et al. (2020). The fishing line and headline of the trawl were 44.5 m and 40.2 m in length, respectively. The trawl belly sections were constructed with the same netting, 170 mm diamond PE twine with Ø (diameter) from 3.5 to 4.0 mm. The headline consisted of 132 floats (20.3 cm Ø). The trawl was equipped with rockhopper groundgear and the diameter of rubber discs ranged between 36 mm and 41 mm Ø. The trawl was rigged with a pair of low-aspect trawl doors, (Injector Door Limited, Søvik, Norway), which were 4 m^2 in area. The door spread was recorded using acoustic sensors during trawling (Notus Electronics Ltd., St. John's, Newfoundland and Labrador, Canada).

We applied the covered codend method to estimate the difference in size selectivity between shaking and T90 codend (Wileman et al., 1996). A 39.7 m long two-seam cover was used for both tested codends, constructed with single 2.5 mm PE twine panels and attached to the end of the extension. The nominal mesh size of the cover codend was 50 mm. To prevent the cover from masking the codend, flexible kites were used following Grimaldo et al. (2009). A total of 29 kites were attached to the cover net.

The codend movement at sea was recorded using a depth sensor capable of going to deep depths (Starmon TD, Star Oddi, Garðabær, Iceland). Depth data was only considered 1 min after the start of the haul and 1 min before haul back. The method applied to determine the amplitude ratio was similar to what was used in the flume tank test, side panel length used to determine the ratio was the same as what was used in the flume tank test. However, vessel depth recordings indicated that bottom depths were continually changing, thus, subsamples of recorded depths were taken to estimate amplitude ratio and period when depths did not change greater than 0.5 m over the considered time interval. In cases of multiple highest or lowest points (of the same value), the middle point between readings was chosen to correspond to the average time recorded between these points. Cheng et al. (2022) showed that the tested T90 codend only had a minimal change in water flow inside the codend with the addition of the covered codend (0.05-0.10 m s^{-1}) during a flume tank test, thus the effect of the cover was considered minimal on codend movement.

Captured redfish from the codend and the cover were landed on the deck separately. A random subsample was taken for lengths measurements for both the codend and cover. All captured redfish were weighed. Redfish fork length measurements were made to the nearest centimeter, and species was determined by anal ray count (Rubec et al., 1991) and reported as *S. mentella* in Cheng et al. (2020). Redfish catches were only considered here, bycatch was reported in Cheng et al. (2020).

2.3.4 Sea trials analysis

Size selectivity analysis was performed using SELNET (Herrmann et al., 2012) and followed techniques previously described in Bayse et al. (2016a), Cheng et al. (2019), and Einarsson et al. (2021). Fish were assumed to enter the codend and either be retained in the codend or escape into the cover. This enables catch data to be considered as a binomial distribution. The function *rj(l)* was used to estimate the probability of a fish of length *l* in haul *j* being retained in the codend, and thus estimate the values of this function for all relevant redfish sizes. The retention probability estimation was carried out for all observed size classes (cm^{-1}) and was expected to vary between hauls (Fryer, 1991). Thus, hauls were pooled between treatments to describe the length-dependent probability averaged over hauls, *rav(l)* (Herrmann et al., 2012). Since more than one model was applied, *rav(l,v)* was used to describe the length-dependent probability retained in the main codend averaged over hauls, where *(v)* are the model parameters. Model parameters were estimated using maximum likelihood estimation. If the model can describe the data well, equation (2.2) was used to maximize the likelihood of data describing the number of fish retained in the codend (nR_{jl}) and cover (nE_{jl}).

$$-\sum_{j=1}^{m}\sum_{l}\left\{\frac{nR_{jl}}{qR_j}\times ln\big(r_{av}(l,\boldsymbol{v})\big)+\frac{nE_{jl}}{qE_j}\times ln\big(1.0-r_{av}(l,\boldsymbol{v})\big)\right\} \qquad (2.2)$$

Subsample factors were qR_j and qE_j for the codend and the cover, respectfully.

A total of eight size selectivity models were tested to describe $r_{av}(l,v)$ for each codend (Eq 2.3). The first four models, Logit, Probit, Gompertz, and Richard, are classical size selectivity models that assume all individual fish that enter the codend have been able to contact the codend meshes in such a way that corresponds to a size-dependent probability of escape (Bayse et al., 2016b). These models are fully described by the size selectivity parameters length at 50% retention (L50) and selection range (length at 75% retention – length at 25% retention; SR), with one additional parameter ($1/\delta$) for the Richard model. These models are described in Wileman et al. (1996).

Another four models (Eq 2.3) are also considered that account for the percentage of fish that will not be able to make contact with the meshes in such a way that will lead to a size-dependent chance to escape (Bayse et al., 2016b). These additional models have an additional parameter C, which represents the assumed length-independent contact probability of fish having contact with the codend meshes that corresponds to a length-dependent chance of escape. If C equals 1.0, then all fish had contact with the meshes to have a length-based size selectivity. If 0.75, then 75% of fish had contact with the meshes to lead to a length-based size selectivity. The last four considered models in Eq 2.3 have an additional subscript c which represents the inclusion of the percentage of fish that are actually estimated to make contact with the codend meshes that leads to length-based size selectivity. These models also have the overall L50 and SR consider which fish had sufficient contact, and are estimated based on the value of C (Sistiaga et al., 2010). Models that included contact probability parameters were considered to investigate whether a shaking codend actually improved the likelihood of redfish having contact with codend meshes in such a way that provides length-based size selectivity. It is plausible that a shaking codend could have more interaction with fish in the codend, either by physical contact only and/or by inducing escape behaviors that lead to contact.

$$r_{av}(l, \boldsymbol{v}) = \begin{cases} Logit(l, \mathrm{L50}, \mathrm{SR}) \\ Probit(l, \mathrm{L50}, \mathrm{SR}) \\ Gompertz(l, \mathrm{L50}, \mathrm{SR}) \\ Richard(l, \mathrm{L50}, \mathrm{SR}, 1/\delta) \\ CLogit(l,\ C,\ \mathrm{L50}_c, \mathrm{SR}_c) = 1.0 - C + C \times Logit(l,\ \mathrm{L50}_c, \mathrm{SR}_c) \\ CProbit(l,\ C,\ \mathrm{L50}_c, \mathrm{SR}_c) = 1.0 - C + C \times Probit(l,\ \mathrm{L50}_c, \mathrm{SR}_c) \\ CGompertz(l,\ C,\ \mathrm{L50}_c, \mathrm{SR}_c) = 1.0 - C + C \times Gompertz(l,\ \mathrm{L50}_c, \mathrm{SR}_c) \\ CRichard\left(l,\ C,\ \mathrm{L50}_c, \mathrm{SR}_c, 1/\delta_c\right) = 1.0 - C + C \times Richard\left(l,\ \mathrm{L50}_c, \mathrm{SR}_c, 1/\delta_c\right) \end{cases} \quad (2.3)$$

How the model fit the data was determined with a goodness-of-fit test described in Wileman et al. (1996). If the p-value was > 0.05, then the model was considered a good fit. If the p-value was < 0.05, then model residuals were investigated for structural problems. The best fit model was determined by the lowest AIC value.

Confidence intervals were produced using the double bootstrap method described in Millar (1993) and Herrmann et al. (2012). The Efron percentile 95% confidence intervals (CIs; Efron and Tibshirani, 1986) were fit for the best fit model with 1000 bootstraps.

Following Larsen et al. (2018), the differences in size selectivity between the shaking and T90 codend were directly compared with a Delta plot using the $\Delta r(l)$ function:

$$\Delta r(l) = r_e(l) - r_c(l) \quad (2.4)$$

where $r_e(l)$ and $r_c(l)$ are the size selectivity models for the shaking codend and the T90 codend, respectively. Confidence intervals were generated for $\Delta r(l)$ from two bootstrap population results (Efron 95% confidence intervals from 1000 bootstraps each) for $r_e(l)$ and $r_c(l)$. Since they were obtained independently, a new bootstrap population for $\Delta r(l)$ was created using:

$$\Delta r(l)_I = r_e(l)_I - r_c(l)_I \; i \in [1 \ldots 1000] \qquad (2.5)$$

where I is the bootstrap repetition index. As explained in Moore et al. (2003), since resampling was random and independent for both groups, it is valid to generate the bootstrap population of results for the difference based on two independently generated bootstrap groups using equation 5. This approach will increase the power of inference between the shaking and T90 codend since the confidence limits for $\Delta r(l)$ cannot go beyond those of $r_e(l)$ and $r_c(l)$, and in general will often be smaller (Moore et al., 2003; Larsen et al., 2018). Significant differences between codend size selectivity were determined by the location of CIs. If CIs do not overlap 0.0 at a particular length class then a significant difference is observed. However, if 0.0 is contained within the CIs then there is no difference in size selectivity between codends at the observed length class (Herrmann et al., 2018).

2.4 Results

2.4.1 Flume tank experiment

The moving angle of the shaking codend at each flow velocity measured in the flume tank is shown in Fig. 2.3. The mean of the moving angle gradually increased from 21.0 (±0.08 SEM) to 22.6° (±0.15 SEM) as flow velocities increased from 1.0 to 1.8 kt (Table 2.1). The linear regression model for the relationship between the moving angle and flow velocity is Moving angle =2.0085*Flow velocity + 19.131 (Table 2.1). Both the intercept and flow velocity parameters had positive slopes indicating that the mean moving angle of the shaking codend increases with increasing flow velocity (p-value < 0.001; Table 2.1).

Total acceleration, amplitude ratio, and period analysis began after 5 min from the beginning of each flow velocity test to allow the codend movement to stabilize. Thus, data for 25 min was recorded for each flow velocity iteration, except flow velocity 1.0 kt for the T90 codend, which was unexpectedly cut short at 9 min and 25 s. An example of one of these data sets is represented in Fig. 2.4.

Mean TA trended higher for the shaking codend for each tested flow velocity and gradually reduced as flow velocity increased with the linear regression showing that the shaking codend had a higher overall TA (Table 2.2). The best model contained codend, flow velocity, and their interaction term (Table 2.3). A subsequent Tukey's HSD post hoc test showed that the mean TAs generated by the shaking codend were significantly higher than those generated by the T90 codend at each corresponding flow velocity (p-value < 0.05; Fig. 2.5). The mean TA of the shaking codend was not significantly different among flow velocities (p-value > 0.05; Fig. 2.5). By comparison, the mean TA of the T90 codend was statistically higher at 1.0 and 1.2 kt compared to the other flow velocities (p-value < 0.001; Fig. 2.5).

The drag forces measured for the T90 codend at the flow velocity of 1.0 kt suffered a mechanical failure and were erroneous and were excluded from the analysis. Thus, the difference in drag forces between the shaking and T90 codends was only compared at the flow velocities of 1.2 - 1.8 kt. The best model contained codend, flow velocity, and their interaction term (Table 2.3). The model showed that the shaking codend had a higher overall drag force (Table 2.4). A subsequent Tukey's HSD post hoc test showed that the mean drag forces generated by the shaking codend were significantly higher than those generated by the T90 codend at each corresponding flow velocity (p-value < 0.001; Fig. 2.5). The mean drag force of the shaking codend was significantly different among flow velocities and increased along with the flow velocity (p-value < 0.001; Fig. 2.5). Though codend drag was higher for the shaking codend, it should be considered that codend drag is only a small proportion of total gear drag (Madsen et al., 2015), and that the observed higher drag would only have a minimal increase in total drag and fuel consumption.

Recorded depths were used to generate amplitude ratio and period results, means are reported in Table 2.2. The best model for amplitude ratio included the codend, flow velocity, and their interaction term (Table 2.3). The model showed that the amplitude ratios generated by the shaking codend were higher than those by the T90 codend (Table 2.4). *Post hoc* analysis showed that for each tested flow velocity, amplitude ratio was higher for the shaking codend, slight but significant differences were observed between amplitude ratios for the shaking codend, and flow velocity did not affect the amplitude ratio for the T90 codend (Fig. 2.5).

For period, the data were first fitted with a generalized linear model (GLM) using a Poisson link function. The dispersion of the model was determined to be underdispersed; thus, a quasi-Poisson link was used. The best model contained codend, flow velocity, and their interaction term (Table 2.3), and showed that the T90 codend had a lower period (Table 2.4). *Post hoc* analysis showed that the period of the shaking codend at each corresponding flow velocity was significantly higher than the T90 codend (p-value < 0.05; Fig. 2.5). The period for each codend was highest at a flow velocity of 1.0 kt and gradually decreased, significantly, as flow velocity increased (p-value < 0.05; Fig. 2.5), except the period for the T90 codend between 1.6 and 1.8 kt (p-value > 0.05; Fig. 2.5).

2.4.2 Sea trials experiment

A total of 15 hauls were completed, including 4 hauls for the shaking codend and 11 hauls for the T90 codend (T90 codend results originally reported in Cheng et al. (Cheng et al., 2020); Table 2.5). The mean depth of the fishing ground was 299.3 m (range: 234.1 to 329.2 m), the average haul duration was 7.8 min (range: 4 to 18 min), and the towing speed was between 2.3 and 2.6 kt (mean = 2.5 ± 0.08 standard deviation (SD)). The mean inside stretched codend mesh size for the T90 codend was 95.0 mm (SD = 2.4 mm) and 49.3 mm (SD =1.9 mm) for the cover. The length of the warp ranged from 594.4 to 777.2 m (mean = 704.1 ± 38.7 SD), and the door spread was 66.2 m (range 63.4 to 68.9 m).

A total of 10250.1 kg redfish were captured during sea trials, 2784.7 kg by the shaking codend and 7465.4 kg by T90 codend. Of those, 8834 redfish were measured, 2477 for the shaking codend and covered codend versus 6357 for the T90 codend and covered codend (Table 2.7). The average redfish length was 22.7 cm (SEM = 1.5 cm) and ranged from 13 – 40 cm. Fishing depth changed over 0.5 m for several hauls, thus depth subsamples were applied to take the time intervals where the depth changed less than 0.5 m. There were 9 subsamples in total for three hauls covering the entirety of the time fishing (Table 2.6). The amplitude ratio ranged from 0.04 to 0.24, with a mean value of 0.11 (SD = 0.07). The mean for period was 9.2 s (SD = 4.92; range 4.0 - 20.7 s).

Based on the AIC values in Table 2.7, the Richard model was the best fit for the shaking codend. The size selectivity curve of the shaking codend showed lower retention for redfish < 21 cm (Fig. 2.6 and 2.7). The L50 was 20.1 (CIs 19.6-21.9; Table 2.8) and SR could not be reasonably determined since only a few data points at the length at 25% retention (L25; SR is L75 - L25) were observed (Fig. 2.6); for similar examples see Cheng et al. (2020), Einarsson et al. (2021). The model had a *p*-value < 0.05 likely due to overdispersion from the low number of hauls sampled. For the T90 codend, the CGompertz model was the best fit (Table 2.7). The L50 and SR could not be reported because they were not reached (Fig. 2.6; Cheng et al., 2020; Einarsson et al., 2021). However, the $L50_c$ was reached (22.6, CIs 20.0-23.8), which includes redfish that were able to make sufficient contact with the meshes which leads to size-dependent selection. The contact parameter, *C*, was 0.5 which indicates that 50% of redfish captured had appropriate contact with the meshes, however, the confidence was over a large range of values (0.3-0.9; Table 2.8). The model did not suffer from overdispersion and had a *p*-value > 0.05 (Table 2.8).

2.5 Discussion

This is the first known study to use a shaking codend at a commercial scale and to produce and compare size selectivity curves between a shaking and non-shaking codend. Our preliminary results obtained during a small-scale sea trial indicated that the shaking codend reduced the capture of undersized redfish in Canada's Gulf of St. Lawrence trawl fishery and was easy to handle and use in a commercial context. Flume tank tests showed that the shaking codend was much more dynamic than the T90 codend, having a larger amplitude ratio, period, and slightly larger TA and also had a higher drag. This movement likely led to the reduction in catch of small redfish, improving contact probability and potentially motivating fish to escape through the codend meshes.

The amplitude ratio for the shaking codend was significantly higher than the T90 codend during the flume tank test, and change in flow velocity showed minimal effects. However, sea trials showed a wide range of amplitude ratios, matching the highest observed in the tank test for the shaking codend (~0.25) to near the lowest observed for the T90 codend (~0.04). Many factors could have led to these results, perhaps with the main difference being the continuing changing depths found during the sea trials that can easily mask any change in amplitude recorded from a depth sensor. Other factors that could have led to these observed differences include changes in current, tow speed (max of 1.8 kt in flume tank and 2.6 kt during commercial fishing), and total catch. Simulated catch was constant in the tank tests but changed haul-to-haul during sea trials.

Similarly, period was significantly higher for the shaking codend when compared to the T90 codend during tank tests. However, during sea trials, wide ranges were also observed that were greater than the shaking codend (20.7 s) and lower than the T90 codend (4.0 s) during tank tests. Likely, this range is due to the factors discussed for the differences between amplitude ratios observed in the tank test and at sea, however period was observed to decrease in the tank test with increasing flow velocity. This would lead to an expectation that period at sea would be on the lower end of what was observed in the tank test (~4.0-7.5 s) since towing speeds were much higher. However, since period was measured to be over 20 s, it can be assumed that the codend movement was much more dynamic at sea.

Kim (2013; 2015) stated that a “shaking” ratio of 0.5 encouraged fish to move and approach codend nettings. Amplitude ratios in the reported study stayed below 0.5, though preliminary results of size selectivity suggest that escapes could have been increased; no video observations were made to determine if these escapes were derived from behavioral, mechanical, or both selectivity mechanisms. However, comparing the amplitude ratio between our study and Kim (2013; 2015)’s should not necessarily be considered one-to-one in terms of the specific amplitude ratio value. Kim (2013; 2015) used metal rings at the end of his codend that the tarp was placed over. The amplitude ratio was based on the diameter of the tarp. This is reasonably similar to what would be expected of the shape of a 2-panel codend, round and bulbous shape, but our study used a 4-panel codend that is not bulbous at the end, as each panel comes to a point at the terminal end. Additionally, differences in how this study and Kim (2013; 2015)’s accounted for distances relative to the gear construction could have led to subtle differences in amplitude ratios between the studies.

Beyond differences in study design between the reported study and Kim (2013; 2015), Kim (2013; 2015) used traditional codend netting (T0) where we used T90. Hansen (2004) and Madsen et al. (2012) showed that the T0 codend's movements are much more dynamic than the T90 codend. The movement of a codend is generally forced by the turbulence intensity inside the codend (Hansen, 2004). Water flow through the codend is lower in a T0 codend, versus a T90 codend, due to the mesh openings remaining more closed under the load of the catch and restricting the water flow (Cheng et al., 2022). This reduction in flow likely increases the turbulence and leads to increased movement. Additionally, since Kim (2013; 2015) used a trawl more closely resembling a 2-panel codend, and we used a 4-panel, it is reasonable to assume that the addition of two more riblines would also produce a more stable codend. Thus, the characteristics of a T90, 4-panel codend has inherit characteristics that may reduce its movement capacity when compared to 2-panel and T0 codends.

Kim (2013) tested a shaking codend at sea, but this was to document the movements only and consisted of the codend attached to a towing frame and opened by metal hoops, not an actual trawl attached to a vessel with warps, spread with doors, etc. Here, we were able to test a shaking codend on a commercial fishing vessel and not only quantify its movement and size selectivity, but assess how such a design could be used in a commercial setting. Certainly, adding a tarp over the codend adds time in terms of opening and closing the codend, since the tarp is overtop of the typical location of the codend opening. However, we were able to use twine to fasten the tarp to the codend, which took approximately 20 min. If such a design was used during commercial fishing, improvements should be considered to shorten the time to take the tarp on-and-off to have access to the codend opening. Using a more fast-opening process, such as a large, heavy-duty zipper (Bayse et al., 2016b) , instead of tying the tarp on-and-off for each haul could be a more time-efficient approach to be used in commercial fisheries. Otherwise, the addition of the tarp was found to have no other observed effect on the handling of the fishing gear.

Smaller redfish were shown to be retained less often by the shaking codend and this may be explained by the improved contact probability of the shaking codend. For example, we could not report the L50 for the T90 codend because fish that small were not captured (these size classes were not present in the fishery (DFO, 2020)), but when only considering fish that had appropriate contact with the codend meshes ($L50_c$), the L50 and $L50_c$ were not significantly different between the shaking and T90 codend. This suggests that what is driving the significant difference between the shaking and T90 codend are small redfish that are not having appropriate contact with codend meshes which leads to size dependent selectivity. Likely, these fish are not able to reach the codend meshes due to congregation of redfish within the codend.

What is causing redfish to have improved contact in the shaking codend is not clear. The shaking codend could simply be providing more physical contact to fish that are not very active in the codend, i.e., the movement leads to more fish having contact with the meshes. Conversely, the shaking codend could be promoting behavior (e.g., escape attempts) that leads to more contact with the codend. Active stimulation devices have been shown to increase small fish escape (Kim and Whang, 2010; Kim, 2013; 2015; Herrmann et al., 2015), which likely could improve the contact probability between fish and the codend meshes. The sweeping of upper and lower panels when the codend moves vertically could reduce the space in the codend (Kim, 2015) that can reduce the available swimming space of fish in the codend, as well as the distance between the meshes and the fish. These effects can lead to an increase in fish contact with the meshes and penetration through the meshes, rather than being impinged to the codend and prevented from escape (Jones et al., 2008). Overall, the escape probability of fish through the codend meshes is related to the distance between fish in the middle of the codend and codend panels. This distance likely can be decreased with increasing amplitude ratio (overall minimum distance to codend panels reduced on average), leading to more fish in the codend coming into contact with the meshes, and therefore increasing escape likelihood. Future work should consider using cameras to document redfish behavior to a shaking codend.

Fish escape through codend meshes can be affected by swimming endurance, which is generally limited once fish have reached the codend (Winger et al., 2010). Additionally, turbulence generated from the rear of the codend can also affect swimming endurance by reducing swimming speed required to maintain station ahead of accumulated catch (Broadhurst et al., 1999; Winger et al., 2010). Likely, the relatively high turbulence created by attaching the canvas at the rear of the codend in this study, combined with the movement of the codend, potentially provide redfish an additional capacity to keep station ahead of accumulated catch and orient to swim through codend meshes (Winger et al., 2010). This could lead to a relatively higher number of redfish, particularly small individuals, to come into contact with the codend meshes to escape, compared with the codend without canvas.

There is some disparity between the number of hauls for the shaking codend and the T90 codend. The data collected for the T90 codend was from a previously published (Cheng et al., 2020), separate study comparing the size selectivity between three T90 codends (90, 100, 110 mm mesh size) and the traditionally used codend (90 mm T0 mesh). Though this was a separate study, the hauls for each codend reported in this study were performed on consecutive days. Thus, we took the opportunity to compare the size selectivity between a shaking codend and a well performing experimental codend (T90, 90 mm mesh size) that isolates the variable of interest (i.e., shaking codend) to quantify its size selectivity performance. Further, the number of replicates reported for the shaking codend, *n* = 4, is relatively small, but not out of line with recent size selectivity publications, Ingólfsson and Brinkhof (2020); *n* = 5 per treatment and Petetta et al. (2021); *n* = 6 per treatment. Additionally, the Ingólfsson and Brinkhof (2020) study has a relative selectivity study design, which has a much lower statistical power (Herrmann et al., 2016b), making the statistical inference at a low haul number much more challenging than for a covered codend design (as used in the present study), where escaped fish sizes are measured. Nevertheless, the difference in replicates between treatments should provide some caution, and further research should continue to fully understand the size selectivity of a shaking codend. That said, both the model fit and confidence interval size shows that the data collected are reasonable for the applied analyses.

In conclusion, our experiment developed a full-scale shaking codend from a 90 mm T90 codend, which has been suggested to replace the currently regulated 90 mm T0 to improve the size selectivity of the Gulf of St. Lawrence redfish fishery (Cheng et al., 2020). Currently, the Gulf of St. Lawrence has a large biomass of deepwater redfish and a commercial fishery is imminent (DFO, 2020). Our preliminary results of sea trials show that a shaking codend further reduced the capture of small fish than the T90 codend alone, which already showed great improvement when compared to the traditionally used T0 codend (Cheng et al., 2020). The development of new methods to sustainably harvest redfish are necessary to prevent overfishing of a species that is sensitive to fishing. In this study, the shaking codend has shown potential to be used to harvest redfish sustainably, capturing fewer undersized fish.

2.6 Acknowledgements

We would like to thank Captains Rodney and Les Dredge and crew of the *F/V Lisa M* for their assistance. Additionally, we would like to thank Bent Herrmann for use of the software SELNET and additional help from Mark Santos and Meghan Donovan.

2.7 References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control 19, 716–723. https://doi.org/10.1109/TAC.1974.1100705

Alverson, D.L., Food and Agriculture Organization, Freeberg, M.H., Murawski, S.A., Pope, J.G., 1994. A Global Assessment of Fisheries Bycatch and Discards. FAO Fisheries Technical Paper 339, 233.

Aphalo, P.J., 2021. ggpmisc: Miscellaneous Extensions to “ggplot2.”

Bayse, S.M., He, P., 2017. Technical conservation measures in New England small-mesh trawl fisheries: Current status and future prospects. Ocean and Coastal Management 135, 93–102. https://doi.org/10.1016/j.ocecoaman.2016.11.009

Bayse, S.M., Herrmann, B., Lenoir, H., Depestele, J., Polet, H., Vanderperren, E., Verschueren, B., 2016a. Could a T90 mesh codend improve selectivity in the Belgian beam trawl fishery? Fisheries Research 174, 201–209. https://doi.org/10.1016/j.fishres.2015.10.012

Bayse, S.M., Rillahan, C.B., Jones, N.F., Balzano, V., He, P., 2016b. Evaluating a large-mesh belly window to reduce bycatch in silver hake (*Merluccius bilinearis*) trawls. Fisheries Research 174, 1–9. https://doi.org/10.1016/j.fishres.2015.08.022

Bellido, J.M., Santos, M.B., Pennino, M.G., Valeiras, X., Pierce, G.J., 2011. Fishery discards and bycatch: solutions for an ecosystem approach to fisheries management? Hydrobiologia 670, 317–333. https://doi.org/10.1007/s10750-011-0721-5

Bolker, B., 2021. Dealing with quasi- models in R.

Bolker, B., R Development Core Team, 2020. bbmle: Tools for General Maximum Likelihood Estimation.

Broadhurst, M.K., Larsen, R.B., Kennelly, S.J., McShane, P.E., 1999. Use and success of composite square-mesh codends in reducing bycatch and in improving size-selectivity of prawns in Gulf St. Vincent, South Australia. Fishery Bulletin 97, 434-448.

Brownscombe, J.W., Marchand, K., Tisshaw, K., Fewster, V., Groff, O., Pichette, M., Seed, M., Gutowsky, L.F.G., Wilson, A.D.M., Cooke, S.J., 2014. The influence of water temperature and accelerometer-determined fight intensity on physiological stress and reflex impairment of angled largemouth bass. Conservation Physiology 2, cou057–cou057. https://doi.org/10.1093/conphys/cou057

Cadigan, N. G., Duplisea, D.E., Senay, C., Parent, G.J., Winger, P.D., Linton, B., Kristinsson, K., 2022. Northwest Atlantic redfish science priorities for managing an enigmatic species complex. Canadian Journal of Fisheries and Aquatic Sciences 79, 1572–1589. https://doi.org/10.1139/cjfas-2021-0266

Cheng, Z., Einarsson, H.A., Bayse, S., Herrmann, B., Winger, P., 2019. Comparing size selectivity of traditional and knotless diamond-mesh codends in the Iceland redfish (*Sebastes spp.*) fishery. Fisheries Research 216, 138–144. https://doi.org/10.1016/j.fishres.2019.04.009

Cheng, Z., Winger, P.D., Bayse, S.M., Kebede, G.E., DeLouche, H., Einarsson, H.A., Pol, M.V., Kelly, D., Walsh, S.J., 2020. Out with the old and in with the new: T90 codends improve size selectivity in the Canadian redfish (*Sebastes mentella*) trawl fishery. Canadian Journal of Fisheries and Aquatic Sciences 77, 1711–1720. https://doi.org/10.1139/cjfas-2020-0063

Cheng, Z., Winger, P.D., Bayse, S.M., Kelly, D., 2022. Hydrodynamic performance of full-scale T0 and T90 codends with and without a codend cover. Journal of Marine Science and Engineering 10, 440. https://doi.org/10.3390/jmse10030440

Cuende, E., Arregi, L., Herrmann, B., Sistiaga, M., Onandia, I., 2020. Stimulating release of undersized fish through a square mesh panel in the Basque otter trawl fishery. Fisheries Research 224, 105431. https://doi.org/10.1016/j.fishres.2019.105431

DFO, 2020. Redfish (*Sebastes mentella* and *S. fasciatus*) stocks assessment in Unit 1 and 2 in 2019. DFO Canadian Science Advisory Secretariat Science Advisory Report 019.

DFO, 2016. Assessment of Redfish Stocks (*Sebastes fasciatus* and *S. mentella*) in Units 1 and 2 in 2015. DFO Canadian Science Advisory Secretariat Science Advisory Report 047.

Duplisea, D.E., 2018. Fishermen's historical knowledge leads to a re-evaluation of redfish catch. Marine and Coastal Fisheries 10, 3–11. https://doi.org/10.1002/mcf2.10006

Efron, B., Tibshirani, R., 1986. Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. Statistical Science 1, 54–75. https://doi.org/10.1214/ss/1177013815

Einarsson, H.A., Cheng, Z., Bayse, S.M., Herrmann, B., Winger, P.D., 2021. Comparing the size selectivity of a novel T90 mesh codend to two conventional codends in the northern shrimp (*Pandalus borealis*) trawl fishery. Aquaculture and Fisheries 6, 382–392. https://doi.org/10.1016/j.aaf.2020.09.005

Fryer, R.J., 1991. A model of between-haul variation in selectivity. ICES Journal of Marine Science 48, 281–290. https://doi.org/10.1093/icesjms/48.3.281

Glass, C.W., 2000. Conservation of fish stocks through bycatch reduction: A review. Northeastern Naturalist 7, 395–410. https://doi.org/10.2307/3858520

Grimaldo, E., Larsen, R.B., Sistiaga, M., Madsen, N., Breen, M., 2009. Selectivity and escape percentages during three phases of the towing process for codends fitted with different selection systems. Fisheries Research 95, 198–205. https://doi.org/10.1016/j.fishres.2008.08.019

Grimaldo, E., Sistiaga, M., Herrmann, B., Larsen, R.B., Brinkhof, J., Tatone, I., 2018. Improving release efficiency of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea demersal trawl fishery by stimulating escape behavior. Canadian Journal of Fisheries and Aquatic Sciences 75, 402–416. https://doi.org/10.1139/cjfas-2017-0002

Hansen, U.J., 2004. Performance of a trawl codend made from 90° turned netting (T90) compared with that of traditional codends. ICES FTFB Working Group Meeting 17.

Hartig, F., 2021. DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. Available from: Available from: https://CRAN.R-project.org/package=DHARMa

Herrmann, B., Krag, L.A., Krafft, B.A., 2018. Size selection of Antarctic krill (*Euphausia superba*) in a commercial codend and trawl body. Fisheries Research 207, 49–54. https://doi.org/10.1016/j.fishres.2018.05.028

Herrmann, B., Priour, D., Krag, L.A., 2007. Simulation-based study of the combined effect on cod-end size selection of turning meshes by 90° and reducing the number of meshes in the circumference for round fish. Fisheries Research 84, 222–232. https://doi.org/10.1016/j.fishres.2006.10.020

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (*Sebastes* spp.) in North Atlantic trawl codends Journal of the Northwest Atlantic Fisheries Science, 44, 1-13.

Herrmann, B., Sistiaga, M., Santos, J., Sala, A., 2016. How many fish need to be measured to effectively evaluate trawl selectivity? PLoS ONE 11, e0161512. https://doi.org/10.1371/journal.pone.0161512

Herrmann, B., Wienbeck, H., Karlsen, J.D., Stepputtis, D., Dahm, E., Moderhak, W., 2015. Understanding the release efficiency of Atlantic cod (*Gadus morhua*) from trawls with a square mesh panel: effects of panel area, panel position, and stimulation of escape response. ICES Journal of Marine Science 72, 686–696. https://doi.org/10.1093/icesjms/fsu124

Hothorn, T., Bretz, F., Westfall, P., 2008. Simultaneous inference in general parametric models. Biometrical Journal 50, 346–363. https://doi.org/10.1002/bimj.200810425

ICES, 2005. Protocol for the use of an objective mesh gauge for scientific purposes (No. 279). ICES Cooperative Research Report, Copenhagen, Denmark. XXp.

Ingólfsson, Ó.A., Brinkhof, J., 2020. Relative size selectivity of a four-panel codend with short lastridge ropes compared to a flexigrid with a regular codend in the Barents Sea gadoid trawl fishery. Fisheries Research 232, 105724. https://doi.org/10.1016/j.fishres.2020.105724

Jones, E.G., Summerbell, K., O'Neill, F., 2008. The influence of towing speed and fish density on the behavior of haddock in a trawl cod-end. Fisheries Research 94, 166–174. https://doi.org/10.1016/j.fishres.2008.06.010

Kelleher, K., 2005. Discards in the World's Marine Fisheries. An Update. FAO Fisheries Technical Paper 470. XXp

Kim, Y.-H., 2015. Escape response of juvenile fish in a shaking codend determined from tank experiments. Fisheries Research 161, 273–279. https://doi.org/10.1016/j.fishres.2014.08.012

Kim, Y.-H., 2013. Shaking motion characteristics of a cod-end caused by an attached circular canvas during tank experiments and sea trials. Fisheries and Aquatic sciences 16, 211–220. https://doi.org/10.5657/FAS.2013.0211

Kim, Y.-H., Whang, D.-S., 2010. An actively stimulating net panel and rope array inside a model cod-end to increase juvenile red seabream escapement. Fisheries Research 106, 71–75. https://doi.org/10.1016/j.fishres.2010.07.005

Koslow, J., Boehlert, G.W., Gordon, J.D.M., Haedrich, R.L., Lorance, P., Parin, N., 2000. Continental slope and deep-sea fisheries: implications for a fragile ecosystem. ICES Journal of Marine Science 57, 548–557. https://doi.org/10.1006/jmsc.2000.0722

Larsen, R.B., Herrmann, B., Sistiaga, M., Brčić, J., Brinkhof, J., Tatone, I., 2018. Could green artificial light reduce bycatch during Barents Sea Deep-water shrimp trawling? Fisheries Research 204, 441–447. https://doi.org/10.1016/j.fishres.2018.03.023

Madsen, N., Hansen, K., Madsen, N.A.H., 2015. Behavior of different trawl codend concepts. Ocean Engineering 108, 571–577. https://doi.org/10.1016/j.oceaneng.2015.08.047

Madsen, N., Herrmann, B., Frandsen, R.P., Krag, L.A., 2012. Comparing selectivity of a standard and turned mesh T90 codend during towing and haul-back. Aquatic Living Resources 25, 231–240. https://doi.org/10.1051/alr/2012021

Madsen, N., Holst, R., 2002. Assessment of the cover effect in trawl codend selectivity experiments. Fisheries Research 56, 289–301. https://doi.org/10.1016/S0165-7836(01)00330-7

Millar, R.B., 1993. Incorporation of between-haul variation using bootstrapping and nonparametric estimation of selection curves. Fishery Bulletin 564–572.

Moore, D.S., McCabe, G.P., Duckworth, W.M., Sclove, S.L., 2003. The practice of business statistics: using data for decisions. The Mathematical Gazette 88, 390–391. https://doi.org/10.1017/S0025557200175783

Pérez Roda, M.A., Gilman, E., Huntington, T., Kennelly, S.J., Suuronen, P., Chaloupka, M., Medley, P.A.H., Food and Agriculture Organization of the United Nations, 2019. A third assessment of global marine fisheries discards. FAO Fisheries and Aquaculture Technical Paper 633, 78.

Petetta, A., Herrmann, B., Virgili, M., Bargione, G., Vasapollo, C., Lucchetti, A., 2021. Dredge selectivity in a Mediterranean striped venus clam (*Chamelea gallina*) fishery. Fisheries Research 238, 105895. https://doi.org/10.1016/j.fishres.2021.105895

Pol, M.V., Herrmann, B., Rillahan, C., He, P., 2016. Impact of codend mesh sizes on selectivity and retention of Acadian redfish Sebastes fasciatus in the Gulf of Maine trawl fishery. Fisheries Research 184, 54–63. https://doi.org/10.1016/j.fishres.2016.06.013

R Development Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Reeves, S.A., Armstrong, D.W., Fryer, R.J., Coull, K.A., 1992. The effects of mesh size, cod-end extension length and cod-end diameter on the selectivity of Scottish trawls and seines. ICES Journal of Marine Science 49, 279–288. https://doi.org/10.1093/icesjms/49.3.279

Richard, G., Bonnel, J., Tixier, P., Arnould, J.P.Y., Janc, A., Guinet, C., 2020. Evidence of deep-sea interactions between toothed whales and longlines. Ambio 49, 173–186. https://doi.org/10.1007/s13280-019-01182-1

Rubec, P.J., McGlade, J.M., Trottier, B.L., Ferron, A., 1991. Evaluation of methods for separation of Gulf of St. Lawrence Beaked redfishes, *Sebastes fasciatus* and *S. mentella* : Malate dehydrogenase mobility patterns compared with extrinsic gasbladder muscle passages and anal fin ray counts. Canadian Journal of Fisheries and Aquatic Sciences 48, 640–660. https://doi.org/10.1139/f91-082

Scandol, J.P., Underwood, T.J., Broadhurst, M.K., 2006. Experiments in gear configuration to reduce bycatch in an estuarine squid- trawl fishery. Fishery Bulletin 104, 533–541.

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R.B., 2010. Assessment of dual selection in grid based selectivity systems. Fisheries Research 105, 187–199. https://doi.org/10.1016/j.fishres.2010.05.006

Tokaç, A., Herrmann, B., Aydın, C., Kaykaç, H., Ünlüler, A., Gökçe, G., 2014. Predictive models and comparison of the selectivity of standard (T0) and turned mesh (T90) codends for three species in the Eastern Mediterranean. Fisheries Research 150, 76–88. https://doi.org/10.1016/j.fishres.2013.10.015

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Cooperative Research Report 215, XXp.

Winger, P., Eayrs, S., Glass, C., 2010. Fish behavior near bottom trawls, In He, P. (Ed.), Behavior of Marine Fishes: Capture Processes and Conservation Challenges. Wiley-Blackwell, Oxford, UK, pp. 65–103. https://doi.org/10.1002/9780813810966.ch4

Winger, P.D., DeLouche, H., Legge, G., 2006. Designing and testing new fishing gears: The value of a flume tank. Marine Technology Society Journal 40, 44–49. https://doi.org/10.4031/002533206787353240

World Bank, Food and Agriculture Organization, 2009. The sunken billions: the economic justification for fisheries reform. The World Bank 47606.

Zeller, D., Cashion, T., Palomares, M., Pauly, D., 2018. Global marine fisheries discards: A synthesis of reconstructed data. Fish Fish 19, 30–39. https://doi.org/10.1111/faf.12233

2.8 Tables

Table 2.1. The mean moving angle of a shaking codend at each flow velocity and linear regression summary.

Mean moving angle

Flow velocity (kt)	Moving angle (°)	SEM
1.0	21.0	0.08
1.2	21.6	0.16
1.4	22.0	0.07
1.6	22.5	0.12
1.8	22.6	0.15

Linear regression summary

Parameter	Estimate	SE	*t* value	*p* value
(Intercept)	19.131	0.2824	67.75	**< 0.001**
Flow velocity	2.0085	0.1977	10.16	**< 0.001**

SEM is the standard error of the mean and SE is the standard error. *p*-values in bold are statistically significant based on an alpha of 0.05.

Table 2.2. The mean values for total acceleration (TA), amplitude ratio, and period of the shaking and T90 codend at five different flow velocities during flume tank testing.

Measurement	**Codend**	**Flow velocity (kt)**				
		1.0	**1.2**	**1.4**	**1.6**	**1.8**
TA (m s^{-2})	Shaking	51.84 (0.04)	51.75 (0.04)	51.68 (0.04)	51.78 (0.04)	51.69 (0.05)
	T90	51.50 (0.06)	51.38 (0.03)	51.06 (0.03)	50.90 (0.04)	50.92 (0.04)
Drag force (kgf)	Shaking	NA	86.60 (0.02)	117.12 (0.04)	152.73 (0.05)	191.50 (0.07)
	T90	NA	77.32 (0.04)	103.47 (0.07)	133.25 (0.1)	166.73 (0.08)
Amplitude ratio	Shaking	0.26 (0.004)	0.25 (0.003)	0.25 (0.003)	0.24 (0.42)	0.26 (0.004)
	T90	0.03 (0.002)	0.03 (0.001)	0.03 (0.001)	0.03 (0.001)	0.03 (0.001)
Period (s)	Shaking	13.63 (13.15-14.12)	11.36 (10.43-12.38)	9.80 (8.99-10.67)	8.52 (7.81-9.27)	7.59 (6.95-8.26)
	T90	8.29 (7.47-9.19)	6.92 (5.93-8.06)	5.96 (5.11-6.95)	5.18 (4.44-6.04)	4.62 (3.95-5.38)

The numbers in parentheses for TA and amplitude ratio are the standard error of the mean (SEM) values, and the numbers in parentheses for period are 95% confidence intervals.

Table 2.3. Flume tank experiment analyses comparing the total acceleration, drag forces, amplitude ratio, and period between the shaking and T90 codend. Independent variables included in models, Akaike information criterion (AICc) or QAIC, delta-AICc (dAICc) or dQAIC, and AICc/QAIC weight (weight) for each model. Bold numbers specify the best model with the lowest AICc or QAIC.

Total acceleration			
Independent variables	AICc	dAICc	weight
Codend * Flow velocity	**51253.0**	0	1
Codend + Flow velocity	51299.4	46.5	<0.001
Codend	51368.7	115.7	<0.001
Flow velocity	51873.0	620.0	<0.001
Null model	51992.6	739.6	<0.001
Drag force			
Independent variables	AICc	dAICc	weight
Codend * Flow velocity	283676.7	0.0	1
Codend + Flow velocity	287503.5	3826.8	<0.001
Codend	309048.7	25372.0	<0.001
Flow velocity	466534.3	182857.6	<0.001
Null model	467448.7	183772.0	<0.001
Amplitude ratio			
Independent variables	AICc	dAICc	weight
Codend * Flow velocity	**-8044.8**	0	0.979
Codend	-8035.7	9.1	0.010

Codend + Flow velocity	-8035.6	9.2	0.009
Flow velocity	-3002.9	5041.9	<0.001
Null model	-2967.0	5077.9	<0.001

Period

Independent variables	QAIC	dQAIC	weight
Codend * Flow velocity	**16837.1**	0	1
Codend + Flow velocity	16841.4	4.3	0.11
Codend	17871	1027.3	<0.001
Flow velocity	18820.1	1976.4	<0.001
Null model	20221.5	3377.8	<0.001

Table 2.4. Summary of total acceleration linear regression, drag force linear regression, amplitude ratio linear regression, and period generalized linear model comparing total acceleration, amplitude ratio, and period between the shaking and T90 codend during a flume tank test.

Total acceleration				
Variable	Estimate	SE	*t* value	*p* value
(Intercept)	51.836	0.038	1331.059	**< 0.001**
CodendT90	-0.331	0.078	-4.251	**< 0.001**
Flow velocity 1.2 kt	-0.085	0.055	-1.545	0.122
Flow velocity 1.4 kt	-0.153	0.055	-2.787	**0.005**
Flow velocity 1.6 kt	-0.052	0.055	-0.953	0.34
Flow velocity 1.8	-0.142	0.055	-2.594	**0.009**
Codend T90:Flow velocity 1.2 kt	-0.037	0.095	-0.39	0.696
Codend T90:Flow velocity 1.4 kt	-0.292	0.095	-3.06	**0.002**
Codend T90:Flow velocity 1.6 kt	-0.550	0.095	-5.764	**< 0.001**
Codend T90:Flow velocity 1.8 kt	-0.439	0.095	-4.597	**< 0.001**
Drag force				
Variable	Estimate	SE	*t* value	*p* value
(Intercept)	86.60321	0.0477	1815.6	**< 0.001**
Codend T90	-9.28177	0.16225	-57.21	**< 0.001**
Flow velocity 1.4 kt	30.5206	0.06739	452.92	**< 0.001**
Flow velocity 1.6 kt	66.12564	0.06802	972.21	**< 0.001**
Flow velocity 1.8 kt	104.9	0.06755	1552.86	**< 0.001**

Codend T90:Flow velocity 1.4 kt	-4.36802	0.22366	-19.53	< **0.001**
Codend T90:Flow velocity 1.6 kt	-10.196	0.26232	-38.87	< **0.001**
Codend T90:Flow velocity 1.8 kt	-15.4948	0.23945	-64.71	< **0.001**

Amplitude ratio

Variable	Estimate	SE	*t* value	*p* value
(Intercept)	0.257	0.002	87.249	< **0.001**
Codend T90	-0.229	0.004	-48.081	< **0.001**
Flow velocity 1.2 kt	-0.003	0.004	-0.857	0.391
Flow velocity 1.4 kt	-0.002	0.003	-0.694	0.487
Flow velocity 1.6 kt	-0.013	0.003	-3.542	< **0.001**
Flow velocity 1.8 kt	-0.001	0.003	-0.114	0.908
Codend T90:Flow velocity 1.2 kt	0.001	0.005	0.32	0.748
Codend T90:Flow velocity 1.4 kt	0.004	0.005	0.778	0.436
Codend T90:Flow velocity 1.6 kt	0.016	0.005	2.987	0.002
Codend T90:Flow velocity 1.8 kt	0.003	0.005	0.687	0.492

Period

Variable	Estimate	SE	*t* value	*p* value
(Intercept)	2.612	0.018	144.228	< **0.001**
Codend T90	-0.496	0.034	-14.301	< **0.001**
Flow velocity 1.2 kt	-0.180	0.025	-7.054	< **0.001**
Flow velocity 1.4 kt	-0.329	0.025	-12.844	< **0.001**
Flow velocity 1.6 kt	-0.469	0.025	-18.343	< **0.001**
Flow velocity 1.8 kt	-0.585	0.025	-22.861	< **0.001**

Codend T90:Flow velocity 1.2 kt	-0.063	0.043	-1.469	0.142
Codend T90:Flow velocity 1.4 kt	-0.052	0.043	-1.225	0.221
Codend T90:Flow velocity 1.6 kt	-0.052	0.043	-1.218	0.224
Codend T90:Flow velocity 1.8 kt	-0.007	0.043	-0.169	0.866

SE is the standard error and the *p* values in bold are statistically significant based on an alpha of 0.05

Table 2.5. Operational conditions for sea trials testing the size selectivity of shaking and T90 codends.

Codend	Haul ID	Date	Number of measurements		Subsampling ratio		Towing duration (min)	Maximum towing depth (m)	Haul velocity (kt)
			Cover	Codend	Cover	Codend			
Shaking	1	July 16, 2019	337	390	0.2643	0.0845	18	129	2.4
	2	July 16, 2019	371	199	0.8690	0.2701	10	129	2.5
	3	July 16, 2019	363	163	0.1974	0.0838	6	132	2.5
	4	July 16, 2019	369	285	0.6452	0.3432	6	140	2.4
T90	5	July 17, 2019	81	287	1	0.6435	5	179	2.4
	6	July 17, 2019	156	133	1	0.2036	9	180	2.3
	7	July 17, 2019	319	349	0.3734	0.0957	10	178	2.6
	8	July 17, 2019	358	358	0.1533	0.0567	9	177	2.5
	9	July 17, 2019	337	234	1	0.0871	7	178	2.5
	10	July 17, 2019	65	138	1	0.2108	7	176	2.5
	11	July 18, 2019	384	384	0.6540	0.1115	7	172	2.4
	12	July 18, 2019	407	362	0.4815	0.0975	8	172	2.4

13	July 18, 2019	339	334	0.2018	0.0839	6	178	2.5
14	July 18, 2019	328	364	0.3385	0.0707	5	177	2.6
15	July 18, 2019	305	335	0.1860	0.0560	4	172	2.4

Table 2.6. Subsample number, amplitude ratio, and period of the shaking codend during sea trials.

Haul ID	Subsampling	Amplitude ratio	Period (s)
2	1	0.13	7.7
	2	0.08	10.5
	3	0.14	9.1
	4	0.24	20.7
3	1	0.07	6.8
	2	0.05	4.6
	3	0.19	10.8
4	1	0.04	4
	2	0.08	8.2

Table 2.7. AIC values for fit size selectivity models.

Codend	Logit	CLogit	Probit	CProbit	Gompertz	CGompertz	Richard	CRichard
Shaking	24,717.52	24,670.35	24,705.70	24,669.43	24,752.95	24,684.75	**24,663.26**	24,665.26
T90	45,281.88	45,257.56	45,269.85	45,256.59	45,302.46	**45,254.85**	45,260.14	45,257.23

Bold numbers specify the best models for each codend with the lowest AIC. The AIC value of CGompertz were lower than others, particularly Richard model, which was used to describe the size selectivity of T90 codend in Cheng et al. (2020).

Table 2.8. Results from the best fit size selectivity models.

Codend	**Shaking**	**T90**
Model	Richard	CGompertz
L50	20.1 (19.6-21.9)	*
C	*	0.5 (0.3-0.9)
$L50_c$	*	22.6 (20.0-23.8)
p-value	0.038	0.594
Deviance	31.26	14.06
DOF	19	16

Values in parentheses represent 95% confidence intervals. * is not applicable value

2.9 Figures

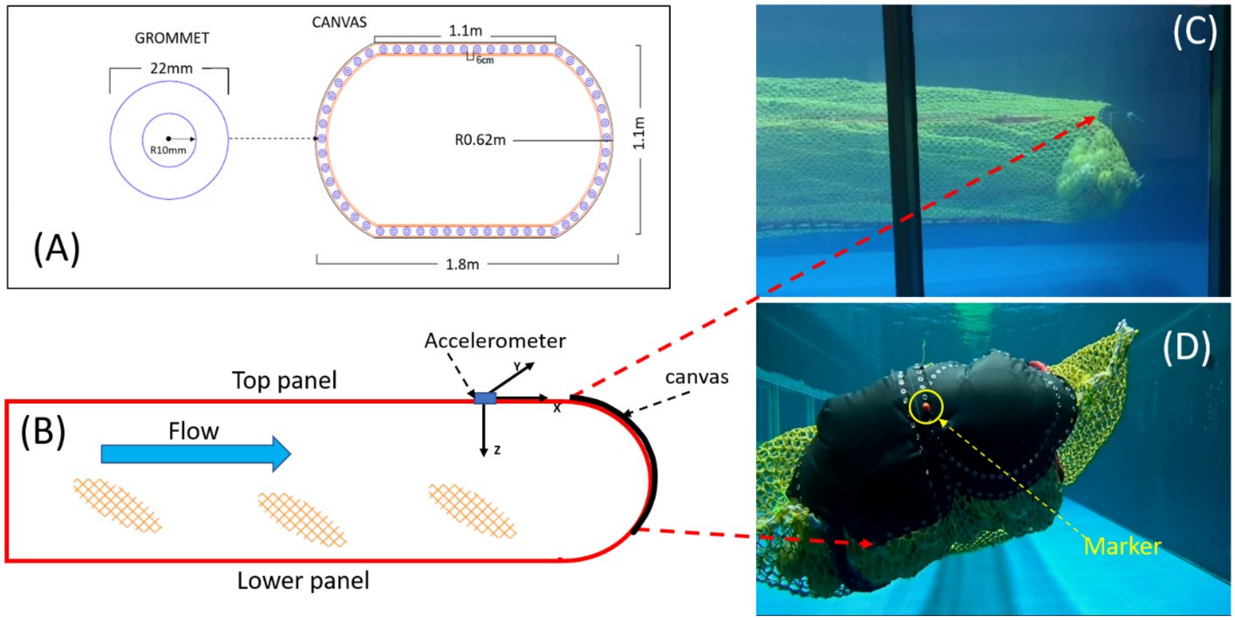


Figure 2.1. Canvas specification and location on codend. (A) detailed plan of canvas; (B) side-profile schematic illustration of the anterior section of the codend; (C) side-profile photo of the anterior section of the codend during flume tank tests; and (D) photo of the posterior of the codend during flume tank tests.

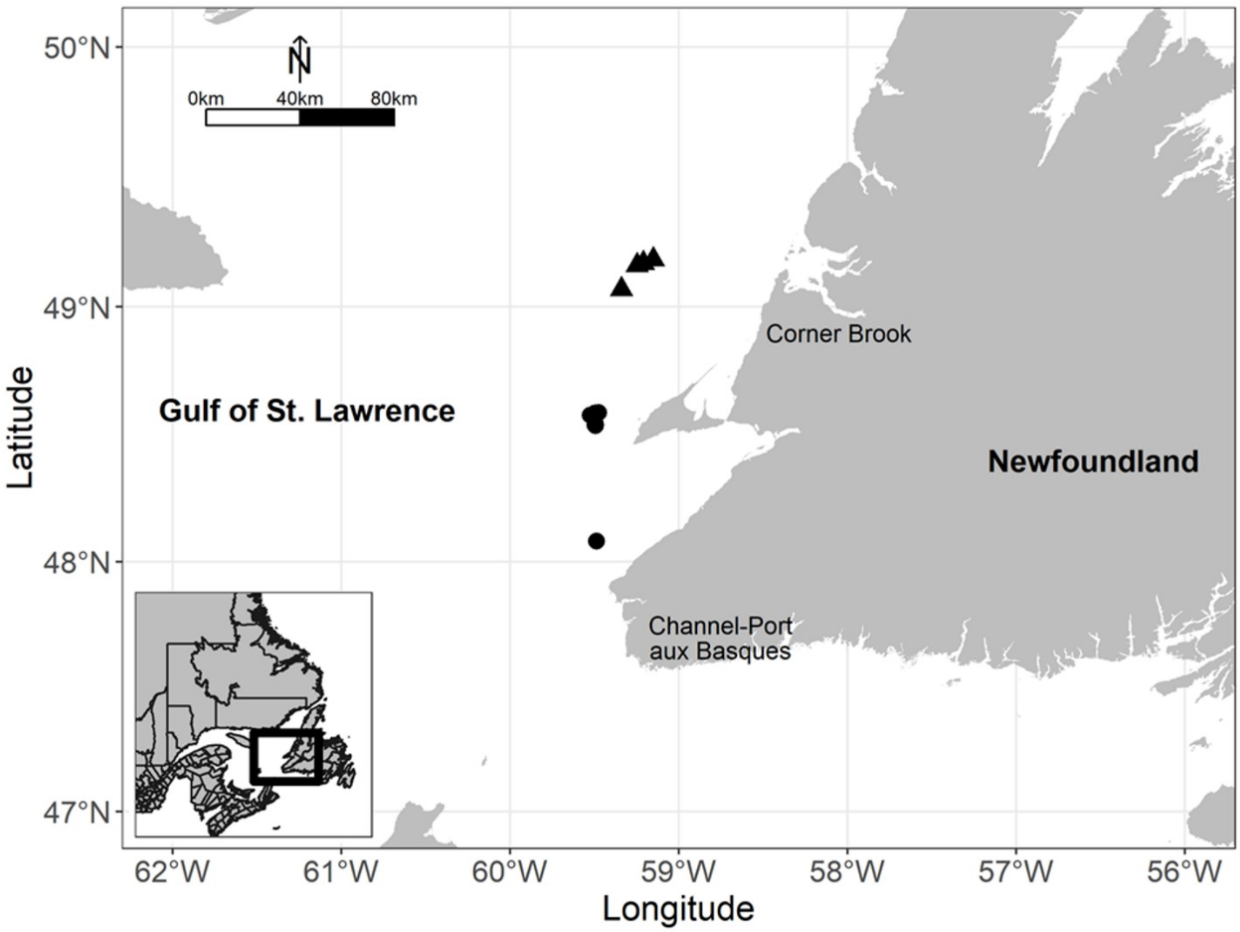


Figure 2.2. Map of fishing trials in the Gulf of St. Lawrence, Canada. Black points represent locations of shaking codend hauls and black triangles represent locations of T90 codend hauls. Reprinted from GADM under a CC BY license, with permission from: https://gadm.org, original copyright (2022).

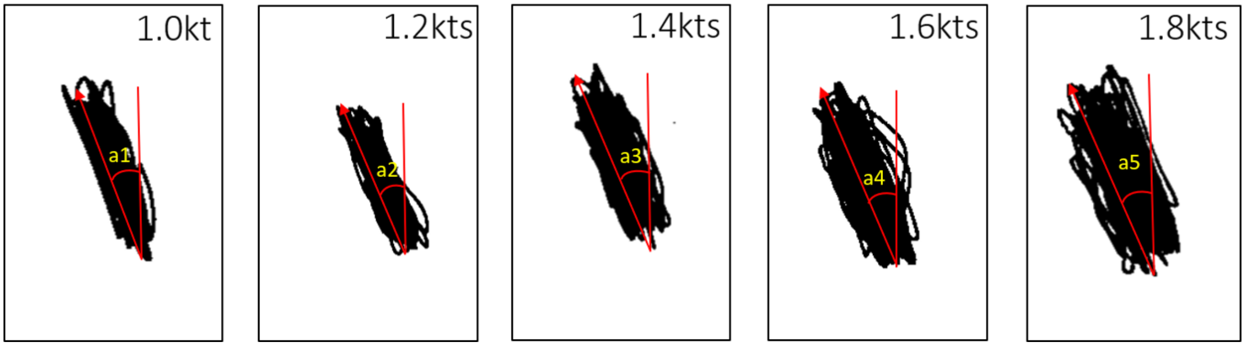


Figure 2.3. Movement of the shaking codend across five flow velocities from 1.0 to 1.8 kt. Black lines track codend movement angles (a1-a5) across 5 flow velocities, 1.0 kt, 1.2 kt, 1.4 kt, 1.6 kt, and 1.8 kt.

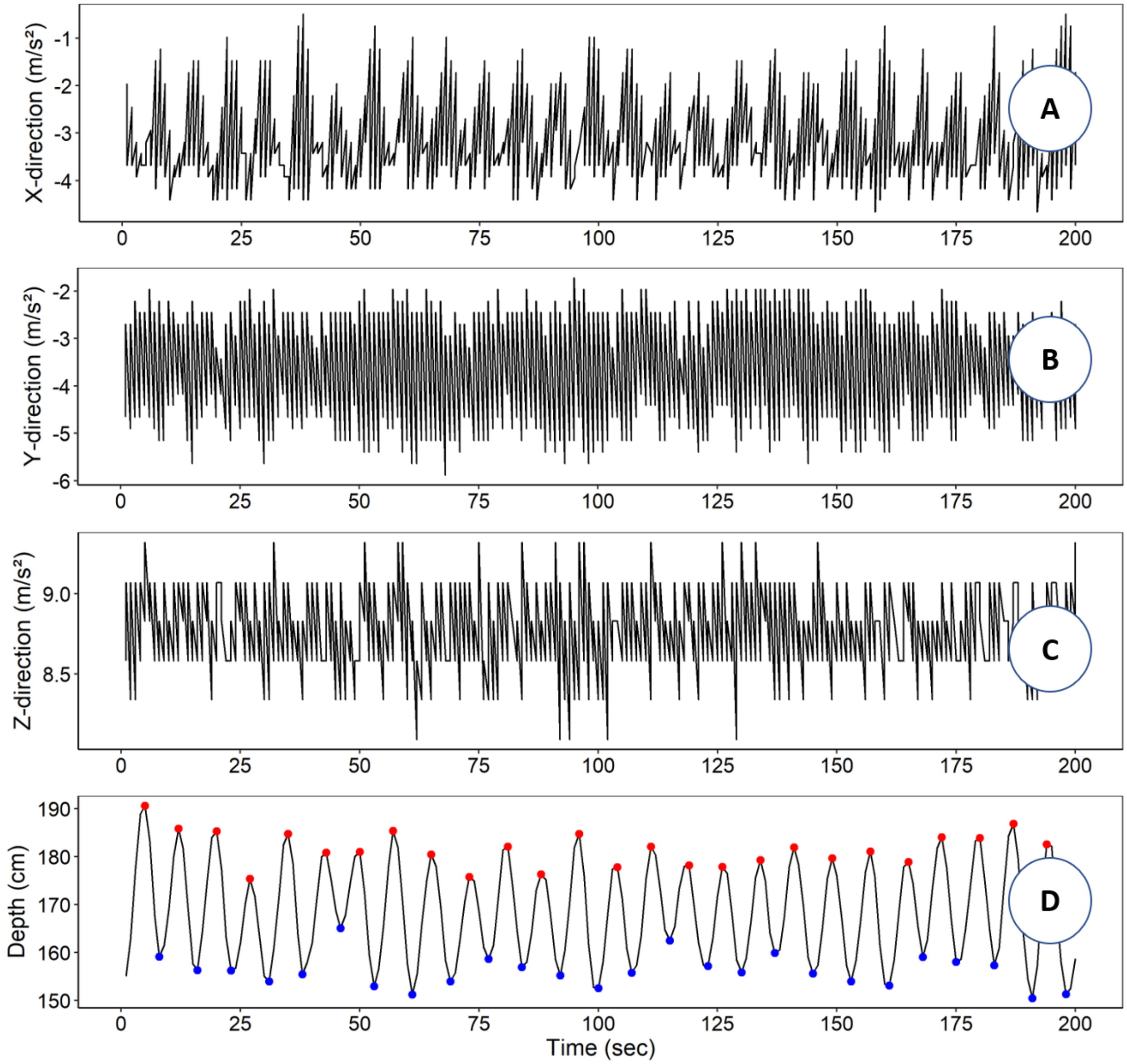


Figure 2.4. Examples of shaking codend acceleration and depth change in flume tank tests. The first three panels A, B and C are the acceleration values recorded in X, Y, and Z directions, respectively. The D panel shows the results of the find_peak analysis applied for depth data to calculate the peak-to-peak amplitude; red points are the peaks and blue points are the valleys for the shaking codend. These examples were taken at a flow velocity of 1.8 kt over 200 secs.

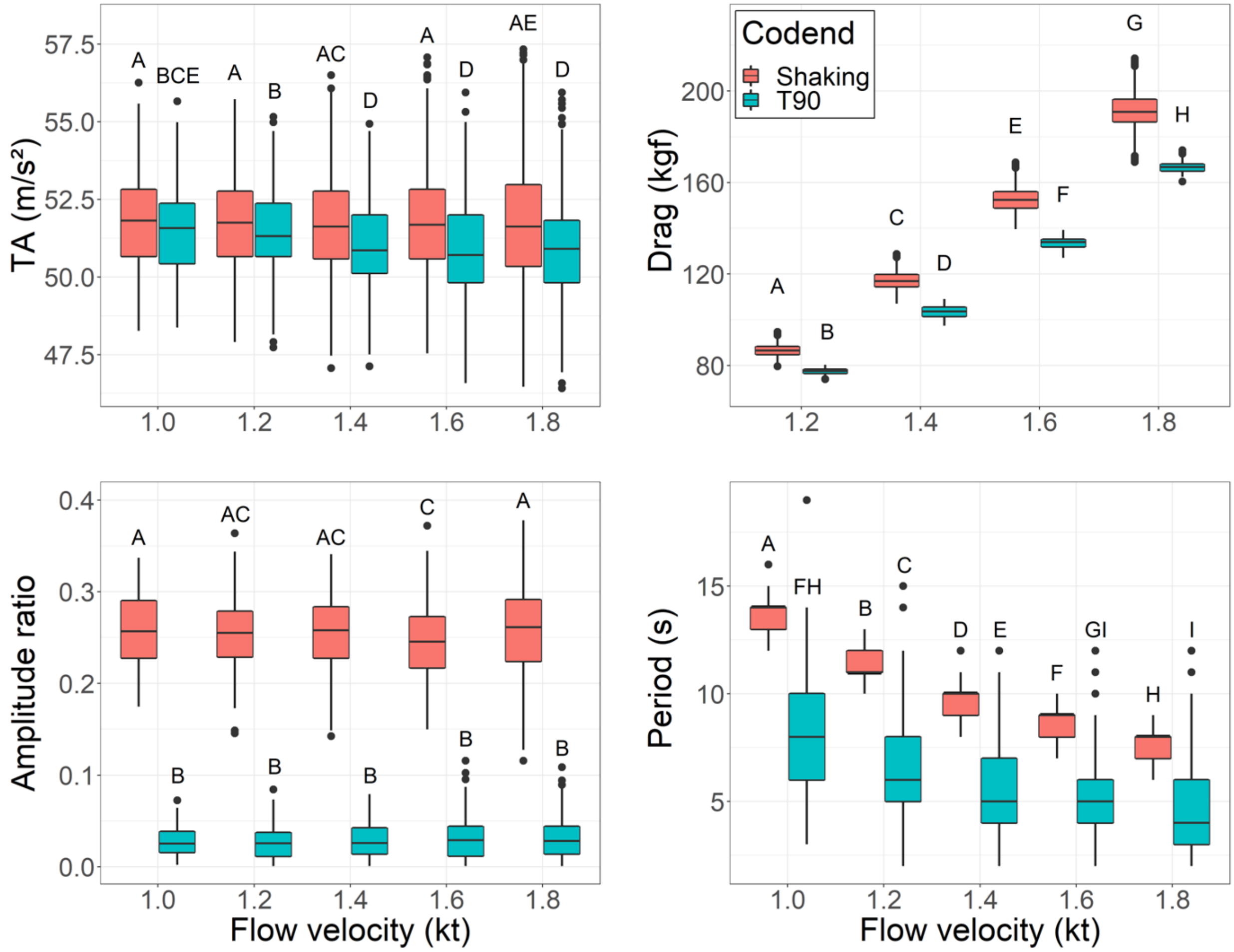


Figure 2.5. Boxplots of total acceleration, amplitude ratio, and period for codends evaluated in a flume tank test. The horizontal line in the middle of the boxes represents the 50th percentile (median) the top and bottom limit of the boxes represents the 75th percentile and 25th percentile, respectively. Upper and lower whiskers are the 75th (or 25th) percentile − 1.5 * interquartile range. Circles are values outside the range of the whiskers. Letters represent a significant difference between treatments (shaking or T90 codend) at a specific water velocity via *post hoc* analysis at an α of 0.05.

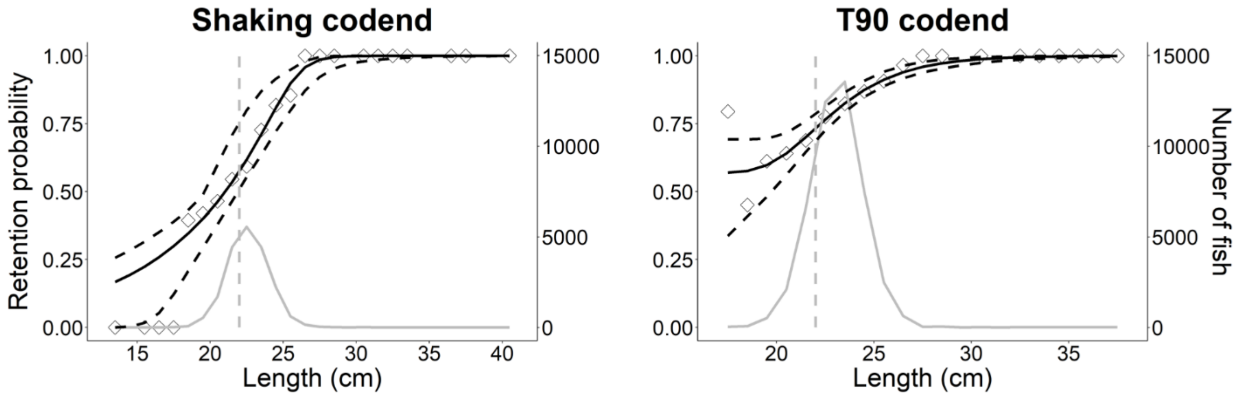


Figure 2.6. Size selectivity plots for the shaking and T90 codends. The black line represents the size selectivity curves. The vertical grey dashed lines represent the minimum landing size (MLS) for the Canadian redfish fishery. Diamonds correspond to the experimental ratios, whereas grey lines represent the size distribution of the redfish population captured during testing. Dashed black lines are the 95% Efron percentile confidence intervals.

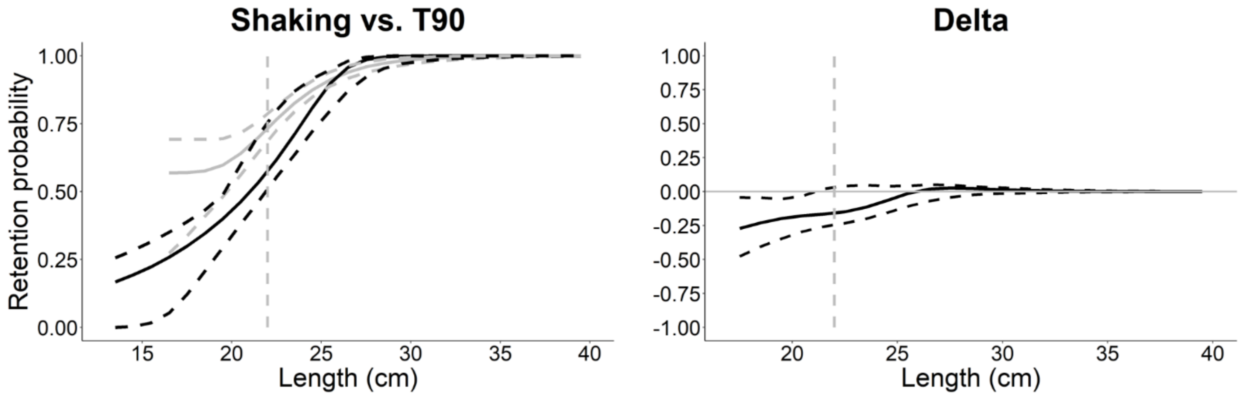


Figure 2.7. Selectivity comparison between the shaking and T90 codend. The left plot compares the size selectivity curves of the shaking codend versus the T90 codend: black and grey lines are the selection curves for the shaking codend and T90 codend, respectively; black and grey dashed lines are the 95% Efron percentile confidence intervals for the shaking and T90 codend, respectively. The right plot illustrates the delta curve: black line is the delta curve; grey dashed lines are the 95% Efron percentile confidence intervals. The vertical grey dashed lines in both plots represent the minimum landing size (MLS) for Canadian redfish fishery.

CHAPTER 3. Developing a semi-pelagic trawl to capture redfish in the Gulf of St. Lawrence, Canada

3.1 Abstract

In this study, we developed a semi-pelagic trawl to target redfish (*Sebastes* spp.) and potentially reduce the capture of bycatch species and seabed impacts in the Gulf of St. Lawrence, Canada. The new trawl used an innovative technique connecting the upper bridles of the trawl to the warps anterior of the trawl doors, leading to the trawl system being fished off the seabed. Such a technique can be used to match the heights of redfish as they move above the seabed during their diurnal cycle while allowing bycatch species related to the seabed to escape under the trawl. A 1:10 scale model of the trawl was constructed and evaluated in a flume tank with different rigging scenarios and then constructed full-scale for sea trials. The preferred rigging from the flume tank test connected the upper bridles 30.5 m anterior of the doors with a warp-to-depth ratio of 2.6:1, which lifted the trawl off the seabed up to 2.3 m (i.e., bottom clearance). Two field experiments subsequently evaluated the trawl at sea. The first field experiment concentrated on the experimental trawl's operation and video observations of redfish behavior in the trawl mouth and its effect on catch efficiency. The second field experiment concentrated on a small-scale preliminary test on the catch of redfish and bycatch species when the trawl was on or off the seabed. Capture results, though preliminary, indicate that redfish can be targeted commercially with a semi-pelagic trawl, though some redfish will escape under the trawl. Additionally, results suggest that the catches of bycatch species may be reduced. In conclusion, this study suggests that a semi-pelagic trawl could be considered an effective technique to harvest redfish sustainably.

3.2 Introduction

The redfish fishery in the Gulf of St. Lawrence (GSL) is currently in moratorium, retaining only a small index fishery (2,000 t year $^{-1}$) (Duplisea, 2018; DFO, 2020). The catches of this fishery are dominated by deepwater redfish (*Sebastes mentella*) and Acadian redfish (*S. fasciatus*), collectively called redfish (DFO, 2020). Redfish are slow-growing, late maturing, and long-lived (Cadigan et al., 2022) and thus are susceptible to overfishing (Koslow et al., 2000). These characteristics combined with a high proportion of small fish landed led to a moratorium in the Gulf of St. Lawrence (GSL) redfish fishery in 1995 (Duplisea, 2018). However, recent strong recruitment events have led to an upcoming commercial redfish fishery (DFO, 2020). The likelihood of an imminent fishery has led to the testing of conservation measures and management concepts in an attempt to maintain a sustainable fishery.

Several technical measures have been implemented to improve the size selectivity – reduce the capture of undersize fish – of the groundfish trawl currently used to target redfish in the GSL (DFO, 2020). While the currently regulated codend (i.e., 90 mm diamond mesh codend) has poor size selectivity (Cheng et al., 2020), modifying the codend mesh construction can improve the size selectivity for redfish (Pol, 2016; Cheng et al., 2020). Prior experiments have shown that the capture of small roundfish could be reduced by using a codend with a different mesh configuration that rotated diamond mesh 90° in the transverse direction, called a T90 codend (Herrmann et al., 2007; Tokaç et al., 2014; Bayse et al., 2016a). Cheng et al. (2020) applied T90 codends in the GSL redfish trawl fishery. These authors revealed that using T90 codends can reduce the capture of small redfish compared with the current 90 mm diamond codend. Increasing the mesh size of the codend has also demonstrated potential for reducing the capture of small redfish in the catch. Pol (2016) showed how increasing diamond codend mesh sizes can improve the size selectivity of redfish.

Potentially problematic rates of bycatch are a concern once the GSL redfish fishery is reopened, which is considered a key issue in redeveloping a sustainable redfish fishery in the near future (Duplisea, 2018; DFO, 2021; Cadigan et al., 2022). Redfish co-occur with many groundfish in the Northwest Atlantic, including Atlantic cod (*Gadus morhua*), white hake (*Urophycis tenuis*), and flatfish (Gomes et al., 1992). These species are associated with the seabed, behaviorally, or overlap in distribution with redfish, and thus, they have been captured as bycatch in the redfish trawl fishery (DFO, 2021). Atlantic cod and flatfish such as Greenland halibut (*Reinhardtius hippoglossoides*) and Atlantic halibut (*Hippoglossus hippoglossus*) could be captured along with redfish as they enter the trawl at heights close to the seabed (Ryer, 2008; Winger et al., 2010; Pol and Eayrs, 2021). The distribution of white hake has shifted to deeper waters, which now overlap with redfish in the GSL (DFO, 2021; Miri and Simpson, 2006). In Unit 1 from 2000-2019, Greenland halibut, white hake, and Atlantic cod made up 9% of the total landings (DFO, 2020). In the southern region of the GSL, a recent small-scale fishery and multi-species survey estimated white hake bycatch on average was 10.5% of the total weight of redfish caught, though the high average was likely due to large bycatch instances, the recorded median was between 0.0-1.6%, still white hake bycatch is a concern once the redfish fishery reopens (DFO, 2021).

The diurnal cycle of redfish has been observed where redfish are close to the seabed during the day and migrate up the water column at night (Beamish, 1966). As a semi-demersal species, redfish typically aggregate in small or large shoals, and make vertical movements from the seabed to intermediate layers, likely associated with feeding behavior (Gauthier and Rose, 2005; Cadigan et al., 2022). Thus, redfish availability to be captured by bottom trawling is affected by the time of day (Atkinson, 1989; Casey and Myers, 1998; Gauthier and Rose, 2005). Given that redfish are commonly found off the seabed, an effective fishing approach includes pelagic trawling, which also has the potential to reduce the bycatch of demersal species.

Semi-pelagic trawling is designed as a hybrid technique that can capture fish distributed on- and off-seabed (He et al., 2021). Semi-pelagic trawling can be considered when doors are fished off-seabed and the trawl in on-seabed, trawl is off-seabed and the doors are on-seabed, or in a hybrid fishing situation where either doors or trawl are moved on- or off-seabed as fishing conditions or motivations change (He et al., 2021; Montgomerie, 2022). Such a rigging technique was developed in the 1990s to fish redfish in the GSL, commonly known as French rigging or fork rigging (Garner, 1978; He and Winger, 2010). This method maintains the doors on the seabed while raising the trawl net off the seabed by connecting the upper bridles to the warps anterior of the doors (Garner, 1978; He and Winger, 2010). In the GSL fishery, this technique was used to target redfish as they migrate off the sea floor and to avoid net damage from a rough seabed (L. Dredge, pers. comm., 2021; Garner, 1978; He and Winger, 2010). Other fisheries have used a similar trawling technique in France and the United Kingdom targeting a variety of species (He and Winger, 2010).

Currently in the GSL, the Northern shrimp (*Pandalus borealis*) stock is at its historical lowest abundance (DFO, 2022). The major factors leading to this low stock level include deep water warming, low dissolved oxygen levels, and predation from redfish, none of which are expected to change soon (DFO, 2022). This scenario has led to a reduced total allowable catch (TAC) for Northern shrimp in the GSL and shrimp active licences (*n*=114; (DFO, 2022) are anxious to target redfish once the fishery reopens (The Ocean Frontier Institute Northwest

Atlantic Redfish Symposium, 2018; Dean-Simmons, 2021). Pelagic trawling is an effective method to target redfish off of the seabed (Duplisea, 2018), however for shrimp trawlers, a pelagic trawl would be excessively expensive (large trawl, new sensors, new doors, etc.) and/or require a more powerful vessel. Thus, a method such as semi-pelagic trawling (i.e., "French rigging") could be a cost effective solution to target redfish off the seabed, only requiring a typical groundfish trawl and a relatively simple modification to the upper bridles and warps.

This study aimed to develop a semi-pelagic trawl to target redfish in the GSL. The gear modification was based on earlier "French rigging" setups used in the 1990s in the GSL redfish fishery. A scale model of the groundfish trawl was constructed and evaluated in a flume tank to optimize the design and then was adapted to a full-size groundfish trawl. Two field experiments were conducted to investigate the effectiveness of the new trawl. Field experiment No. 1 investigated the semi-pelagic trawl system's performance and the behavior of redfish at the trawl entrance. For field experiment No. 2, a small experiment made preliminary assessments of how the semi-pelagic trawl captured target and bycatch species in comparison to the conventional trawl. A successful new trawl design would be a functional alternative to sustainably target redfish in the GSL and provide an economical alternative to target redfish off of the seabed for fishers transitioning from targeting Northern shrimp. Further, this study provides additional insights into redfish responses at the trawl entrance, which is not well understood.

3.3. Materials and Methods

3.3.1. Model construction, flume tank test, and full-scale modifications

A 1:10 scale model of an existing groundfish balloon trawl was constructed using a combination of Froude and Newton scaling principles (Dickson, 1959; Fridman, 1973). Force and geometric modelling laws were used during the scaling process to approximate full-scale bottom trawl characteristics and performance (Araya-Schmidt et al., 2021). The model was evaluated in a flume tank (Fig. 3.1) located at the Fisheries and Marine Institute of Memorial University of Newfoundland, Canada (Winger et al., 2006). The model was spread with a pair of Morgere PF doors and evaluated across a range of towing speeds and rigging configurations. The full-scale net plan of the trawl is described in Cheng et al. (2020). It has a headline height of 40.2 m, and a fishing line of 44.5 m. The rockhopper groundgear consists of 40.6 cm ∅ rollers on average and the headline consists of 132 floats (20.3 cm ∅). The trawl belly sections were constructed with the same netting, 170 mm diamond PE twine with a 3.5 to 4.0 mm ∅. (Winger et al., 2006).

Off-seabed trawling is represented by seabed clearance, which was tested at different rigging scenarios. Seabed clearance is defined as the vertical distance between groundgear and the seabed (in this case the flume tank belt), calculated by subtracting headline height (the height of the headline to the seabed) and vertical opening (headline to groundgear). The headline height and vertical opening parameters were recorded using a side-looking camera (Cheng et al., 2022). A total of five rigging scenarios were tested and scaled to full-size terms, detailed in Table 3.1. The first rigging scenario was to connect the upper bridles to the warps at 30.5 m forward of the doors (i.e., fork connection forward of the door; Fig. 3.2) and tested at four flow velocities (i.e., 2.5, 2.8, 3.0, and 3.2 kt). Rigging scenarios 2 and 3 were to reduce the fork connection from 30.5 m to 20.42 and 15.24 m, respectively and tested at a flow velocity of 2.8 kt. Scenarios 4 and 5 tested the rigging scenario 3 with different warp-to-depth ratios, where the warp-to-depth ratio increased (i.e., from 2.6:1 for scenario 4 to 6.9:1 for scenario 5).

3.3.2. Field tests

Two field experiments were conducted off the west coast of Newfoundland in the GSL, CA, in April 2021 and April 2022 (Fig. 3.3) onboard the commercial fishing trawler F/V *Lisa M* (overall length 19.8 m; gross tonnage 122.5 t; engine power 700 hp; 1 hp = 746 W). The trawl used for field experiments was a groundfish balloon trawl, described in section 2.1 and Cheng et al. (2020). The trawl was spread with a pair of low-aspect trawl doors (Injector Door Limited, Søvik, Norway), which were 4 m^2 in area. Fishing locations were based on the fisher's experience and fishing occurred 24 h a day. During field experiment No. 1, the codend had to remain open because we could not land redfish due to a combination of no available redfish quota, licensing constraints, and no local market for redfish at the time of fishing. For field experiment No. 2, the codend was closed. A T90 codend (nominal 90 mm mesh size) described in Cheng et al. (2020) was used. Mesh measurements (wet) were obtained with an Omega gauge (Fonteyne, 2005), $n = 60$ with a mean of 89.5 mm and a standard deviation (SD) of 3.3.

Field experiment No. 1

Experimental design and data collection

Trawl mensuration included door spread, headline height, and vertical opening (headline to groundgear) using Notus trawl mensuration sensors (Notus Electronics Ltd. St. John's, Newfoundland and Labrador, CA). Cameras and lights were used to observe the interaction between groundgear and seabed, and fish behavior at the trawl mouth. A set up with a camera (GoPro, Woodman Laboratories, Inc., Half Moon Bay, CA, USA) and two flashlights (DIV08W diving lights from Brinyte Technology Ltd., Guangdong, China) placed within waterproof housings. I used red light . Cameras and lights were connected to a plastic panel and attached to the middle of the trawl mouth. The position of the camera system was just aft of the fishing line, looking forward and at a slight angle toward the port to observe more footage of fish interacting with the groundgear and clearer documentation of when the trawl was on or off the seabed (Fig. 3.4). Videos collected were analyzed using Adobe Premiere Pro (Adobe Systems, Inc., San Jose, CA, USA) by a single observer. Interaction between groundgear and seabed (trawl state) was determined at the start of the tow and defined as when the trawl was fishing off- (groundgear was off the seabed) or on-seabed (groundgear was slightly off-seabed, light on seabed or hard on the seabed). Trawl state was confirmed via video. The duration of each trawl state was counted every minute (min) from underwater videos.

Redfish behavior at the trawl mouth

Fish behavior and its effects on the capture outcome of the trawl were analyzed based on observations and behaviors of individual redfish at the center of the trawl mouth (Figs. 3.4 and 3.5). Methods were derived from a similar behavioral study outlined by Bayse et al. (2016b). Variables were determined between the first detection on video until Capture outcome that included trawl entrance (Captured; fish entered trawl above the fishing line) or escape (Escaped; fish escaped under the fishing line) and observations and behaviors were then placed into eight categories detailed in Table 3.2. Fish that went off screen without a clear Capture outcome were considered unknown and removed from analysis. Of the eight categories, fish position (Position) was considered at first detection and was split into Above or Below the fishing line. Orientation is noted by the direction of the fish head in relation to the towing direction and the middle roller of the groundgear as: the head that oriented with and against the towing direction was classified as “away” and “toward”, and the head oriented to the left and right of middle roller of the groundgear were classified as “left” and “right”, respectively. Swimming behavior was classified into two categories, Swimming behavior 1 and Swimming behavior 2. Swimming behavior 1 considered behaviors in the horizontal plane and included swimming with (With; fish that were swimming in the direction of trawling, swimming against (Against; fish that were swimming in the opposite direction of trawling), and passive (Passive) fish that were not swimming – holding station – or lying on the seabed. Swimming behavior 2 considered behaviors in the vertical plane and included swimming up (Up; fish that swam upward), swimming down (Down; fish that swam downward towards the seabed), and no change (NC; fish that had no changes in their swimming direction in the vertical plane).

The variable Contact considered any contact between any section of the groundgear and redfish (Table 3.2). Other variables considered in the analysis included, time (period from first detection to Capture outcome), trawl state (trawl on or off the seabed), and period (trawling during day or nighttime).

The observed effects from variables listed in Table 3.2 on the capture outcome of redfish were analyzed using a binomial generalized linear mixed model (GLMM). The model included Capture outcome as the dependent variable, and independent variables listed in Table 3.2. Each individual tow (Tow) was considered a random effect on the intercept to account for variations in observations among tows due to extrinsic factors (i.e., environmental conditions, fish density, etc.). Model diagnostics were considered by investigating the data and models with the DHARMa package (Hartig, 2021) and multicollinearity with the vif function from the car package (Fox et al., 2012). Model selection was evaluated by information criterion (IC), both the Bayesian Information Criterion (BIC; Schwarz, 1978) and Akaike information criterion (AIC; Akaike, 1974) value with a correction for small sample sizes (AICc) were investigated. Initially all model combinations (*n*=256) with Tow as a random effect on the intercept were run and parameters were estimated by maximum likelihood using the automated model selection package glmulti (Calcagno and de Mazancourt, 2010) to narrow down which variables were important using IC and the relative importance of model terms plot in the glmulti package. The final models were run using the glmer function in the lme4 package (Bates et al., 2015), and the best model was determined from the minimum IC calculated from the BICtab or AICctab function from the bbmle package (Bolker and R Development Core Team, 2020). A delta IC of 2 or less indicated that models were similar, and the lowest IC was considered the best model.

Redfish behavior under the groundgear

Redfish behavior under the groundgear was recorded when the camera (in the same location as described above and in Fig. 3.4) was pointed straight down observing the area of the groundgear just under and behind the fishing line (Fig. 3.6). Redfish were observed before and after interacting with the passing groundgear. Noted observations and behaviors include, Position (Left or Right), Orientation (Left, Right, Toward, and Away in relation to head position to the trawl path), Swimming Behavior, Turning (Turn or No turn), Trawl state (On- or Off-bottom), and Contact (Contact or No contact). Swimming Behavior was grouped into passive swimming (PS; i.e., fish were laying on their side on the seabed, or sitting or touching the seabed with no swimming in response to upcoming trawl' components), active swimming (i.e. swimming with or against the trawling direction; holding station), and startled reaction (swam sideways in relations to groundgear after being startled). The number of fish that contacted the groundgear was also noted for several swimming behavior categories. Fish that passed under the groundgear (i.e. passing between rollers and rolled over by the rollers) was counted.

Field experiment No. 2

A small experiment compared both the semi-pelagic trawl described above at full-scale, as well as the trawl rigged as a conventional trawl, which simply involved the removal of the extended bridle cables and attached the warp/upper bridle back to the door. The conventional trawl setup is described in Cheng et al. (2020) and Nguyen et al. (2023). The goal of this work was to test both trawls ability to capture or avoid redfish and bycatch. Catches were transferred from the codend to a hopper that fed a conveyer system. Redfish went directly to the fish hold and redfish total catch was estimated by the fisheries observer which is standard practice in the fishery. Bycatch was sorted, counted, and weighed to the nearest 0.1 kg by Marine Institute scientists. Large Atlantic halibut weights were visually estimated since we did not have large enough equipment to weigh them. The gear mensuration setup matched that described in Experiment 1.

3.4 Results

3.4.1. Flume tank test and full-scale modifications

Overall, the flume tank test showed that the semi-pelagic trawl was effective at fishing off the seabed and was dynamic in fishing between off- and on- the seabed. The first scenario indicated that the seabed clearance was between 0.8 and 2.3 m when connecting the upper bridles to the warps at 30.5 m toward the doors, and the seabed clearance increased with increasing flow velocities. Reduction in bridle extension length reduced the seabed clearance (i.e., rigging scenarios 2 and 3; Table 3.1). Further, increasing the warp-to-depth ratios from 2.6:1 to 6.9:1 changed the trawl from being off-seabed to on-seabed (i.e., rigging scenarios 4 and 5; Table 3.1). Rigging scenario 1 was adapted to the existing groundfish trawl for the subsequent field experiments by extending the upper bridle with a 38.1 m cable (1.27 cm Ø) to the warp with a G-hook. A 30.5 m cable (1.27 cm Ø) was attached between previously described connections to the door. An additional 4.27 m chain was added to the aft of the lower bridles (Fig. 3.2).

3.4.2 Field experiment No. 1

Gear handling, performance, and efficiency

A total of 28 tows were carried out during the experiment. One tow was not considered because a cable was wrapped up in the trawl, which affected the gear's performance; thus, 27 valid hauls were used for analyses (Table 3.3). The mean depth of the fishing ground was 282.4 m (range: 255.7 to 308.9 m), the average haul duration was 166.1 min (range: 82 to 225 min), the towing speed was between 2.0 and 2.8 kt. The mean door spread was 65.5 m (range: 61.8 to 70.0 m), and the mean length of the warp deployed was 581.3 m (range: 548.6 to 640.1 m). Bottom water temperature was unable to be measured due to a malfunctioning instrument, however, according to Galbraith et al. (2022), the temperature was likely between 6 and 8° C.

There were no problems in handling the semi-pelagic trawl, and the hauling back process was similar to typical operations. The only exception being a slight delay (2-3 min) from when the G-hook passed through the warp winch from the connection point of the upper bridle extension, though this could be negated by splicing the upper bridle into the warp. The average observed seabed clearance of the semi-pelagic trawl was 2.5 m (ranged from 0.5 to 11.7 m; Table 3.3). For 7 tows, the seabed clearance was not observed due to equipment malfunction. The trawl was able to perform effectively on or off-seabed as desired. Of 27 tows implemented during the field experiment, 19 were considered off-seabed, and 8 were on-seabed. The total time observed for off-seabed and on-seabed tows was 38.4 h and 13.1 h, respectively. Off-bottom trawling was more accessible and consistent, whereas trawling on-bottom led to the trawl being either hard on the bottom, light on the bottom (groundgear barely touching the sea floor), or frequently coming off-seabed a short distance (observed from video). Additionally, the trawl was aimed to fish off-seabed when fishing with the tide; while fishing against the tide, the trawl was observed to fish on-seabed. This arrangement assessed the capacity of the trawl to fish in a “best case” scenario. To fish the trawl in the opposite way (e.g., off-seabed when against the tide) required letting out more warp or increasing the tow speed. Overall, the trawl fished effectively with regard to lifting the trawl system off the seabed, and the seabed clearance could be controlled by changes in towing speed and warp length.

Fish behavior analysis

Fish behavior was analyzed using 22 of 27 valid tows that had video collected during the experiment, 19 tows (~42 h) focused on redfish behavior in the trawl mouth and 3 tows (~6.5 h) with the camera pointed down towards the seabed.

Fish behavior at the trawl mouth

A total of 2196 redfish were observed, including 2099 individuals with a known capture outcome and 97 with an unknown capture outcome. Thus, redfish with an unknown capture outcome were removed from the analysis. Of the 2099 redfish, 1168 were observed to enter the trawl, and 931 escaped under the fishing line. The majority of redfish were first detected under the fishing line (73.1%), and 26.9% were observed above the fishing line of the trawl (Table 3.4). Redfish that were detected above the fishing line had a lower escape percentage (26.6%) than those seen on the bottom (50.9%). The most frequent swimming behavior observed was fish that were swimming against the trawling direction (62.3%), second was swimming with the trawl (22.0%), followed by Passive (15.8%). Escape rates for redfish swimming with the trawl (77.7%)

were higher than those either passive or swimming with the trawl (62.2% and 28.1%, respectively) (Table 3.4). In relation to the vertical plane, many (60%) of redfish had no change in their swimming direction, 34% swimming upward, and 6.2% swimming downward. Redfish that were swimming downward had a higher escape rate (94.6%) than those had no change in their swimming direction (63.9%); a few (0.8%) redfish that were swimming upward escaped under the trawl.

The vast majority (81.7%) of redfish did not contact the groundgear, while 18.3% had contact (Table 3.4). The mean time of redfish that entered the trawl was 1.05 s (± 0.07 SEM (standard error of the mean)) vs. 0.99 s (± 0.02 SEM) for those that escaped underneath the fishing line. Many (77.6%) of redfish were observed when the trawl was on-seabed, compared to 22.4% when the trawl was off-seabed. Table 3.5 and 3.6 showed the fish behavior when the trawl was on- and off-seabed, respectively. Additionally, more redfish (62.5%) were observed during the day than the night (37.5%, Table 3.4).

The automated model selection process showed convergence issues which were improved by removing the variable Orientation. Thus, the total number of models ran was 128. AICc had nine models within ~2 delta AICc and BIC had only two. AICc had lower IC values for more complicated models in comparison to BIC. The relative importance plots were similar between the different ICs. Both considered the three most important variables to be Position, Swimming behavior 1, and Swimming behavior 2. However, AICc valued Swimming behavior 1 equal to Position and Swimming behavior 2, whereas BIC had Swimming behavior 1 at ~20% lower than the other two variables. Thus, following the principal of parsimony and a clear model preference, BIC was used to determine that the best model included Position and Swimming behavior 2 (Table 3.7).

Redfish behavior under the groundgear

A total of 603 redfish were observed under the trawl, just behind the fishing line. Of those, 528 clearly escaped, while 75 had an unknown escape (swam out of view; though likely escaped) and were not further described. In general, redfish escape behavior under the groundgear was observed in three ways: 291 (55%) were observed to show passive swimming (including 96 individuals laid on the seabed and 195 individuals were sitting or touching the seabed without swimming), 196 (37%) swam actively (i.e., swimming with or against the trawling direction), and 41 (7.7%) showed a startled response and swam sideways in relation to towing direction (Table 3.8). These different swimming behaviors led to differences in the ways that fish passed under the groundgear, where a total of 461 redfish passed between groundgear rollers versus 67 that were rolled over by the groundgear rollers. Most fish that swam against the upcoming trawl escaped through the escape opening between rollers, and these fish did not contact the groundgear. Fish that swam with the trawl direction kept the upcoming trawl at a short distance and mostly returned to escape between rollers until the trawl came closer. Though occasionally some of these fish were passed over or rolled over by the rollers as they swam slower than the upcoming trawl. Redfish that were startled in a sideways direction were observed to contact the front side or impinge with the inside of the rollers as they passed under the trawl. Most of fish that have contact with the groundgear were observed when trawling on the seabed.

3.4.3 Field experiment No. 2

A total of 15 hauls were completed during the experiment, including 6 hauls for the experimental trawl vs. 9 hauls for the conventional trawl. Due to circumstances that included poor weather, vessel breakdowns, gear mensuration malfunctions, and lower than expected catch at the beginning of trials; comparative fishing was not attempted, and these data were considered as a preliminary assessment of how each trawl performed in terms of catching redfish and avoiding bycatch. Tows could not be paired for comparison and any day and nights effects could not be delineated. Clearance was only measured for the final two tows due to an equipment malfunction. For these tows, the trawl averaged 1.0 m (SD=0.2) off of the seabed. The mean warp length was 791.0 m (range: 731.5 to 890.6 m). Two different warp length ranges were tested, hauls 1-10 were shorter (758.5 m mean, range 731.5-789.9 m), however, to match how surrounding vessels in the fishery were fishing at the time, and with the goal to match higher catch totals, warp lengths were increased for hauls 11-15 to a mean of 849.3 m, and range of 823.0-890.6 m. For the shorter warp length range, the average haul duration was 93.2 min (range: 55 to 148 min), the mean tow speed was 2.5 kt (range: 2.3 to 2.7 kt), the mean door spread was 61.1 m (range: 58.7 to 62.8 m), the mean depth of the fishing ground was 341.0 m (range: 330 to 354.7 m), and the average RPM (engine revolution per minute) was 1405.6 (range: 1356 to 1459). For the longer warp length range, the average haul duration was 91.6 min (range: 55 to 125 min), the mean tow speed was 2.4 kt (range: 2.3 to 2.5 kt), the mean door spread was 60.7 m (range: 57.4 to 65.7), the mean depth of the fishing ground was 350.7 m (range: 334.6 to 361.1 m), and the RPM was 1441.8 on average (range: 1419.5 to 1464). The mean bottom water temperature was 7.3° C (SD = 0.1).

For redfish, a total of 26,341.0 kg (nine tows) was estimated to be caught during the experiment, including 3,347.5 kg (six tows) by the experimental trawl and 22,993.5 kg by the conventional trawl. The total catch of redfish caught during the shorter warp length tows was 1,129.5 kg estimated for the experimental trawl versus 4,866.2 kg estimated for the conventional trawl. The total catch of redfish caught during the longer warp length tows was 2,218.1 kg estimated for the experimental trawl versus 18,143.7 kg estimated for the conventional trawl.

A total of 15 bycatch species were observed during the experiment. Of those bycatch species, four species had a capture total above 50 kg, including Atlantic halibut (340.0 kg conventional trawl; 13.0 kg semi-pelagic trawl), white hake (175.2 kg conventional trawl; 13.0 kg semi-pelagic trawl), Atlantic cod (110.5 kg conventional trawl; 8.0 kg semi-pelagic trawl), and thorny skate (*Amblyraja radiata*; 75.0 kg conventional trawl; 3.0 kg semi-pelagic trawl). The total catch of Atlantic halibut, white hake, Atlantic cod, and thorny skate caught during the shorter warp length tows were 31, 68.2, 40.5, and 17 kg, respectively. The total capture of these bycatch species increased during the longer warp length tows (i.e., 322 kg, 132 kg, 78 kg, and 61 kg estimated for Atlantic halibut, white hake, Atlantic cod, and thorny skate, respectively).

3.5 Discussion

This study developed a functional semi-pelagic trawl via simple modifications added to the warps and bridles of a typical groundfish trawl. The flume tank and field experiments provide evidence for the engineering effectiveness of the rigging to lift the trawl from the seabed while maintaining the doors on bottom, providing potential for reduced seabed impacts and potential bycatch reduction. Preliminary fishing showed that the semi-pelagic trawl can catch commercial amounts of redfish, though further work is required to fully understand how best to use the gear. The operation of the trawl, including handling and fishing, were very similar to the conventional trawl and a few more modifications could make this fishing process almost identical (i.e., splicing the bridles to the warps). The fishing experiment, though small and preliminary, shows promise for this gear as commercial catch rates of redfish were observed and some bycatch species may be captured at reduced rates. Importantly, this gear could provide a reasonable solution for fishers switching from targeting shrimp to the future redfish fishery in the GSL. Such a change reduces the economic impact of transitioning from a bottom trawl to a pelagic/midwater trawl.

How groundfish respond to the fishing gear can influence the capture outcome, as shown in previous studies (Kim and Wardle, 2003; He et al., 2008; Winger et al., 2010; Brinkhof et al., 2017). Fish responses at the trawl mouth can be related to their vertical distribution, reaction tendency, and swimming behavior, which can lead fish to enter or escape the trawl different ways (Main and Sangster, 1981; Godø and Walsh, 1992; Kim and Wardle, 2003). Similarly, Redfish were observed in the current study distributed at different heights at the center of the groundgear, separating into different positions above (73.1%) and under the fishing line (26.9%). These different heights altered the escape rates of redfish. Our study estimated a little over half of redfish observed on the bottom escaped, whereas most redfish observed above the fishing line entered the trawl. This implies that as a poor swimmer, redfish may seek escape openings under the groundgear for escaping rather than rising above the fishing line, and becoming available for capture. Of note, 26.6% of redfish observed above the fishing line escaped. These escapees may be explained by the escape behavior that redfish were observed at heights close to the fishing line, particularly small fish, likely searching for escape openings under the fishing line (Engås et al., 1988).

Our analysis showed that the swimming behavior of redfish directly influences the capture outcome. In terms of swimming direction in relation to the tow direction, many redfish that were swimming against the oncoming trawl tend to enter the trawl; these tended to enter the trawl rather than escape under the fishing line. These fish were observed to maintain their swimming direction from the first direction to entering the trawl. This behavior is similar to the optomotor response of haddock near the groundgear, described by Kim and Wardle (2003). Contrary, most redfish that were swimming in the towing direction (i.e. swimming with) and passively swimming escaped under the fishing line. Many of these fish were observed to swim less than the tow speed, allowing the trawl to pass over; some showed erratic swimming and therefore escaping.

In addition to swimming behavior, a large proportion of redfish was swimming up above the fishing line, resulting in most fish being caught. This swimming behavior is similar to Main and Sangster (1981) and Godø and Walsh (1992), who found that roundfish remained close to the bottom but rose above the fishing line when they came into contact with the footgear. Inversely, a proportion of fish was observed to swim down, leading to the highest escape rate relative to other swimming behaviors. These fish were observed just a bit above the fishing line, oriented toward the approaching trawl, and tended to swim down in order to seek the spaces under the footgear for escape.

Previous observations revealed that contacting the groundgear can lead to fish and benthic organisms becoming available for capture (Nguyen et al., 2014; Bayse et al., 2016b). However, this study found over half of the individual redfish were observed to enter the trawl without groundgear contact even when the trawl was on or off the seabed (Table 3.5 and 3.6). These fish were first detected on the bottom and rose above the fishing line when approaching the upcoming trawl's groundgear as discussed above. This behavior is similar to the entry behavior of roundfish, observed by Main and Sangster (1981) and Thomsen (1993). There was a considerable proportion of redfish that had contact with the groundgear and escaped through spaces between rollers. These escaping fish may erratically respond to the groundgear in a short distance, suddenly dart away by using a kick and glide gait, or run over by the groundgear for escape (Kim and Wardle, 2003).

The fate of escapees from capture potentially influences populations (Main and Sangster, 1983; Ingólfsson and Jørgensen, 2006; Ingólfsson et al., 2007). Observations have shown that the survival capacity of escaping fish under the trawl was related to their groundgear contact (Ingólfsson and Jørgensen, 2006; Nguyen et al., 2014; Bayse et al., 2016). The authors suggested that contacting the groundgear induced more injured fish than did no contact, potentially resulting in the mortality of fish when escaping under the fishing line. In the current study when the trawl was off the seabed, redfish that escaped under the fishing line typically did not have contact with the groundgear. While redfish mortality by escaping under the trawl was not quantified, reducing groundgear contact by using a semi-pelagic trawl might reduce injuries, physiological stress, and potential predation risk, leading to a reduction in redfish mortality. This would be beneficial for upcoming redfish fisheries in the GSL with regard to avoiding declines in population due to escape mortality.

The second field experiment provided preliminary results on targeting redfish between tested trawls. These results should be interpreted with caution. Only 15 tows were tested and we were unable to have any sort of balanced design (different warp-to-depth ratios, day vs. night, alternating of treatments). Catch rates were lower than expected for the first 9 tows, and after 4 tows the trawl was adjusted to fish on the bottom, entirely removing the semi-pelagic rigging. An increase in warp (and warp-to-depth ratio) directly led to catch rates at least doubling. Unfortunately, only 5 tows were fished like this, and only 2 with the semi-pelagic setup. At this point, the vessel broke down and ended further investigation. This is not enough to directly compare these gears by any means, however, it does allow a proof of concept that the semi-pelagic trawl is at least capable of capturing commercial quantities of redfish (i.e. the highest catch of 1814.4 kg at Tow 15). What drove the improved catch rates is not specifically known; unfortunately, the gear mensuration equipment was not functioning for the first 13 tows only allowing an investigation into the last tows. Likely, the increase in warp-to-depth ratio increased the trawl opening horizontally while reducing the headline height, allowing for a more efficient trawling scenario. However, the collected data do not necessarily point to this conclusion, which is difficult when only evaluating 2 tows, but this assumption is based on experience and the literature (Fujimori et al., 2005).

The behavioral differences of fish at the trawl mouth have been utilized to modify the gear regarding increasing vertical distance between the fishing line and seabed to separate flatfish and other species related to the seabed from the catch (Main and Sangster, 1985; Engås et al., 1998; Krag et al., 2010). Flatfish response to an oncoming trawl has been observed either resting close to the seabed and passed over by the groundgear (Walsh and Hickey, 1993) or rising to enter the trawl within 1 m from the seabed (Main and Sangster, 1981; Bublitz, 1996; Underwood et al., 2015). Thus, it is not surprising that there were few captures of flatfish and skate species when the trawl was off the seabed at 1.0 m on average. The semi-pelagic trawl relative to the conventional trawl captured fewer Atlantic cod and white hake. This could be explained by the behavioral tendency of fish at the trawl mouth. When aggregating at the center of the trawl mouth, large individuals with greater swimming capacity tend to rise from the seabed and enter the trawl (Main and Sangster, 1981; Thomsen, 1993; Ingólfsson and Jørgensen, 2006; Krag et al., 2010). Some of these fish may reach the heights available to be captured by the semi-pelagic trawl.

A semi-pelagic trawl was evaluated for use in the GSL redfish fishery to target redfish off of the seabed. This approach shows promise as fishers transition from targeting Northern shrimp to redfish. Here, we have documented steps to take to modify a traditional groundfish trawl to a semi-pelagic trawl. Potential unintended benefits of using this gear include reducing negative seabed impacts. Doors would still cause damage, however having the groundgear off the seabed would greatly reduce the bottom impact when compared to a traditional trawl. Logically, demersal bycatch could be reduced since the gear is off of the seabed. Results here are too preliminary to have much confidence, however large differences were observed between when the trawl was on or off the seabed, with important bycatch species such as Atlantic halibut, white hake, and Atlantic cod having very low catches when the trawl was fished semi-pelagically, which agrees with results from DFO (DFO, 2020). Pelagic trawling traditionally was most successful when redfish were highly aggregated (Duplisea, 2018). Video analyses here, though only describing a small portion of the trawl mouth area, suggest that redfish can avoid capture by going under the trawl, and perhaps at times of day/season, semi-pelagic trawling could be more or less effective than bottom trawling. Future research should investigate this further. Importantly, here we show that this fishing technique can capture a commercial quantity of redfish, which was indicated as a necessary step in gear innovation by the Ocean Frontier Institute's Northwest Atlantic Redfish Symposium (Cadigan et al., 2022).

3.6 Acknowledgements

We would like to thank Captains Rodney and Les Dredge and the crew of the F/V *Lisa M* for their assistance. Additionally, we would like to thank Mark Santos (Fisheries and Marine Institute), Francis Parrot (Notus Electronics), Morgan Snook (Hampidjan Canada Ltd.), and David Kelly (Hampidjan Canada Ltd.) for their kind help during the project. We would also like to thank our funders, the Canadian Centre for Fisheries Innovation (CCFI); the Government of Newfoundland and Labrador through the Department of Industry, Energy and Technology; The Canada First Research Excellence Fund (CFREF) through the Ocean Frontier Institute (Module H); and the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant.

3.7 References

Akaike, H., 1974. A new look at the statistical model identification 19, 716–723. https://doi.org/10.1109/TAC.1974.1100705

Araya-Schmidt, T., Legge, G., Santos, M., Bayse, S., Winger, P., Adelowo, S., 2021. Flume tank testing of an innovative footgear technology using simulated seabeds. Journal of Ocean Technology 16(2), 64-84.

Atkinson, D.B., 1989. Diel movements of beaked redfish and the implications of these for stratified random bottom trawl estimates of biomass and abundance. North American Journal of Fisheries Management 9, 163–170.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software 67. https://doi.org/10.18637/jss.v067.i01

Bayse, S.M., Herrmann, B., Lenoir, H., Depestele, J., Polet, H., Vanderperren, E., Verschueren, B., 2016a. Could a T90 mesh codend improve selectivity in the Belgian beam trawl fishery? Fisheries Research 174, 201–209. https://doi.org/10.1016/j.fishres.2015.10.012

Bayse, S.M., Pol, M.V., He, P., 2016b. Fish and squid behavior at the mouth of a drop-chain trawl: factors contributing to capture or escape. ICES Journal of Marine Science 73, 1545–1556. https://doi.org/10.1093/icesjms/fsw007

Beamish, F.W.H., 1966. Vertical migration by demersal fish in the Northwest Atlantic. Journal of the Fisheries Research Board of Canada 23, 109–139. https://doi.org/10.1139/f66-009

Bolker, B., R Development Core Team, 2020. bbmle: Tools for General Maximum Likelihood Estimation.

Brinkhof, J., Larsen, R.B., Herrmann, B., Grimaldo, E., 2017. Improving catch efficiency by changing ground gear design: Case study of Northeast Atlantic cod (*Gadus morhua*) in the Barents Sea bottom trawl fishery. Fisheries Research 186, 269–282. https://doi.org/10.1016/j.fishres.2016.10.008

Bublitz, C.G., 1996. Quantitative evaluation of flatfish behavior during capture by trawl gear. Fisheries Research 25, 293–304. https://doi.org/10.1016/0165-7836(95)00431-9

Cadigan, N.G., Duplisea, D.E., Senay, C., Parent, G.J., Winger, P.D., Linton, B., Kristinsson, K., 2022. Northwest Atlantic redfish science priorities for managing an enigmatic species complex. Canadian Journal of Fisheries and Aquatic Sciences 79, 1572–1589. https://doi.org/10.1139/cjfas-2021-0266

Calcagno, V., de Mazancourt, C., 2010. glmulti: An R Package for Easy Automated Model Selection with (Generalized) Linear Models. Journal of Statistical Software 34, 1–29. https://doi.org/10.18637/jss.v034.i12

Casey, J.M., Myers, R.A., 1998. Diel variation in trawl catchability: is it as clear as day and night? Canadian Journal of Fisheries and Aquatic Sciences 55, 2329–2340.

Cheng, Z., Winger, P.D., Bayse, S.M., Kebede, G.E., DeLouche, H., Einarsson, H.A., Pol, M.V., Kelly, D., Walsh, S.J., 2020. Out with the old and in with the new: T90 codends improve size selectivity in the Canadian redfish (*Sebastes mentella*) trawl fishery. Canadian

Journal of Fisheries and Aquatic Sciences 77, 1711–1720. https://doi.org/10.1139/cjfas-2020-0063

Cheng, Z., Winger, P.D., Bayse, S.M., Kelly, D., 2022. Hydrodynamic performance of full-scale T0 and T90 codends with and without a codend cover. Journal of Marine Science and Engineering 10, 440. https://doi.org/10.3390/jmse10030440

Dean-Simmons, B., 2021. Atlantic Canada fishing industry prepping for redfish revival. Saltwire. Retrieved from https://www.saltwire.com/atlantic-canada/business/atlantic-canada-fishing-industry-prepping-for-redfish-revival-100579736/. Accessed March 1, 2023.

DFO, 2022. Assessment of Northern Shrimp stocks in the Estuary and Gulf of St. Lawrence in 2021. Canadian Science Advisory Secretariat Science Advisory Report 2022/006.

DFO, 2021. Impact of an expanding Redfish (*Sebastes spp.*) fishery on southern Gulf of St. Lawrence White Hake (*Urophycis tenuis*). DFO Canadian Science Advisory Secretariat Science Advisory Report 2021/033, 25.

DFO, 2020. Redfish (*Sebastes mentella* and *S. fasciatus*) stocks assessment in Unit 1 and 2 in 2019. DFO Canadian Science Advisory Secretariat Science Advisory Report 019.

Dickson, W., 1959. The use of model nets as a method of developing trawling gear. In: Modern Fishing Gear of the World, p. 166-174.

Duplisea, D.E., 2018. Fishermen's historical knowledge leads to a re-evaluation of redfish catch. Marine and Coastal Fisheries 10, 3–11. https://doi.org/10.1002/mcf2.10006

Engås, A., Jacobsen, J.A., Soldal, A.V., 1988. Catch comparison between rockhoppers and bobbins ground gear on the Norwegian bottom sampling trawl, In: ICES C.M. 1988/B:

31. Presented at the Fish Capture Committee, International Council for the Exploration of the Sea, p. 12.

Engås, A., Jørgensen, T., West, C.W., 1998. A species-selective trawl for demersal gadoid fisheries. ICES Journal of Marine Science 55, 835–845. https://doi.org/10.1006/jmsc.1998.0352

Fonteyne, R., 2005. Protocol for the use of an objective mesh gauge for scientific purposes (ICES Cooperative Research No. 279).

Fox, J., Weisberg, S., Adler, D., Bates, D., Baud-Bovy, G., Ellison, S., Firth, D., Friendly, M., Gorjanc, G., Graves, S., Heiberger, R., 2012. Package 'car,' 16. Foundation for Statistical Computing, Vienna.

Fridman, A.L., 1973. Theory and design of commercial fishing gear. Israel Program for Scientific Translations, Jerusalem 489.

Fujimori, Y., Chiba, K., Oshima, T., Miyashita, K., Honda, S., 2005. The influence of warp length on trawl dimension and catch of walleye pollock *Theragra chalcogramma* in a bottom trawl survey. Fisheries Science 71. https://doi.org/10.1111/j.1444-2906.2005.01023.x

Galbraith, P.S., Chassé, J., Dumas, J., Shaw, J.-L., Caverhill, C., Lefaivre, D., Lafleur, C., 2022. Physical oceanographic conditions in the Gulf of St. Lawrence during 2021, Research Document 2022/034. Canadian Science Advisory Secretariat (CSAS), Ottawa ON.

Garner, J., 1978. Pelagic and semi-pelagic trawling gear, In: Fishing News Books. England, p. 59.

Gauthier, S., Rose, G.A., 2005. Diel vertical migration and shoaling heterogeneity in Atlantic redfish: effects on acoustic and bottom-trawl surveys. ICES Journal of Marine Science 62, 75–85. https://doi.org/10.1016/j.icesjms.2004.10.001

Gauthier, S., Rose, G.A., 2002. Acoustic observation of diel vertical migration and shoaling behavior in Atlantic redfishes. Journal of Fish Biology 61, 1135–1153. https://doi.org/10.1111/j.1095-8649.2002.tb02461.x

Godø, O.R., Walsh, S.J., 1992. Escapement of fish during bottom trawl sampling - implications for resource assessment. Fisheries Research 13, 281–292.

Gomes, M.C., Haedrich, R.L., Rice, J.C., 1992. Biogeography of groundfish assemblages on the Grand Bank. Journal of Northwest Atlantic Fishery Science 14, 13–27. https://doi.org/10.2960/j.v14.a1

Hartig, F., 2021. DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models.

He, P., Chopin, F., Suuronen, P., Ferro, R.S.T., Lansley, J., 2021. Classification and illustrated definition of fishing gears, FAO Fisheries and Aquaculture Technical Paper. FAO, Rome. 94p. https://doi.org/10.4060/cb4966en

He, P., Smith, T., Bouchard, C., 2008. Fish behavior and species separation for the Gulf of Maine multispecies trawls. The Journal of Ocean Technology 3(2), 60-77.

He, P. (Ed.), Winger, P., 2010. Effect of trawling on the seabed and mitigation measures to reduce impact, In: Behavior of Marine Fishes: Capture Processes and Conservation Challenges. pp. 295–314. https://doi.org/10.1002/9780813810966.ch12

Herrmann, B., Priour, D., Krag, L.A., 2007. Simulation-based study of the combined effect on cod-end size selection of turning meshes by 90° and reducing the number of meshes in the circumference for round fish. Fisheries Research 84, 222–232. https://doi.org/10.1016/j.fishres.2006.10.020

Ingólfsson, Ó.A., Jørgensen, T., 2006. Escapement of gadoid fish beneath a commercial bottom trawl: Relevance to the overall trawl selectivity. Fisheries Research 79, 303–312. https://doi.org/10.1016/j.fishres.2005.12.017

Ingólfsson, Ó.A., Soldal, A.V., Huse, I., Breen, M., 2007. Escape mortality of cod, saithe, and haddock in a Barents Sea trawl fishery. ICES Journal of Marine Science 64, 1836–1844. https://doi.org/10.1093/icesjms/fsm150

Kim, Y.-H., Wardle, C.S., 2003. Optomotor response and erratic response: quantitative analysis of fish reaction to towed fishing gears. Fisheries Research 60, 455–470. https://doi.org/10.1016/S0165-7836(02)00114-5

Koslow, J., Boehlert, G.W., Gordon, J.D.M., Haedrich, R.L., Lorance, P., Parin, N., 2000. Continental slope and deep-sea fisheries: implications for a fragile ecosystem. ICES Journal of Marine Science 57, 548–557. https://doi.org/10.1006/jmsc.2000.0722

Krag, L.A., Holst, R., Madsen, N., Hansen, K., Frandsen, R.P., 2010. Selective haddock (*Melanogrammus aeglefinus*) trawling: Avoiding cod (*Gadus morhua*) bycatch. Fisheries Research 101, 20–26. https://doi.org/10.1016/j.fishres.2009.09.001

Main, J., Sangster, G., 1981. A study of the fish capture process in a bottom trawl by direct observation from a towed underwater vehicle. Scottish Fisheries Research Report 23, 1–23.

Main, J., Sangster, G.I., 1985. Report on the direct observation experiments with the chalut 28.90/37.1m JCB trawl during July 3–23, 1984. ICES CM 1985/B: 9/Ref K 19.

Main, J., Sangster, G.I., 1983. Fish reactions to trawl gear: a study comparing light and heavy ground gear, Scottish fisheries research report. Dept. of Agriculture and Fisheries for Scotland, Aberdeen.

Miri, C., Simpson, M., 2006. Update of the Status of White Hake (*Urophycis tenuis,* Mitchill 1815) in NAFO Divisions 3L, 3N, 3O, and Subdivision 3Ps.

Montgomerie, M., 2015. Basic fishing methods. A comprehensive guide to commercial fishing methods. SEAFISH, 103p.

Nguyen, T.X., Winger, P.D., Legge, G., Dawe, E.G., Mullowney, D.R., 2014. Underwater observations of the behavior of snow crab (*Chionoecetes opilio*) encountering a shrimp trawl off northeast Newfoundland. Fisheries Research 156, 9–13. https://doi.org/10.1016/j.fishres.2014.04.013

Nguyen, V.Y., Bayse, S.M., Cheng, Z., Winger, P.D., DeLouche, H., Kebede, G.E., Legge, G., 2023. Developing a full-scale shaking codend to reduce the capture of small fish. PLoS ONE 18, e0280751. https://doi.org/10.1371/journal.pone.0280751

Pol, M., Eayrs, S., 2021. Behavior in a bottom trawl: moving forward to limit catches of Atlantic cod. ICES Journal of Marine Science fsab106. https://doi.org/10.1093/icesjms/fsab106

Pol, M.V., 2016. Impact of codend mesh sizes on selectivity and retention of Acadian redfish *Sebastes fasciatus* in the Gulf of Maine trawl fishery. Fisheries Research 184, 54-63.

Ryer, C.H., 2008. A review of flatfish behavior relative to trawls. Fisheries Research 90, 138–146. https://doi.org/10.1016/j.fishres.2007.10.005

Schwarz, G., 1978. Estimating the dimension of a model. The Annals of Statistics 6, 461–464.

The Ocean Frontier Institute Northwest Atlantic Redfish Symposium, 2018. Fisheries and Marine Institute, Memorial University of Newfoundland, St. John's, NL, CA, Nov. 15-16, 2018.

Thomsen, B., 1993. Selective flatfish trawling. ICES Marine Science Symposia 196, 161–164.

Tokaç, A., Herrmann, B., Aydın, C., Kaykaç, H., Ünlüler, A., Gökçe, G., 2014. Predictive models and comparison of the selectivity of standard (T0) and turned mesh (T90) codends for three species in the Eastern Mediterranean. Fisheries Research 150, 76–88. https://doi.org/10.1016/j.fishres.2013.10.015

Underwood, M.J., Winger, P.D., Fernö, A., Engås, A., 2015. Behavior-dependent selectivity of yellowtail flounder (*Limanda ferruginea*) in the mouth of a commercial bottom trawl. Fishery Bulletin 113, 430–441. https://doi.org/10.7755/FB.113.4.6

Walsh, S.J., Hickey, W.M., 1993. Behavioral reactions of demersal fish to bottom trawls at various light conditions. ICES Marine Science Symposia 196, 68–76.

Winger, P., Eayrs, S., Glass, C., 2010. Fish behavior near bottom trawls, In He, P. (Ed.): Behavior of Marine Fishes: Capture Processes and Conservation Challenges. pp. 65–103. https://doi.org/10.1002/9780813810966.ch4

Winger, P.D., DeLouche, H., Legge, G., 2006. Designing and testing new fishing gears: The value of a flume tank. Marine Technology Society Journal 40, 44–49. https://doi.org/10.4031/002533206787353240

3.8 Tables

Table 3.1. The geometry of a scaled semi-pelagic trawl comparing rigging scenarios tested in a flume tank.

Rigging scenario	Description	Upper bridle length (m)	Tow speed (kt)	Door spread (m)	Headline opening (m)	Vertical opening (m)	Seabed clearance (m)
1	Connect the top bridles to a 30.5 m (1.27 cm Ø) to the warp forward of door	85.4	2.5	67.8	8.0	7.2	0.8
			2.8	67.4	7.3	5.7	1.6
			3.0	67.1	6.9	5.0	1.9
			3.2	67.4	6.6	4.3	2.3
2	Connect the top bridles to a 20.42 m to the warp forward of door	75.32	2.8	66.4	7.0	6.4	0.6
3	Connect the top bridles to a 15.24 m to a warp forward of door	70.14	2.8	66.3	6.7	6.4	0.3
4	Warp-to-depth (ratio between the warp length and depth) 2.6:1	70.14	2.8	65.0	7.3	6.3	1.0
5	Warp-to-depth (ratio between the warp length and depth) 6.9:1	70.14	2.8	66.4	6.3	6.3	0.0

Table 3.2. Detailed description of each variable used to describe the behavioral sequence of redfish at the trawl mouth of semi-pelagic trawl.

Redfish variables	Categories	Description
Position (A/B)	Above	Fish appear above the fishing line
	Below	Fish appear under the fishing line
Swimming behavior 1	Swimming with (With)	Fish swim in the trawling direction
	Swimming against (Against)	Fish swim opposite to the direction of trawling
	Passive swimming (PS)	Fish drifted into the trawl or passed over by the groundgear
Swimming behavior 2	Swimming up (Up)	Fish first detected under the fishing line and rose up to enter the trawl

	Swimming down (Down)	Fish first detected above the fishing line on the top of the camera screen and swum down to escape under the footgear
	No change (NC)	Fish had no changes in their swimming direction in the vertical plane.
Orientation	Away	Head oriented away from the trawl
	Toward	Head oriented toward the trawl (codend)
	Left	Head oriented to the port
	Right	Head oriented to the starboard
Groundgear contact	Contact	Fish had contact with the groundgear
	No contact	Fish did not have contact with the groundgear
Time	Seconds	Period between the first detection and entering the trawl or escaping under the trawl
Trawl state	On-seabed	When the trawl is on-seabed
	Off-seabed	When the trawl is off-seabed
Period	Day	When fishing during the day-time
	Night	When fishing during the night-time

Table 3.3. Trawl system performance observed for each haul during field experiment No. 1.

Tow	Trawl state	Duration (min)	Warp length (m)	Door spread (m)	Headline height (m)	Vertical opening (m)	Seabed clearance (m)	Depth (m)	Tow speed (kt)	Warp to Depth Ratio
1	Off	145	571.5	63.3	14.3	11.2	3.1	265.4	2.5	2.2
2	Off	144	548.6	65.6	22.0	11.0	11.7	267.8	2.6	2.0
3	Off	116	548.6	64.1	13.1	11.2	1.9	258.7	2.5	2.1
4	Off	128	548.6	66.9	12.8	10.7	2.3	261.5	2.4	2.1
5	On	144	548.6	68.6	11.5	15.8	-	255.7	2.7	2.1
6	NA	177	548.6	-	-	-	-	-	2.2	-
7	Off	188	548.6	-	12.9	11.9	2.4	258.6	2.3	2.1
8	Off	175	548.6	-	16.4	11.7	2.8	257.4	2.4	2.1
9	Off	160	548.6	62.5	-	-	-	276.5	2.4	2.0
10	Off	182	548.6	61.9	17.5	11.0	8.2	283.6	2.5	1.9
11	Off	225	571.5	63.1	15.6	-	-	282.7	2.3	2.0
12	Off	168	594.4	66.4	16.5	-	-	288.6	2.6	2.1
13	On	197	594.4	66.0	12.4	-	-	278.2	2.4	2.1
14	Off	203	594.4	66.8	12.8	-	-	277.3	2.3	2.1
15	On	198	548.6	64.8	13.5	-	-	277.1	2.5	2.0

16	Off	187	548.6	61.8	14.4	12.9	1.8	304.1	2.3	1.8
17	Off	118	594.4	63.4	13.4	11.9	1.7	298.5	2.2	2.0
18	Off	165	640.1	68.3	12.2	12.1	1.1	308.9	2.5	2.1
19	Off	185	640.1	65.6	12.4	12.0	1.0	302.0	2.3	2.1
20	Off	189	640.1	63.6	14.4	11.8	2.9	300.7	2.2	2.1
21	Off	82	594.4	66.0	13.8	12.1	1.1	289.8	2.3	2.1
22	On	180	594.4	67.0	12.1	12.1	0.7	291.9	2.3	2.0
23	On	182	594.4	68.9	12.2	12.3	0.8	292.5	2.5	2.0
24	On	185	594.4	64.1	14.5	12.2	2.6	290.6	2.6	2.0
25	Off	113	594.4	65.7	11.9	12.1	0.5	293.6	2.2	2.0
26	Off	157	594.4	64.2	13.6	11.6	2.2	285.4	2.1	2.1
27	On	175	640.1	70.0	11.2	11.8	0.9	289.2	2.4	2.2
28	On	184	594.4	69.1	11.7	12.3	0.8	289.6	2.4	2.1

Table 3.4. Observed behavior of redfish at the trawl mouth in relation to capture outcome (enter the trawl or escape under the groundgear). A/B represents above/below, PS represents passive swimming, and NC represents no changes in their swimming direction in the vertical plane.

Variables	Observations	% Total	Capture	% Capture	Escape	% Escape
Position (A/B)						
Above	564	26.9	414	73.4	150	26.6
Below	1535	73.1	754	49.1	781	50.9
Swimming behavior 1						
With	461	22	103	22.3	358	77.7
Again	1307	62.3	940	71.9	367	28.1
PS	331	15.8	125	37.8	206	62.2
Swimming behavior 2						
Up	714	34.0	708	99.2	6	0.8
Down	130	6.2	7	5.4	123	94.6
NC	1255	59.8	453	36.1	802	63.9
Groundgear contact						
Contact	385	18.3	121	31.4	264	68.6
No contact	1714	81.7	1140	55.3	923	44.7
Trawl state						
On-seabed	1629	77.6	891	54.7	738	45.3
Off-seabed	470	22.4	277	58.9	193	41.1
Period						
Day	1311	62.5	732	55.8	579	44.2
Night	788	37.5	436	55.3	352	44.7

Table 3.5. Fish behavior when on-bottom trawling. A/B represents above/below, PS presents passive swimming, and NC presents no changes in their swimming direction in the vertical plane.

Variables	n	% Total	Capture	% Capture	Escape	% Escape
Position (A/B)						
Above	277	17.0	234	84.5	43	15.5
Below	1352	83.0	657	48.6	695	51.4
Orientation						
Toward	356	21.9	230	64.6	126	35.4
Away	597	36.6	363	60.8	234	39.2
Left	348	21.4	169	48.6	179	51.4
Right	328	20.1	129	39.3	199	60.7
Swimming behavior 1						
With	426	26.2	83	19.5	343	80.5
Again	994	61.0	756	76.1	238	23.9
PS	209	12.8	52	24.9	157	75.1
Swimming behavior 2						
NC	987	60.6	30	15.7	161	84.3
Up	614	37.7	608	99.0	6	1.0
Down	28	1.7	0	0.0	28	100.0
Groundgear contact						
Yes	354	16.9	111	31.4	243	68.6
No	1275	60.7	780	61.2	495	38.8
Period						
Day	1026	63.0	564	55.0	462	45.5
Night	603	37.0	327	54.2	276	45.8

Table 3.6. Fish behavior when off-bottom trawling. A/B represents above/below, PS represents passive swimming, and NC represents no changes in their swimming direction in the vertical plane.

Variables	n	% Total	Capture	% Capture	Escape	% Escape
Position (A/B)						

Above	287	61.1	180	62.7	107	37.3
Below	183	38.9	97	53.0	86	47.0
Orientation						
Toward	215	49.5	131	52.2	120	47.8
Away	120	27.6	89	74.2	31	25.8
Left	28	6.5	20	71.4	8	28.6
Right	71	16.4	37	52.1	34	47.9
Swimming behavior 1						
With	35	7.4	20	57.1	15	42.9
Against	313	66.6	184	58.8	129	41.2
PS	122	26.0	52	24.9	157	75.1
Swimming behavior 2						
NC	268	57.0	170	63.4	98	36.6
Up	100	21.3	100	100.0	0	0.0
Down	102	21.7	7	6.9	95	93.1
Groundgear contact						
Yes	31	6.6	10	32.3	21	67.7
No	439	93.4	267	60.8	172	39.2
Period						
Day	324	70.4	189	58.3	135	41.7
Night	146	29.6	88	60.3	58	39.7

Table 3.7. BICc values were estimated for two best models

Model	BIC	dBIC	df	weight
Capture outcome ~ Position + Swimming behavior 2 + (1 | Tow)	782.6	0.0	5	0.77
Capture outcome ~ Position + Swimming behavior 1 + Swimming behavior 2 + (1 | Tow)	785.0	2.4	7	0.23

Table 3.8. Observed behavior of escaping redfish at the trawl mouth. L/R stands for left/right, PS presents passive swimming.

Variables	n	% Total	Contact	% Contact	No contact	% No contact
Position (L/R)						
Left	336	63.2	104	31.0	232	69.0
Right	196	36.8	71	37.0	121	63.0
Orientation						
Left	77	14.5	40	52.0	37	48.0
Right	125	23.7	51	40.8	74	59.2
Toward	142	26.9	27	19.0	115	81.0
Away	184	34.8	57	31.0	127	69.0
Swimming behavior						
Against	79	15.0	39	49.4	40	50.6
With	117	22.2	65	55.6	52	44.4
Startle	41	7.7	28	68.3	13	31.7
PS	291	55.1	43	14.8	248	85.2
Turning						
Turn	193	36.6	114	59.1	79	40.9
No turn	335	63.4	61	18.2	274	81.8
Trawl state						
On-seabed	294	55.7	168	57.1	126	42.9
Off-seabed	234	44.3	7	3.0	227	97.0
Contact						
Contact	175	33.1	113	64.6	62	35.4
No contact	353	66.9	348	98.6	5	1.4

3.9 Figures

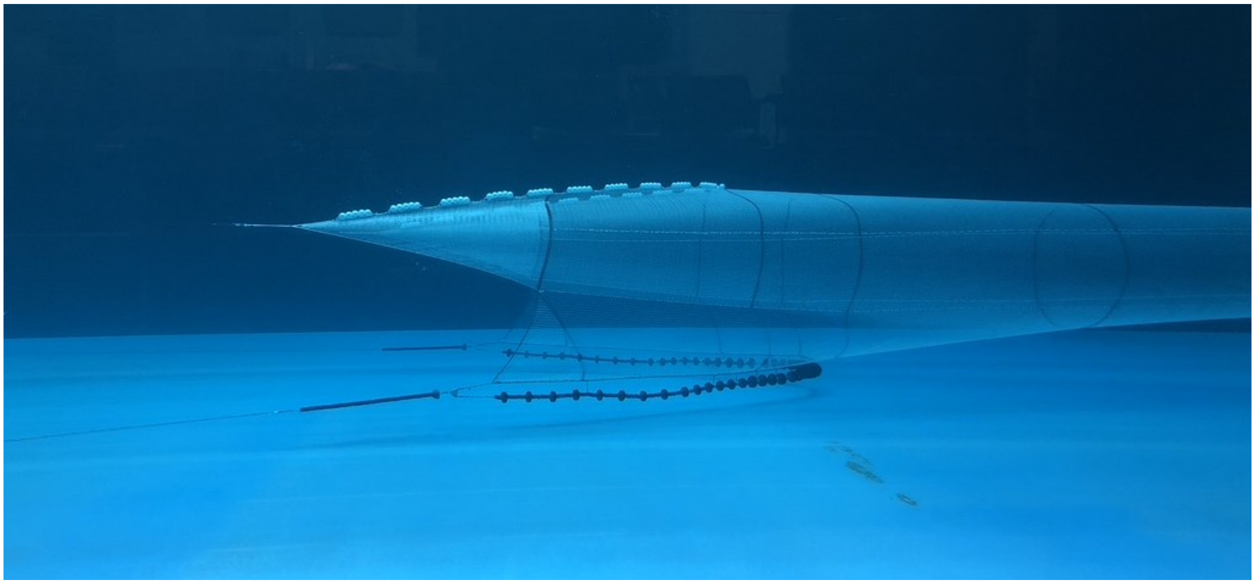


Figure 3.1. A 1:10 scale model was evaluated in the flume tank located at the Fisheries and Marine Institute of Memorial University of Newfoundland, Canada.

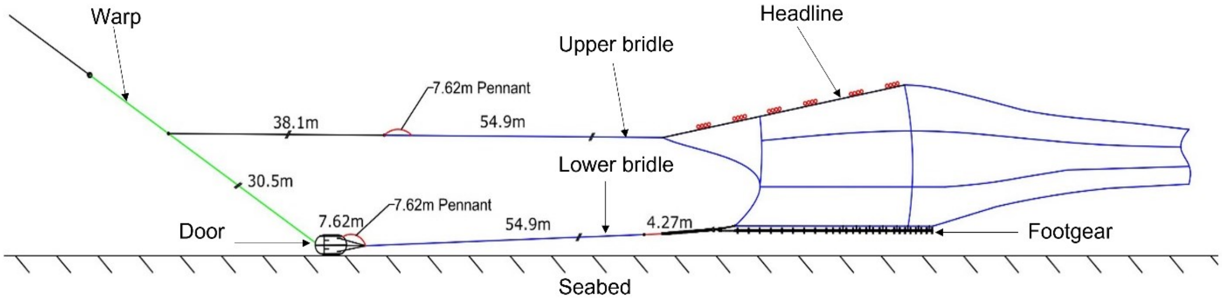


Figure 3.2. Side profile schematic of the semi-pelagic trawl system.

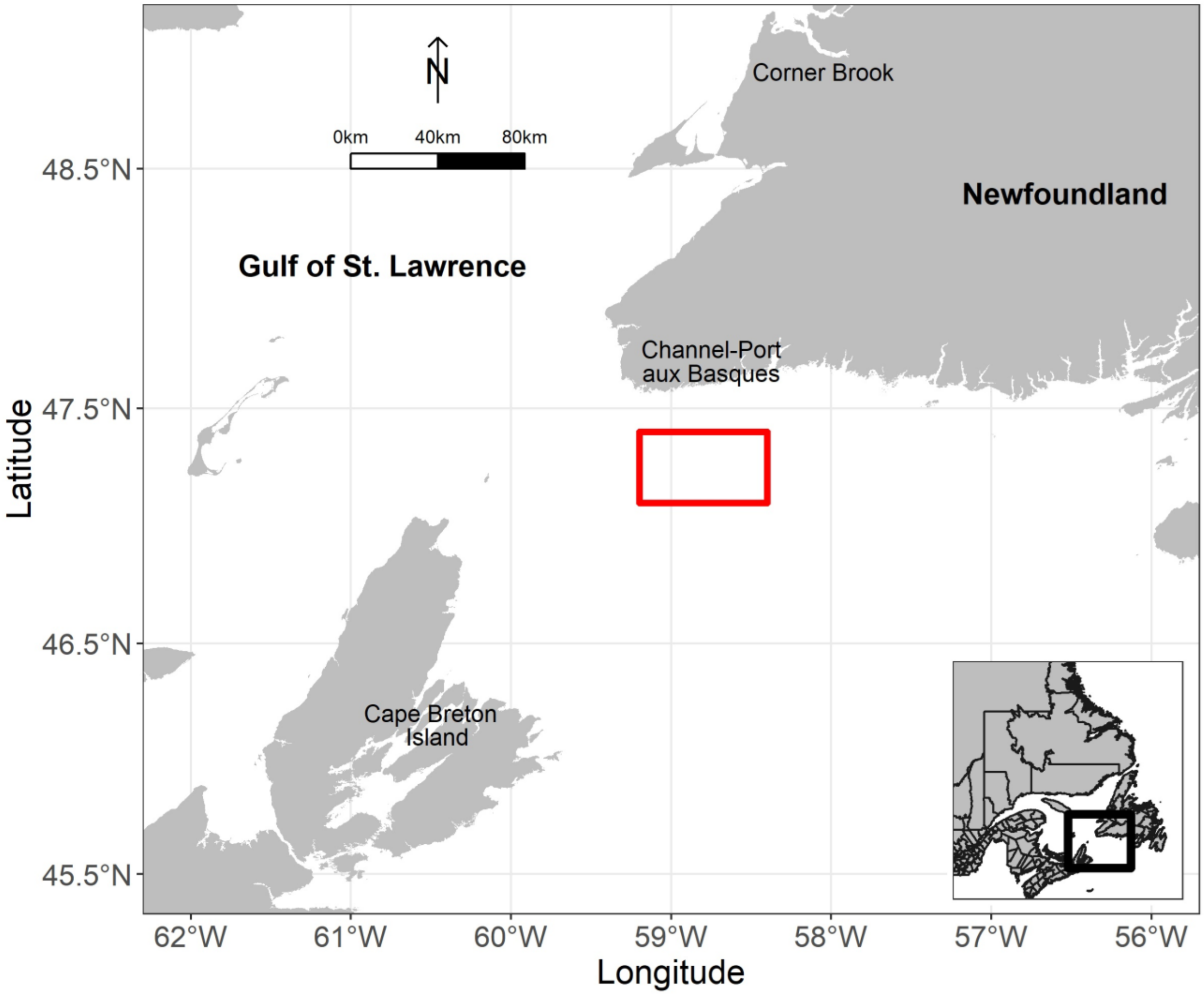


Figure 3.3. Location of field experiments (red rectangle) in the Gulf of St. Lawrence, Canada. Map is created using the data derived from global administrative areas (https://gadm.org/); GADM license.

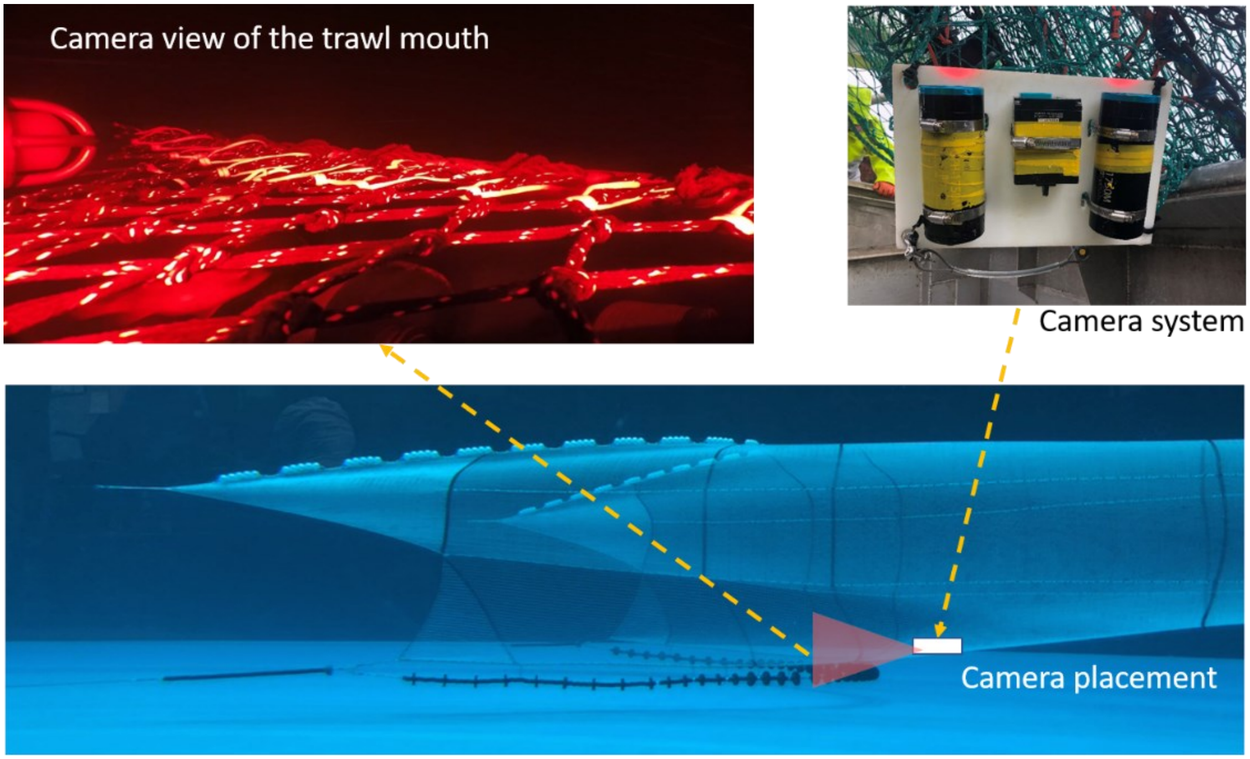


Figure 3.4. Camera placement and view at the trawl mouth. Top left: screen capture from video collected during sea trials, groundgear is in the lower center of the shot. Top right: camera system included a camera placed in the middle and two flashlights using red light. Bottom: illustration of semi-pelagic trawl; the red triangle is the area within the center of the trawl mouth observed by a camera.

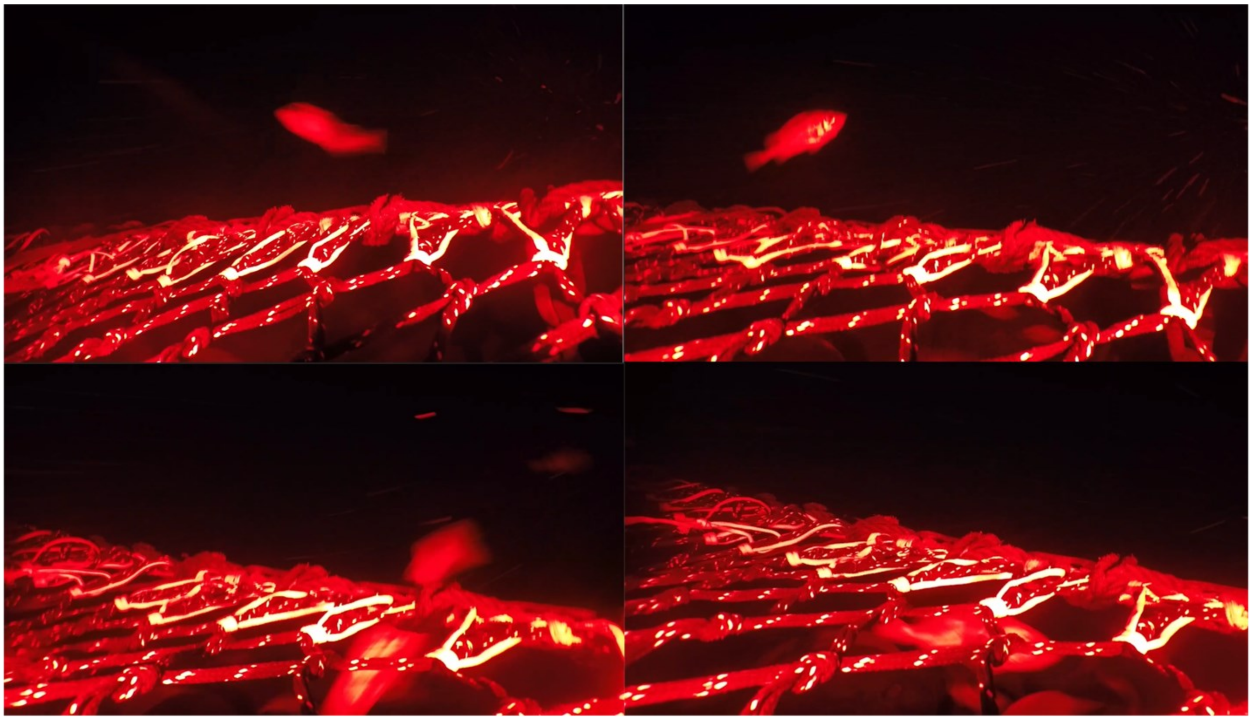


Figure 3.5. Screen capture of video frames illustrates redfish behavior at the center of trawl mouth. Top left illustrates redfish detected at the Above position, swimming against the trawl path and entering the trawl. Top right illustrates redfish detected at the Above position and swimming with the trawl path and allowing the groundgear to pass below. Bottom left illustrates redfish detected at the bottom position and swimming against the trawl path and escaping under the trawl. Bottom right illustrates redfish detected at the bottom position, turning 180^0 before contacting the groundgear.

Figure 3.6. Screen capture of video frames illustrates redfish behavior under the groundgear. Top left and right illustrate redfish laid on their side and were pressed by a roller. Bottom left illustrates redfish was swimming against the trawl and escaped between rollers. Bottom right illustrates redfish was swimming with the tow direction and allowing the groundgear to pass over.

CHAPTER 4. Quantifying fish escape under a bottom trawl

4.1 Abstract

In this study, we investigated the length-dependent escape of groundfish underneath a commercial bottom trawl. Escaped fish were captured in three collecting bags (center (bosom) and wings (port and starboard)) mounted underneath the fishing line and behind the rockhopper footgear and compared to fish that were captured in the codend. Generally, how fish escaped under the trawl was often species-specific and differed according to size. For roundfish, length-dependent escape was pronounced for Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), and blue ling (*Molva dypterygia*) with the proportion of escapes decreasing as fish length increased. However, saithe (*Pollachius virens*) showed a limited length-based effect and redfish (*Sebastes* spp.) none. For flatfish, the escape proportion of American plaice (*Hippoglossoides platessoides*) and dab (*Limanda limanda*) decreased as fish length increased. However, European plaice (*Pleuronectes platessa*) had a very small length effect. Monkfish (*Lophius piscatorius*) escape decreased with size. However, monkfish retention probability remained less than 30% at the largest lengths observed. Differences in escape proportion between day and night were found for Atlantic cod, haddock, and dab, but not for other species. Small Atlantic cod and haddock escaped more often at night, and mid-sized dab (between 18 and 30 cm) escaped more often during the day. Results show that overall trawl selectivity is strongly affected at the trawl mouth, particularly for small fish of specific species.

4.2 Introduction

The use of rockhopper footgear in trawl fisheries has been shown to improve the effectiveness of commercial trawls in terms of improved catch rates and reduced trawl damage (Main and Sangster, 1985; Engås and Godø, 1989; Walsh, 1992). Relative to the traditional steel bobbin, the rockhopper is structured using large and dense rubber discs, which are threaded onto a chain to form the footgear (Engås and Godø, 1989; Ingólfsson and Jørgensen, 2006). By using larger discs, rockhopper footgear can reduce the damage to the fishing line and netting panels of the lower wings and belly in comparison with other footgear (Engås et al., 1988; Ingólfsson and Jørgensen, 2006; Larsen et al., 2018). Additionally, the use of rockhopper footgear allows the trawl to fish on rougher bottoms and catch fish close to the seabed more efficiently (Main and Sangster, 1985; Engås and Godø, 1989). This is presumably due to increased contact of the footgear to the seabed.

Icelandic groundfish fisheries have utilized stern trawlers using a large bottom trawl equipped with rockhopper footgear to capture mixed-species, including roundfish (Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), redfish (*Sebastes* spp.), and saithe (*Pollachius virens*), Greenland halibut (*Reinhardtius hippoglossoides*), and other flatfish. Groundfish fisheries play the most important role in Icelandic fisheries, contributing 75-80% of the total catch value (Arnason, 1996; Halliday and Pinhorn, 1996; Nielsen et al., 2018). However, capturing small fish in the catch is the greatest concern for this fishery (Pálsson, 2003 Woods et al., 2015). Many regulatory actions have focused on increasing the mesh size of the trawl codend and minimum reference length (MRL) for each species (Halliday and Pinhorn, 1996; Thorsteinsson, 1980). Nevertheless, mixed-species that are retained in the trawl codend have different body shapes, making size selectivity designs difficult. This has been the most important reason for high catch rates of bycatch in the capture of Icelandic groundfish fisheries, challenging Icelandic fisheries managers and fishers (Halliday and Pinhorn, 1996; Woods et al., 2015). In this case, developing trawl selectivity should take place at earlier stages of the capture process (i.e., trawl mouth) to increase the escape of small fish based on behavioral differences of fish according to size (Walsh, 1992; Winger et al., 2010).

The herding effect of the trawl aggregates fish in the trawl mouth that swim at equal to or a greater speed than advancing sweeps (Winger et al., 2010). In the front of the trawl mouth, fish alter their course and swim opposite the towing direction (Winger et al., 2010). These fish responses were observed to be species-specific. Roundfish, such as Atlantic cod, haddock, and saithe with greater swimming capacity, maintained station with advancing trawl components for a long period, known as an optomotor response (Kim and Wardle, 2003). In comparison with roundfish, flatfish were characterized by low swimming capacity and swam over a short period of less than 1.0 min in response to the upcoming trawl (Main and Sangster, 1981; Godø, 1994; Ryer, 2008), though longer times have been observed for some larger-sized species (Bayse et al., 2016). These behavioral patterns can be driven by varying light conditions. Several underwater observations have suggested that the optomotor response dominated during high light conditions, often resulting in fish swimming to keep a safe distance in front of the trawl components in the trawl mouth (Kim and Wardle, 1998; Winger et al., 2010). By contrast, in dark conditions, fish erratically respond to the approaching gear, represented by a short reaction distance, swimming in different directions, and colliding with gear components and other fish (Glass and Wardle, 1989; Walsh and Hickey, 1993).

Differences in fish response to the herding effect of the trawl caused variations in fish entering the trawl or escaping (fish that actively swim through escape openings between rollers of footgear or are passed over by the footgear) under the footgear (Winger et al., 2010). This different entry behavior has been observed to be species-specific and size-dependent (Main and Sangster, 1981; Wardle, 1993; Albert et al., 2003). For roundfish, like haddock and saithe, the typical behavior observed has been for fish to rise above the fishing line and fall back into the trawl (Main and Sangster, 1981; Godø and Walsh, 1992). Atlantic cod have been described to stay close to the seafloor (Main and Sangster, 1982) but have also been shown to rise above low opening trawls (Pol and Eayrs, 2021). Fish size is considered an important factor in driving the heights at which fish rise to enter the trawl. Generally, large fish with greater swimming capacity prefer cruising and falling back into the trawl above the fishing line, while small fish with poor swimming capacity tend to be positioned close to the seabed and seek escape under the footgear, likely due to fatigue (Winger et al., 2004; Ingólfsson and Jørgensen, 2006; Ryer, 2008).

The entry behavior of flatfish has been classified by two distinct behavioral patterns, including escape and avoidance behavior (Bublitz, 1996). The escape behavior is characterized by fish flipping over the footrope and entering the trawl. During the avoidance behavior, fish rise slowly to heights above the fishing line and enter the trawl. The heights that flatfish typically enter the trawl are close to the fishing line, less related to the fish size, and species-specific (Winger et al., 2010). These behavioral differences at the trawl mouth influence the catch efficiency of bottom trawls concerning overall trawl selectivity.

Several studies have investigated fish escape under the footgear. Engås and Godø (1989) found length-dependent escape for Atlantic cod and haddock underneath a survey trawl in the Barents Sea, where small individuals escaped more often under the footgear than did large individuals. Walsh (1992) reported that the escape of Atlantic cod, American plaice (*Hippoglossoides platessoides*), and yellowtail flounder (*Pleuronectes ferrugineus*) was length-dependent under a survey trawl in the Northwest Atlantic. Danby et al. (2022) observed that there were more small anglerfish (*Lophius* spp.) that escaped under a survey trawl than large individuals. A survey trawl with a rockhopper footgear showed more effective capture of small Atlantic cod and haddock relative to traditional bobbins (Engås and Godø, 1989). Ingólfsson and Jørgensen (2006) found length-dependent escape for Atlantic cod but less pronounced for haddock and not for saithe. Recently, Larsen et al. (2018) reported a slight length-dependent escape for haddock. As documented in these studies, length-dependent escape of fish underneath the trawl may vary between gear types (i.e., survey trawl vs. commercial trawl), fishing grounds (i.e., substrate types), fishing conditions (i.e., the ambient light intensity, depth, and temperature), and species.

The objective of this study was to quantify the length-dependent escape of a wide variety of species under a commercial bottom trawl in Iceland water using size selectivity techniques. This study applied an Icelandic commercial trawl that had three collecting bags (one on each wing and one in the bosom) mounted underneath and behind the footgear to retain all escapees beneath the trawl (Ingólfsson and Jørgensen, 2006). Previous research has focused primarily on gadoid species, confirming that the length-dependent escape of fish under the rockhopper footgear could be a part of the overall selectivity of the trawl, which is essential for development of gear designs to reduce bycatch of small fish in the catch (Walsh, 1992; Ingólfsson and Jørgensen, 2006). However, less work has focused on the wide assortment of species observed in the mixed-species nature of a typical commercial bottom trawl in Iceland. Here we investigated any length-dependent relationships observed per species and considered how the fish escape was affected by diurnal variations (i.e., day vs. night). The results not only provide information on length-dependent and species-specific escape of groundfish underneath a bottom trawl, which is essential for developing the gear designs to advance bycatch reductions in Icelandic groundfish fisheries, but also provide additional insights into the understanding of length-dependent efficiency of rockhopper footgear of bottom trawls.

4.3 Materials and Methods

4.3.1 Sea trials

Sea trials were carried out onboard the research vessel "Árni Friðriksson" (70 m, 4 × 1000 kW) off the West-fjords, NE Iceland from 7 to 13 September 2009 (Fig. 4.1). Fishing was carried out 24 h a day, where night hauls were defined between 22:20 (sunset) and 4:30 (sunrise), based on the local time zone of the study area (see timeanddate.com). Both day and night hauls were towed at speeds of 1.8 - 2.0 m s^{-1} (3.5 – 3.8 kt). An echograph was used to define haul duration by viewing when the trawl was on and off bottom.

4.3.2 Gear specifications

The "Gulltoppur" trawl was used, a common design for Icelandic stern trawlers (Fig. 4.2). The trawl was typical to common commercial standards except that the meshes in the trawl body and lower wings were smaller to retain small fish, and an inner lining of 20 mm mesh was used to prevent small fish from escaping through the codend. This design combined with the small bags described below allow the capture of all fish that enter the trawl or collection bag for comparison. A commercial rockhopper footgear with 60 cm diameter discs at the center and the three rearmost discs of the wing was used, the rest of the wing discs were 53 cm. The gear weight in seawater was approximately 30 kg m^{-1}. The length of the rockhopper gear was 22 m. The front of the gear was connected by a 13 m long 19 mm steel chain. Bridles were 67 m and sweeps 65 m. Small mesh collecting bags were used to retain all fish that escaped underneath the trawl, where three collecting bags were used in total including a bosom bag and two wing bags (Fig. 4.3). Each collecting bag was attached to the footgear where the headline was joined to the fishing line. Each collecting bag had a footgear made up of 12 cm rubber discs threaded on a 24.8 m long and 16 mm steel chain. Additionally, a 1.0 m long chain extension (19 mm steel) was used to connect the front end of the gear to the front ends of the fishing line. There were no gaps between the bags.

4.3.3 Catch sampling

Catches from both the codend and three collecting bags were processed separately where individuals were counted and measured to the nearest centimeter below total length. Subsampling took place when large numbers of a species were encountered.

4.3.4 Data analysis

Length-dependent escape

Catch-at-length data per species was analyzed using SELNET (Herrman et al., 2012) following size selectivity techniques outlined in Wileman et al. (1996), Herrmann et al. (2012), and Einarsson et al. (2021), to determine length-dependent retention of species captured during sea trials. Using traditional size selectivity techniques allows for a clear understanding of the proportion of fish that escape beneath the trawl as a function of length. The modeling approach followed the assumption that all fish presented in the trawl mouth have one of two fates, (1) enter the trawl and are retained in the codend, or (2) escape under the footgear and are retained by the collecting bags (the three collecting bags catches were combined). This enables the catch data to be considered as a binomial distribution. These data were used to estimate the probability of a fish of length *l* in haul *j* being retained in the codend relative to the collecting bags using the function $r_j(l)$. The retention probability estimation was carried out for all observed size classes (cm^{-1}) and was expected to vary between hauls (Fryer, 1991). Thus, all experimental hauls were pooled to describe the length-dependent probability averaged over each haul, where $r_{av}(l)$ (Herrmann et al., 2012). Since more than one model was applied, $r_{av}(l,v)$ was used to describe the length-dependent probability retained in the trawl codend averaged overhauls, where (v) is the model parameters.

Maximum likelihood was used to estimate model parameters. If the model described the data well, equation (4.1) was applied to maximize the likelihood of data describing the number of fish retained in the codend (*nRjl*) and collecting bags (*nEjl*).

$$-\sum_{j=1}^{m}\sum_{l}\left\{\frac{nR_{jl}}{qR_j}\times ln\left(r_{av}(l,v)\right)+\frac{nE_{jl}}{qE_j}\times ln\left(1.0-r_{av}(l,v)\right)\right\} \qquad (4.1)$$

where qR_j and qE_j were subsample factors for the codend and the collecting bags, respectfully.

Eight different models were used to describe $r_{av}(l,v)$ (Eq. (4.2)). Logit, Probit, Gompertz, and Richard (Eq. 4.2) are traditionally used size selectivity models described in Wileman et al. (1996) and used here to quantify length-dependent escape under the trawl (Ingólfsson and Jørgensen, 2006a). Each model assumes that all individual fish are subject to the same size selection process (Herrmann et al., 2016; 2018) using the parameters L50 (length at 50% retention) and selection range (SR; length at 75% retention – length at 25% retention).

$$r_{av}(l,\boldsymbol{v}) = \begin{cases} Logit(l,\boldsymbol{v}) \\ Probit(l,\boldsymbol{v}) \\ Gompertz(l,\boldsymbol{v}) \\ Richard(l,\boldsymbol{v}) \\ CLogit(l,\ C,\ \boldsymbol{v}) = 1.0 - C + C \times Logit(l,\ \boldsymbol{v}) \\ DLogit(l, C_1, \boldsymbol{v}) = C_1 \times Logit(l, \boldsymbol{v}_1) + (1.0 - C_1) \times Logit(l, \boldsymbol{v}_2) \\ TLogit(l, C, \boldsymbol{v}) = C_1 \times Logit(l, \boldsymbol{v}_1) + C_2 \times Logit(l, \boldsymbol{v}_2) + (1.0 - C_1 - C_2) \times Logit(l, \boldsymbol{v}_3) \\ Poly4(l,\boldsymbol{v}) = \dfrac{exp\left(v_0 + v_1 \times \frac{l}{100} + v_2 \times \frac{l^2}{100^2} + v_3 \times \frac{l^3}{100^3} + v_4 \times \frac{l^4}{100^4}\right)}{1.0 + exp\left(v_0 + v_1 \times \frac{l}{100} + v_2 \times \frac{l^2}{100^2} + v_3 \times \frac{l^3}{100^3} + v_4 \times \frac{l^4}{100^4}\right)} \end{cases} \tag{4.2}$$

Additional models (Eq. 4.2) were used that considered more than one size selective process (DLogit, TLogit; Cheng et al., 2019; Einarsson et al., 2021), contact probability (CLogit; Sistiaga et al., 2010), or were highly flexible (Poly4; Cheng et al., 2019; Einarsson et al., 2021). The reason to use these models was due to the potential of more than one selection process given the dynamic scenario of fish escaping at the trawl mouth (i.e., in comparison to the codend). The DLogit considers that a portion ($C1$) of fish entering the trawl will be subject to one logistic size selection process (consisting of parameters L501 and SR1) while the remaining portion (1.0 – $C1$) is subject to another logistic size selection process with parameters L502 and SR2 (Herrmann et al., 2016). The TLogit adds an additional size selection process (1.0 – $C1$ – $C2$) with the parameters L503 and SR3 (Frandsen et al., 2010).

The CLogit model considers the percentage of fish that will not make contact with the gear that will lead to a length-dependent chance of escape (Bayse et al., 2016b). An additional parameter C in the CLogit model represents the fish length-dependent contact probability. If C equals 1.0, then all fish had contact with the groundgear to have a length-based selectivity. If 0.75, then 75% of fish had contact with the groundgear, leading to a length-based retention

(Sistiaga et al., 2010; Bayse et al., 2016b). The last model was a group of highly flexible models (up to a quartic polynomial; Poly4) that used the Akaike information criterion (AIC) (Akaike, 1974) to select the best fit of 31 potential models when removing one or more parameters.

How the model fit the data was determined with a goodness-of-fit test described in Wileman et al. (1996). If the p-value was > 0.05, then the model was considered a good fit. If the p-value was < 0.05, then model residuals were investigated for structural problems. The model selection was based on the AIC values. The best model was the model with the lowest AIC value. Models that have a difference in AIC > 2, are considered sufficiently different models. If multiple models are within 2 AIC, then the simplest model was chosen based on the rule of parsimony (Burnham and Anderson, 2004).

Confidence intervals of the fit model were produced using the double bootstrap method described in Millar (1993) and Herrmann et al. (2012). The Efron percentile 95% confidence intervals (CIs; Efron, 1982) were fitted for the best fit model with 1000 bootstraps.

Diurnal effects on length-dependent escape

Effects of diurnal variability and changes in fishing depth on the escape of fish under the trawl were investigated using Generalized Linear Mixed Models (GLMMs). The GLMMs included the retention rates as the dependent variable. The independent variables included Length (fish length), Scenario (day or night), Depth, and interactions between each independent variable. We used the random effect Tow (haul) for both the intercept and slope terms to account for variations in retention probability between tows and fish of the same length class between tows. Random effects were simplified (i.e. only used the random effect Tow on the intercept) or removed if models could not converge or had singularity. Generalized linear models (GLMs) were used when random effects were completely removed. Subsample ratio (fraction of fish measured to counted), if required, was used as an offset. The GLMMs were performed with a binomial error using the glmer function of the lme4 package (Bates et al., 2015) and GLMs using R statistical software (R Development Core Team, 2020) base functions.

Model selection was based on the minimum AIC value with a correction for small sample sizes (AICc). AICc value of each model was calculated using AICctab function in the bbmle package (Bolker and R Development Core Team, 2020). A model with the lowest AICc value was chosen as the best fit model. If there were multiple models within 2 AICc, the model that had highest AICc weight was considered as the best model.

The effect of day versus night was further investigated by length-dependent analyses separately considering day and night retention following the procedures described in 4.3.4. The differences in retention for each species between day and night ultimately were determined by a direct comparison with a Delta curve using the $\Delta r(l)$ function (Herrmann et al., 2018):

$$\Delta r(l) = r_d(l) - r_n(l) \tag{4.3}$$

where $r_d(l)$ is the length-dependent probability retained of each species during the day and $r_n(l)$ is the length-dependent probability retained of each species during the night. The location of CIs determined the significant differences in retention between day and night. If CIs overlap 0.0 at a particular length class, then a significant difference is observed. However, if 0.0 is contained within the CIs, there is no difference in retention between environmental conditions at the observed length class (Herrmann et al., 2018). Further details of this method are found in (Larsen et al., 2018b).

This study was performed by the Marine and Freshwater Research Institute, which complies with the regulation imposed by the Icelandic "Food ministry", which allows to land all fish captured during sea trials.

4.4 Results

A total of 34 hauls were carried out during the sea trials. There were seven invalid hauls removed from the analyses due to sampling inconsistencies. Thus, 27 valid hauls were used, including 21 day hauls, five night hauls, and one carried out in both day and night (Table 4.1). The average haul length was 44 min (range: 23-79 min) with an average speed of 3.8 knots (2.0 m s^{-1}), ranging from 3.5 to 3.9 knots (1.8 – 2.0 m s^{-1}). The average fishing depth was 73 m (range: 26-192 m). The average warp length was 217.5 m (range: 122.5- 484.6 m), and the average door spread was 58.5 m (range: 43-96 m) (Table 4.1).

Out of 31 species caught during the experiment, ten dominate species were chosen for analysis, including six roundfish: Atlantic cod, haddock, saithe, whiting (*Merlangius merlangus*), blue ling (*Molva dypterygia*), and redfish (*Sebastes norvegicus*); three flatfish: European plaice (*Pleuronectes platessa*), dab (*Limanda limanda*), and American plaice; and monkfish (*Lophius piscatorius*). For roundfish, Atlantic cod and haddock were the most frequently occurring, observed in 27 valid hauls, followed by saithe and whiting, observed in 8 and 6 valid hauls, respectively, and blue ling and redfish, observed in 3 valid hauls (Table 4.2). For flatfish, the most frequently observed species was European plaice, observed in 23 hauls, followed by dab and American plaice, observed in 11, and 10, respectively. Monkfish was observed in 9 valid hauls (Table 4.2). Subsampling occurred on five hauls for European plaice, four hauls for haddock, and two hauls for redfish and dab. For Atlantic cod, saithe, and American plaice, one haul was subsampled. For subsampled hauls, at least 52.5% of fish or more were measured, except redfish and American plaice, whose subsampling was less than 20% in the codend. No tows were subsampled for whiting, blue ling, and monkfish.

4.4.1 Length-dependent escape

Atlantic cod

A total of 6775 Atlantic cod were caught, 6773 measured for analysis, including 2963 in the codend and 3810 in collecting bags (Table 4.2). The TLogit model was the best-fit model with the lowest AIC value (Table 4.3). The model described the experimental data adequately despite the p-value < 0.05 (Table 4.4). Thus, we considered the low p-value likely due to overdispersion that occurred when pooling experimental data. Overall, the retention probability of Atlantic cod increased with length (Fig. 4.4). The retention was near 0.0 at the smallest lengths, and gradually increased to 40% at the minimum reference length (MRL) of 55 cm (based on the lower CI), and reached about 90% at 115 cm (Fig. 4.4). Fish length ranged from 6 to 115 cm.

Haddock

Out of 10339 haddock that were caught during the experiment, 9824 individuals were measured for analysis, including 6637 measured in the codend and 3187 in collecting bags (Table 4.2**)**. Both DLogit and TLogit models were appropriate to describe the experimental data (Table 4.3), and the DLogit model was then chosen as the simplest model. The high p-value supported that the model fitted the experimental data adequately (p-value = 0.81, Table 4.4). The model curve showed that the retention probability for haddock was steep to around 75% at 15 cm. For catch > 15 cm, the retention probability rapidly increased and approached retention probability of 1.0 (Fig. 4.4). The overall fish length ranged from 6 to 85 cm; most individuals were less than the current MRL of 45 cm (Fig. 4.4).

Saithe

A total of 286 saithe were captured, 282 saithe measured for analysis, including 263 in the codend and 19 in the collecting bags (Table 4.2). The Richard model best described the retention probability for saithe (Table 4.3) and was a good fit (*p*-value = 0.97, Table 4.4). Retention probability was very high at lengths < 30 cm (100%) and decreased to 75% at the MRL of 55 cm (Fig. 4.4). For catch > 55 cm, high CI values were observed due to a relatively small number of individuals captured at these lengths; however, the data trend of high retention was maintained (Fig. 4.4). The L50 and SR could not be estimated due to the model consistently being above the L50 (Table 4.4; Fig. 4.4). The lengths of observed individuals ranged between 15 to 81 cm.

Whiting

For whiting, a total of 361 were captured, 172 in the codend and 189 in the collecting bags (Table 4.2). Both Poly4 and Logit were appropriate to fit the model with an identical AIC value, thus Logit was chosen since it was the simplest (Table 4.3) and the model fit well (*p*-value > 0.05; Table 4.4). The retention probability increased as the length increased, from approximately 0% (based on the low CI) at 7 cm to 98% at 55 cm (Fig. 4.4). Whiting currently does not have an MRL. Fish length ranged from 7 to 55 cm.

Blue ling

For blue ling, a total of 516 individuals were captured during the experiment, 379 by the codend and 137 by the collecting bags (Table 42). DLogit was the best model with the lowest AIC value, however, Gompertz had a similar AIC and was chosen due to parsimony (Table 4.3). Inspecting fit statistics indicated that the model described the experimental data adequately despite the *p*-value < 0.05 (Table 4.4). The low *p*-value was likely due to overdispersion from pooling the data; thus, the model could be applied confidently. The model showed that the retention probability gradually increased as length increased, beginning with 10% at 24 cm and increasing to 90% at the length of 119 cm (Fig. 4.4). The population lengths ranged from 24 to 119 cm.

Redfish

A total of 1041 redfish were captured, 721 redfish measured for analysis, 599 in the codend and 122 by the collecting bags (Table 4.2). The model curve was best described by a Richard (Table 4.3). The *p*-value = 0.161 supported that the model fit was good (Table 4.4). Results showed a very high retention probability over all lengths, beginning at 90% at 25 cm and increasing to 99% at 48 cm (Fig. 4.4). The L50 and SR could not be estimated because the curve was above 75% retention over all lengths (Table 4.4; Fig. 4.4). The length frequency of redfish ranged from 25 to 48 cm.

European plaice

For European plaice, out of 6911 individuals that were captured, 6400 were measured, including 4439 in the codend and 1961 in the collecting bags (Table 4.2). The best model was the Richard model, with the lowest AIC value (Table 4.3). The model fit had a *p*-value < 0.05 (Table 4.4), however, the modeled curve reflected the trends of the experimental data well; thus, we considered the low *p*-value as overdispersion in pooling data, and the model was applied with confidence. The model showed that the retention probability was greater than 70% overall length classes and had a slightly negative trend, with a slight reduction in retention as fish length increased (Fig. 4.5). The L50 and SR could not be determined due to high retention (Table 4.4; Fig. 4.5). The length range of the observed catch was between 10 and 65 cm, but most individuals captured were greater than MRL of 33 cm.

Dab

A total of 1109 dab were captured during the experiment; 1061 dab were measured for analysis; 653 were measured in the codend and 408 in the collecting bags (Table 4.2). DLogit was the best model having the lowest AIC (Table 4.3), and the model fit was good (*p*-value = 0.21, Table 4.4). The model curve showed that the retention probability quickly increased from 0.0 at the smallest length to 60% at 20 cm and remained relatively constant for lengths between 20 and 40 cm (Fig. 4.5). For fish greater than 40 cm, the retention probability steeply increased to 1.0. The population lengths ranged between 6 and 44 cm.

American plaice

A total of 1126 American plaice were caught during the experiment, 1034 measured, 349 in the codend, and 685 in the collecting bags (Table 4.2). The Poly4 was the best model (Table 4.3) and a *p*-value = 0.205 (Table 4.4) determined that the model fit the data well. The retention probability increased as fish length increased but for lengths > 35 cm CIs were very wide due to few observations (Fig. 4.5). The population lengths ranged from 4 to 51 cm.

Monkfish

For monkfish, 322 fish were captured, 45 in the codend and 277 by in the collecting bags (Table 4.2). By comparing the AIC values in Table 4.3, the Logit was the best model and was a good fit (*p*-value = 0.91; Table 4.4). The model showed an increase in retention rates as length increased, however retention remained low throughout, with a maximum of approximately 30% at the largest size classes (Fig. 4.5). The population length ranged between 15 and 86 cm.

4.4.2 Diurnal and depth variations in length-dependent escape

Based on AICc values in Table 4.5, the best model for each species did not include Depth; thus changes in fishing depths did not influence the escape of fish under the trawl. For Atlantic cod and haddock, the best models (including all random effects) included Length and Scenario and the model included interaction between those variables were within 2 AICc value; thus the model without that interaction was chosen as the simplest model. The model showed that there was a significant day versus night effect on retention. The best model (including all random effects) for whiting just included Length, but there was some signal for a potential scenario effect, with the Scenario and Length variable model being within 1 AICc of the best model (Table 4.5). European plaice model selection was able to include all random effects, however the model included the Length variable only was chosen from four candidate models as the simplest model (Table 4.5), meaning that no Scenario effect was found. The best model for Dab included all random effects and Scenario and Length was included in the best model. The best model approach for American plaice included Length only, having no Scenario effect. For Monkfish, a mixed model approach for monkfish could not be performed due to singularity. Thus, GLMs were used. Both models with and without interaction between Length and Scenario were the best models, the model without that interaction was then chosen as the simplest. Saithe, blue ling, and redfish were captured only in the daytime; thus, these species were not included in the day-night analyses (Table 4.2).

Table 4.6 shows the AIC values for the best fit models per species and Scenario. Model fits were sufficient (p-value > 0.05) at day and night for roundfish (Table 4.7), flatfish and monkfish (Table 4.8) with the exception of Atlantic cod (day) and European plaice (day). Model residuals did not show structure and the resultant *p*-values were considered caused by overdispersion.

Fig. 4.6 shows the retention for Atlantic cod, haddock, and whiting between day and night. For Atlantic cod, differences in retention were observed at lengths between 15 and 60 cm, where more individuals were retained during the day than the night. For haddock, the catch between 12 and 40 cm was significantly higher during the day than the night. Whiting had a higher retention probability as length increased, however the difference was not significant. The sample size was small for whiting between scenarios, and the data should be interpreted with caution.

Flatfish and monkfish retention between day and night is shown in Fig. 4.7. European plaice showed no retention effect for day or night. For dab, although the confidence intervals for the selectivity curve during the night were wide, the curve followed the experimental rates well. The retention probability plot for dab shows a retention probability of ~50% for the most commonly captured size classes during the day and ~75% or greater for the most commonly caught size classes during the night. A significant difference was observed at lengths between 17 and 30 cm, where the trawl retained significantly fewer individuals of these sizes during the day than the night. The length classes where this was not significant is due to smaller sample sizes which is a common result in size selectivity studies (fewer observations at the extreme ends of the size classes). American plaice had similar retention probabilities between day and night, slightly increasing with fish length. For most length classes, there was no significant difference, however a slight difference was observed between 9 and 13 cm; very few fish were observed at these length classes and caution should be used when interpreting results at theses sizes. Monkfish had a slight increase in retention during the day, when compared to night, as fish size increased but sample sizes were low.

4.5 Discussion

In this study, we investigated the length-dependent escape of 10 species beneath a trawl. Generally, results showed that how the fish escape under the trawl is typically size-dependent and species-specific, though with a few exceptions directly related to a species' typical behavior. For most roundfish, the proportion of escapes decreased with fish size, and retention curves followed general trends observed in size selectivity studies where retention increased with size. However similar, interesting subtle differences were observed among this study and codend size selectivity studies. The selection range for this study was higher for Atlantic cod (He, 2007) and lower for haddock (Özbilgin et al., 2006) when generally considering codend size selectivity literature, which is likely due to swimming capacity and behavior as a function of size driving retention. In contrast, retention in codends is mostly related to fish girth in relation to mesh size and shape (Herrmann et al., 2009). Saithe and redfish showed almost no length-dependent effect. These results are likely directly related to these species having a high swimming capacity (saithe; He and Wardle, 1988) and/or preference for remaining off the bottom in the water column (Main and Sangster, 1982; Main and Sangster, 1985; Gauthier and Rose, 2005).

Dab and American plaice retention increased with size, likely European plaice would have also if more small fish had been captured, retention rates where similar between the three species where each had high capture rates. Larger flatfish likely use previously described behaviors (Bublitz, 1996) to enter the trawl at the conclusion of herding while small individuals are likely overtaken by the trawl due to a reduced swimming capacity (i.e., unable to keep station). Monkfish had a low retention overall, indicating that they do not have the swimming capacity to swim with the trawl enough to rise and enter, suggesting that captured individuals have had contact with the groundgear to increase trawl entry likelihood.

At reduced light intensities, the structure of fish behavior to trawls stops and typically becomes erratic (Glass and Wardle, 1989), directly affecting trawl capture efficiency (Arimoto et al., 2010). This proved true for three species in this study. Small Atlantic cod and haddock (<MRL) were observed to escape more often during night than day, confirming previous studies (Glass and Wardle, 1989; Walsh and Hickey, 1993; Krag et al., 2010). Small gadoids likely kept station in front of the approaching trawl components during the day, swimming in front in reaction to their visual presence, whereas at night, fish were unable to orient to the oncoming trawl, were overtaken, and many subsequently escaped underneath the footgear. In contrast, mid-sized dab escaped more often during the day. Results for dab are biologically meaningful and are explained based on the visual range of fish and their ability to detect underwater objects at varying light intensities (i.e., day vs. night). The likely underlying cause of this phenomenon is that when dab can see the trawl, ~50% escape between gaps in the footgear, and at night dab cannot see these means of escape and are more often captured (~75%, Fig. 4.7). This trend is shown in the Delta plot, where the entire model indicates that more dab were caught at night

(almost the entire model is below 0.0) and was shown significantly different at 18-30 cm, the most commonly observed size classes.

The findings for dab are similar to what Walsh and Hickey (1993) found; that flatfish generally remained on the seabed in response to an oncoming trawl during high light intensities (i.e., did not swim in front of approaching groundgear), resulting in fish being passed over by the gear and not captured. American plaice results suffered from low sample sizes that led to clear results showing no effect. Conversely, European plaice results were unexpected, where high sample sizes showed no difference between day and night retention. During the day, European plaice's retention probability was ~75% (25% higher than dab for example) which was similar to European plaice's retention probability at night (also roughly 75%) and clearly showing no difference. Likely, there is a behavioral difference at the trawl mouth between European plaice and dab, and more broadly what is believed to be flatfish behavior at the trawl mouth between night and day. Referring to Nguyen et al. (2023), which inferred escape behaviors between the center and wing sections of the trawl mouth, a pronounced difference was observed between European place and dab where European plaice of all sizes more often escaped in the wing sections versus dab that escaped more often in the center (for the most observed length classes). This perhaps points to behavior or herding differences between these species that directly affects retention at the trawl mouth.

Results from this study match others (Engås and Godø, 1989; Walsh, 1992; Ingólfsson and Jørgensen, 2006a; Krag et al., 2010). Where the escape of Atlantic cod has been shown to depend on the size, and smaller individuals more often pass underneath the trawl compared with larger individuals. Early studies of Atlantic cod behavior (Main and Sangster, 1981) showed that they remained close to the seabed in response to the approaching groundgear. However, Thomsen (1993) and Pol and Eayrs (2021) suggested that Atlantic cod rose up and over the groundgear as they passed through the net. The latter behavioral tendency combined with the swimming capacity can explain how more large individuals were captured than small ones, which follows the results of the current study. Large Atlantic cod, which have a greater swimming capacity, could swim or rise up to the heights above the fishing line and enter the trawl more easily than small individuals, likely driving the difference in retention. Contrary to large fish, small individuals may quickly seek escape openings under the fishing line and/or spaces between the rockhopper discs due to their lower swimming capacity (Ingólfsson and Jørgensen, 2006a).

Similar to Atlantic cod, the length-dependent escape of haddock beneath the trawl matched previous studies (Engås and Godø, 1989; Ingólfsson and Jørgensen, 2006a; Larsen et al., 2018a). The majority of haddock less than MRL of 45 cm entered the trawl, with a low L50 of 12.3 cm. Retention was low for haddock < 10 cm, but rapidly increased to > 75% by 15 cm. Thus, with such little separation of unwanted sizes of haddock at the trawl opening, commercial trawls will have to rely on size selection further back, such as selection grids and mesh sizes to sort out undersized of haddock.

Similar to the Atlantic cod and haddock, the escape of whiting and blue ling was length-dependent, with retention gradually increasing as fish size increased. This finding is similar to that of (Main and Sangster, 1981), that described whiting rising off the sea bed. This behavior being length-dependent, is presumably due to whiting swimming capacity increasing with size. Blue ling escape rates under the trawl have not been previously described, and generally appear similar to other gadoid species, being most similar to whiting in this study.

In previous studies, the heights at which flatfish rose up to enter the trawl mouth were within 1 m from the seabed (Main and Sangster, 1981; Bublitz, 1996; King et al., 2004; Ryer, 2008). In a separator trawl experiment, Main and Sangster (1985) observed that the proportion of flatfish captured in the upper compartment was reduced when increasing the heights of the separator panel from 0.45 to 0.75 m. In the current study, the rockhopper groundgear was made of 0.6 m diameter discs. Therefore, the distance between the fishing line and seabed would be less than 1.0 m. Thus, it is not surprising that the trawl would catch a large number of flatfish. Our results estimated about 70% of large individuals (> MRL) for European plaice and dab were retained in the codend on average, and smaller flatfish (< ~20 cm) capture was mostly avoided. Thus, this trawl design effectively targets flatfish. In terms of the capture of undersize flatfish, small American plaice had low retention, which follows previously published results (Walsh, 1992; Winger et al., 2004). European plaice is not known since low catch rates were observed for sizes less than the MRL for both compartments. There is some problematic retention of dab from size 5 to 25 cm at ~ 70% retention probability.

Several previous studies have focused on quantifying the escape under the trawl of gadoid species, particularly Atlantic cod and haddock. However, our study provides additional insights into those species' escape patterns and includes new data for other gadoid species (whiting and blue ling) as well as flatfish and monkfish. These findings support results of studies such as Ingólfsson and Jørgensen (2006) that show that overall trawl selectivity is highly influenced by retention rates at the trawl mouth where, for most species, size-based selectivity at the trawl mouth leads to larger fish being more available for retention in the codend when compared to smaller individuals. With the exception of saithe, gadoids were observed to have a retention gradually increasing with fish length, and few redfish were observed to escape beneath the trawl. Flatfish escape patterns matched logical expectations from known responses from observed herding effects at trawl entry (Walsh, 1992; Bublitz, 1996; Winger et al., 2004; Bayse et al., 2016b) small individuals more often being overtaken by the trawl and larger individuals rising up and being captured. The effect of light on escape at the trawl mouth suffered from low sample sizes for many species, but when sufficient data was present, results clearly showed that the structure of fish behavior breaks down at low light, which results in reduced capture of Atlantic cod and haddock, but conversely increases the catch of dab. In conclusion, this study clearly shows the management implications of large numbers of fish that interact with trawl gear but are undocumented as they escape capture well before the capture process begins within the trawl. Thus, the number of animals that interact with the trawl, especially for small-sizes, are underestimated as well as changing trawl efficiency during day or night conditions.

4.6 Acknowledgements

We would like to thank the crew of the research vessel "Árni Friðriksson" for their assistance. Additionally, we would like to thank Bent Herrmann for the use of the software SELNET. This research was funded by the MFRI project. Student salary and travel was provided by the Canada First Research Excellence Fund's OFI (Module H.3).

4.7 References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control 19, 716–723. https://doi.org/10.1109/TAC.1974.1100705

Albert, O.T., Harbitz, A., Høines, Å.S., 2003. Greenland halibut observed by video in front of survey trawl: behavior, escapement, and spatial pattern. Journal of Sea Research 50, 117–127. https://doi.org/10.1016/S1385-1101(03)00063-7

Arimoto, T., Glass, C.W., Zhang, X., 2010. Fish vision and its role in fish capture, In: He, P. (Ed.), Behavior of Marine Fishes: Capture Processes and Conservation Challenges. Blackwell Publishing, Ames, Iowa, USA, pp. 25–44.

Arnason, R., 1996. On the ITQ fisheries management system in Iceland. Reviews in Fish Biology and Fisheries 6, 63–90. https://doi.org/10.1007/BF00058520

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software. Vol 1 Issue 1 2015. https://doi.org/10.18637/jss.v067.i01

Bayse, S.M., Herrmann, B., Lenoir, H., Depestele, J., Polet, H., Vanderperren, E., Verschueren, B., 2016a. Could a T90 mesh codend improve selectivity in the Belgian beam trawl fishery? Fisheries Research 174, 201–209. https://doi.org/10.1016/j.fishres.2015.10.012

Bayse, S.M., Pol, M.V., He, P., 2016b. Fish and squid behavior at the mouth of a drop-chain trawl: factors contributing to capture or escape. ICES Journal of Marine Science 73, 1545–1556. https://doi.org/10.1093/icesjms/fsw007

Bolker, B., R Development Core Team, 2020. bbmle: Tools for General Maximum Likelihood Estimation.

Bublitz, C.G., 1996. Quantitative evaluation of flatfish behavior during capture by trawl gear. Fisheries Research 25, 293–304. https://doi.org/10.1016/0165-7836(95)00431-9

Burnham, K.P., Anderson, D.R., 2004. Multi-model inference: Understanding AIC and BIC in model selection. Sociological Methods & Research 33, 261–304. https://doi.org/10.1177/0049124104268644

Cheng, Z., Einarsson, H.A., Bayse, S., Herrmann, B., Winger, P., 2019. Comparing size selectivity of traditional and knotless diamond-mesh codends in the Iceland redfish (*Sebastes spp.*) fishery. Fisheries Research 216, 138–144. https://doi.org/10.1016/j.fishres.2019.04.009

Danby, R.E., Clarke, E.D., Kynoch, R.J., Reid, D.G., Fernandes, P.G., 2022. Estimating and accounting for fish losses under the footrope of a survey trawl: The case of northern shelf anglerfish. Fisheries Research 255, 106431. https://doi.org/10.1016/j.fishres.2022.106431

Efron, B., 1982. The jackknife, the bootstrap and other resampling plans. SIAM Monograph No. 38, CBSM-NSF.

Einarsson, H.A., Cheng, Z., Bayse, S.M., Herrmann, B., Winger, P.D., 2021. Comparing the size selectivity of a novel T90 mesh codend to two conventional codends in the northern shrimp (*Pandalus borealis*) trawl fishery. Aquaculture and Fisheries. 6, 382–392. https://doi.org/10.1016/j.aaf.2020.09.005

Engås, A., Godø, O.R., 1989. Escape of fish under the fishing line of a Norwegian sampling trawl and its influence on survey results. ICES Journal of Marine Science 45, 269–276. https://doi.org/10.1093/icesjms/45.3.269

Engås, A., Jacobsen, J.A., Soldal, A.V., 1988. Catch comparison between rockhoppers and bobbins ground gear on the Norwegian bottom sampling trawl, In: ICES C.M. 1988/B: 31. Presented at the Fish Capture Committee, International Council for the Exploration of the Sea, p. 12.

Frandsen, R.P., Herrmann, B., Madsen, N., 2010. A simulation-based attempt to quantify the morphological component of size selection of *Nephrops norvegicus* in trawl codends. Fisheries Research 101, 156–167. https://doi.org/10.1016/j.fishres.2009.09.017

Fryer, R.J., 1991. A model of between-haul variation in selectivity. ICES Journal of Marine Science 48, 281–290. https://doi.org/10.1093/icesjms/48.3.281

Gauthier, S., Rose, G.A., 2005. Diel vertical migration and shoaling heterogeneity in Atlantic redfish: effects on acoustic and bottom-trawl surveys. ICES Journal of Marine Science 62, 75–85. https://doi.org/10.1016/j.icesjms.2004.10.001

Glass, C.W., Wardle, C.S., 1989. Comparison of the reactions of fish to a trawl gear, at high and low light intensities. Fisheries Research 7, 249–266.

Godø, O.R., 1994. Factors affecting the reliability of groundfish abundance estimates from bottom trawl surveys. In Marine Fish Behavior in Capture and Abundance Estimation, pp. 166–199. Ed. by A. Ferno¨ , and S. Olsen. Fishing News Books, Oxford.

Godø, O.R., Walsh, S.J., 1992. Escapement of fish during bottom trawl sampling - implications for resource assessment. Fisheries Research 13, 281–292.

Halliday, R.G., Pinhorn, A.T., 1996. North Atlantic fishery management systems: A comparison of management methods and resource trends. Journal of Northwest Atlantic Fishery Science 21, 3–135. https://doi.org/10.2960/j.v20.a1

He, P., 2007. Selectivity of large mesh trawl codends in the Gulf of Maine: I. Comparison of square and diamond mesh. Fisheries Research 83, 44–59. https://doi.org/10.1016/j.fishres.2006.08.019

He, P., Wardle, C.S., 1988. Endurance at intermediate swimming speeds of Atlantic mackerel, *Scomber scombrus* L., herring, *Clupea harengus* L., and saithe, *Pollachius virens* L. Journal of Fish Biology 33, 255–266. https://doi.org/10.1111/j.1095-8649.1988.tb05468.x

Herrmann, B., Krag, L.A., Feekings, J., Noack, T., 2016. Understanding and predicting size selection in diamond-mesh cod ends for Danish seining: A study based on sea trials and computer simulations. Marine and Coastal Fisheries 8, 277–291. https://doi.org/10.1080/19425120.2016.1161682

Herrmann, B., Krag, L.A., Frandsen, R.P., Madsen, N., Lundgren, B., Stæhr, K.-J., 2009. Prediction of selectivity from morphological conditions: Methodology and a case study on cod (*Gadus morhua*). Fisheries Research 97, 59–71. https://doi.org/10.1016/j.fishres.2009.01.002

Herrmann, B., Krag, L.A., Krafft, B.A., 2018. Size selection of Antarctic krill (*Euphausia superba*) in a commercial codend and trawl body. Fisheries Research 207, 49–54. https://doi.org/10.1016/j.fishres.2018.05.028

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (*Sebastes spp.*) in North Atlantic trawl codends Journal of the Northwest Atlantic Fisheries Science, 44, 1-13.

Ingólfsson, Ó.A., Jørgensen, T., 2006. Escapement of gadoid fish beneath a commercial bottom trawl: Relevance to the overall trawl selectivity. Fisheries Research 79, 303–312. https://doi.org/10.1016/j.fishres.2005.12.017

Kim, Y.-H., Wardle, C.S., 2003. Optomotor response and erratic response: quantitative analysis of fish reaction to towed fishing gears. Fisheries Research 60, 455–470. https://doi.org/10.1016/S0165-7836(02)00114-5

Kim, Y.-H., Wardle, C.S., 1998. Measuring the brightness contrast of fishing gear, the visual stimulus for fish capture. Fisheries Research 34, 151–164. https://doi.org/10.1016/S0165-7836(97)00087-8

King, S.E., Hannah, R.W., Parker, S.J., Matteson, K.M., Berkeley, S.A., 2004. Protecting rockfish through gear design: development of a selective flatfish trawl for the U.S. west coast bottom trawl fishery. Canadian Journal of Fisheries and Aquatic Sciences 61, 487–496. https://doi.org/10.1139/f03-153.

Krag, L.A., Holst, R., Madsen, N., Hansen, K., Frandsen, R.P., 2010. Selective haddock (*Melanogrammus aeglefinus*) trawling: Avoiding cod (*Gadus morhua*) bycatch. Fisheries Research. 101, 20–26. https://doi.org/10.1016/j.fishres.2009.09.001

Larsen, R.B., Herrmann, B., Brinkhof, J., Grimaldo, E., Sistiaga, M., Tatone, I., 2018a. Catch efficiency of groundgears in a bottom trawl fishery: A case study of the Barents Sea haddock. Marine and Coastal Fisheries 10, 493–507. https://doi.org/10.1002/mcf2.10048

Larsen, R.B., Herrmann, B., Sistiaga, M., Brčić, J., Brinkhof, J., Tatone, I., 2018b. Could green artificial light reduce bycatch during Barents Sea deep-water shrimp trawling? Fisheries Research 204, 441–447. https://doi.org/10.1016/j.fishres.2018.03.023

Main, J., Sangster, G.I., 1982. A study of a multi-level bottom trawl for species separation using direct observation techniques. Aberdeen : Dept. of Agriculture and Fisheries for Scotland, Aberdeen.

Main, J., Sangster, G., 1981. A study of the fish capture process in a bottom trawl by direct observation from a towed underwater vehicle. Scottish fisheries research report 23, 1–23.

Main, J., Sangster, G.I., 1985. Report on the direct observation experiments with the chalut 28.90/37.1m JCB trawl during July 3–23, 1984. ICES CM 1985B 9Ref K 19.

Millar, R.B., 1993. Incorporation of between-haul variation using bootstrapping and nonparametric estimation of selection curves. Fishery Bulletin. 564–572.

Nielsen, M., Asche, F., Bergesen, O., Blomquist, J., Henriksen, E., Hoff, A., Nielsen, R., Viðarsson, J.R., Waldo, S., 2018. The myth of the poor fisher: Evidence from the Nordic countries. Marine Policy 93, 186–194. https://doi.org/10.1016/j.marpol.2018.04.003

Nguyen, V.Y., Bayse, S.M., Einarsson, H.A., Ingólfsson, Ó.A., 2023. Inferring fish behavior at the trawl mouth from escape location. PeerJ 11, e14746. https://doi.org/10.7717/peerj.14746

Özbilgin, H., Ferro, R.S.T., Robertson, J.H.B., Holtrop, G., Kynoch, R.J., 2006. Seasonal variation in trawl codend selection of northern North Sea haddock. ICES Journal of Marine Science 63, 737–748. https://doi.org/10.1016/j.icesjms.2005.01.025

Pálsson, Ó.K., 2003. A length-based analysis of haddock discards in Icelandic fisheries. Fisheries Research. 59, 437–446. https://doi.org/10.1016/S0165-7836(02)00017-6

Pol, M., Eayrs, S., 2021. Behavior in a bottom trawl: moving forward to limit catches of Atlantic cod. ICES Journal of Marine Science 78, 2317–2324. https://doi.org/10.1093/icesjms/fsab106

R Development Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ryer, C.H., 2008. A review of flatfish behavior relative to trawls. Fisheries Research 90, 138–146. https://doi.org/10.1016/j.fishres.2007.10.005

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R.B., 2010. Assessment of dual selection in grid based selectivity systems. Fisheries Research 105, 187–199. https://doi.org/10.1016/j.fishres.2010.05.006

Thomsen, B., 1993. Selective flatfish trawling. ICES Marine Science Symposia 196, 161–164.

Thorsteinsson, G., 1980. Iceland bottom trawl and Danish seine codend selection experiments on cod, haddock, redfish and plaice in 1972-1976. ICES Fish Capture Committee C.M. 1980/B3, 14.

Walsh, S.J., 1992. Size-dependent selection at the footgear of a groundfish survey trawl. North American Journal of Fisheries Management 12, 625–633.

Walsh, S.J., Hickey, W.M., 1993. Behavioral reactions of demersal fish to bottom trawls at various light conditions. ICES Marine Science Symposia 196: 68-76.

Wardle, C.S., 1993. Fish behavior and fishing gear, in: Pitcher, T.J. (Ed.), Behavior of Teleost Fishes. Chapman & Hall, London, pp. 609–643.

Wileman, D.A., Ferro, R.S.T, Fonteyne, R, Millar, R.B, 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Cooperative Research Report. No. 215. XXp

Winger, P.D., Eayrs, S., Glass, C.W., 2010. Fish behavior near bottom trawls, In: He, P. (Ed.), Behavior of Marine Fishes: Capture Processes and Conservation Challenges. Wiley-Blackwell, Oxford, UK, pp. 65–103. https://doi.org/10.1002/9780813810966.ch4

Winger, P.D., Walsh, S.J., He, P., Brown, J.A., 2004. Simulating trawl herding in flatfish: the role of fish length in behavior and swimming characteristics. ICES Journal of Marine Science 61, 1179–1185. https://doi.org/10.1016/j.icesjms.2004.07.015

Woods, P.J., Bouchard, C., Holland, D.S., Punt, A.E., Marteinsdóttir, G., 2015. Catch-quota balancing mechanisms in the Icelandic multi-species demersal fishery: Are all species equal? Marine Policy 55, 1–10. https://doi.org/10.1016/j.marpol.2015.01.004

4.8 Tables

Table 4.1. Operational conditions for valid hauls during sea trials. NA is not applicable.

Haul	Duration (min)	Depth (m)	Towing speed (kt)	Door spread (m)	Vertical opening (m)	Warp length (m)	Time
1	24	72	3.5	52	7	155.4	Night
2	36	69.5	3.5	54	7	164.6	Night
3	24	70	3.5	48	7	146.3	Day
4	35	72	3.5	53	6.8	164.6	Day
5	34	72.5	3.5	-	7	164.6	Day
6	33	62	3.8	-	-	164.6	Day
7	43	81	3.8	-	6.1	274.3	Day
8	64	98	3.5	72	6.8	265.2	Day
9	37	98	3.5	54	7	146.3	Night
10	97	79	3.5	60	7	164.6	NA
11	34	70	3.5	54	7	192.0	Day
12	46	67	3.5	60	7	192.0	Day
13	23	42	3.8	56	7	164.6	Day
14	60	42.5	3.5	51	7	164.6	Day
15	30	41	3.5	45	7	146.3	Night
16	74	40.5	3.9	46	7	146.3	Day
17	62	41	3.5	57	7	128.0	Day

18	30	46.5	3.8	69	6	274.3	Day
19	35	95.5	3.8	73	7	150.0	Day
20	54	53	3.7	60	7	164.6	Day
21	77	40.5	3.5	48	7	146.3	Night
22	29	72.5	3.7	61	7	197.5	Day
23	44	37	3.8	-	6.4	192.0	Day
24	25	37	3.8	43	7	122.5	Day
25	61	179	3.7	93	7	457.2	Day
26	34	192	3.8	88	6.3	457.2	Day
27	34	NA	3.8	96	7	484.6	Day

Table 4.2. Overview of collected data.

	Valid hauls	Day hauls	Night hauls	Fish in codend	Fish in collection bags	Min. length (cm)	Max. length (cm)
Atlantic cod	27	21	5	2963	3810	6	115
Haddock	27	21	5	6637	3187	6	85
Saithe	8	8	0	263	19	15	114
Whiting	6	4	2	172	189	7	55
Blue ling	3	3	0	379	139	24	119
Redfish	3	3	0	599	122	25	48

European plaice	23	18	5	4439	1961	10	65
Dab	11	7	4	653	408	6	44
American plaice	10	7	3	349	685	4	51
Monkfish	9	6	3	45	277	15	86

In 27 valid hauls where Atlantic cod and haddock dominated, there were 21 day hauls, five night hauls, and one haul fished across day and night time and was not listed in the table.

Table 4.3. AIC estimated for each candidate model by species. Bold numbers specifies the model with the lowest AIC or within 2 AIC. * denotes the best model selected as either having the lowest AIC, or is the simplest (by parsimony).

Model	Logit	Probit	Gompertz	Richard	DLogit	TLogit	Poly4	CLogit
Atlantic cod	7560.0	7557.9	7535.0	7538.2	7531.2	**7506.8**	7539.2	7562.0
Haddock	8634.9	8768.7	8456.6	8476.9	**8088.7***	**8087.8**	8160.4	8440.1
Saithe	175.3	179.4	173.1	141.9	160.1	166.1	**139.1**	156.1
Whiting	**473.3***	**473.4**	**473.7**	**475.2**	476.7	**474.3**	**473.3**	475.3
Blue ling	534.3	535.4	**533.5***	535.5	**532.2**	535.7	534.8	536.3
Redfish	995.9	998.0	995.1	**994.6***	996.3	998.0	6190.1	**992.9**
European plaice	8919.4	8921.4	8915.5	**8889.2***	8890.6	8896.6	**8888.5**	**8889.8**
Dab	1475.9	1476.2	1474.6	1476.7	**1439.5**	1445.5	1443.1	1477.9
American plaice	1735.3	1735.0	1728.4	1731.2	**1715.8**	1718.4	**1715.6***	1737.3
Monkfish	**255.1***	**254.9**	**254.7**	256.7	256.0	258.5	**255.1**	257.1

Table 4.4. Parameters of selected models estimated for each species. Values in () illustrate Efron percentile 95% CI. NA is not applicable value.

	A. cod	Hadd.	Saithe	Whit.	B. Ling	Redfish	E. plaice	Dab	A. plaice	Monk.
Model	TLogit	DLogit	Poly4	Logit	Gomp.	Richard	Richard	DLogit	Poly4	Logit
L50	53.3 (41.6-66.4)	12.3 (11.9-15.0)	NA	26.4 (5.4-35.6)	60.9 (51.5-66.3)	NA	NA	12.8 (9.1-15.5)	22.0 (19.9-200.0)	102.1 (82.5-158.8)
SR	49.9 (37.3-65.5)	2.7 (1.7-7.1)	NA	18.6 (9.9-77.0)	47.5 (33.8-81.7)	NA	NA	31.1 (6.5-185.9)	35.6 (0.0-40.9)	50.5 (25.7-100.0)
L501	9.8 (9.0-107.5)	20.9 (14.6-44.7)	NA	NA	NA	NA	NA	41.5 (29.3-200.0)	NA	NA
SR1	0.1 (0.1-84.9)	27.0 (0.1-45.1)	NA	NA	NA	NA	NA	0.1 (0.1-100.0)	NA	NA
L502	31.5 (9.2-109.5)	12.1 (11.6-15.0)	NA	NA	NA	NA	NA	11.2 (8.4-13.1)	NA	NA
SR2	4.5 (0.1-100.0)	1.5 (0.8-6.2)	NA	NA	NA	NA	NA	3.5 (0.1-8.5)	NA	NA
L503	68.8 (9.5-110.9)	NA	NA	NA	NA	NA	NA	NA	NA	NA
SR3	39.6 (0.1-100.0)	NA	NA	NA	NA	NA	NA	NA	NA	NA
p-value	0.001	0.983	0.906	0.113	0.008	0.161	0.002	0.251	0.205	0.914
Dev.	152.7	45.2	30.5	48.7	115.4	24.98	83.4	36.9	42.7	36.9
DOF	102	68	42	38	82	19	51	32	36	50

Table 4.5. AICc values were estimated for several models applied to examine the light effect on the escape of several species. The bold number is the lowest AICc specifies the selected model. * shows the AICc is chosen from similar or not significantly different AICc values based on AICc weight.

Atlantic Cod			
Independent variables	AICc	ΔAICc	Weight
Length + Scenario	**3080.4**	0	0.86
Length	3084.1	3.7	0.14
Null model	4580.1	1499.7	<0.001
Haddock			
Independent variables	AICc	ΔAICc	Weight
Length + Scenario	**2105.0**	0	0.86
Length	2108.6	3.7	0.14
Null model	4705.2	2600.2	<0.001
Whiting			
Independent variables	AICc	ΔAICc	Weight
Length	**196.1***	0	0.6
Length + Scenario	**196.9**	0.8	0.4
Null model	232.7	36.6	<0.001
European plaice			
Independent variables	AICc	ΔAICc	Weight
Length	**1972.4**	5	0.66
Null model	1974.8	2	0.2

Length + Scenario	1975.5	7	0.14
Dab			
Independent variables	AICc	ΔAICc	Weight
Length + Scenario	**622.8**	0	0.975
Length	630.1	7.4	0.025
Null model	652.9	30.1	<0.001
American plaice			
Independent variables	AICc	ΔAICc	Weight
Length + Scenario	**607.1**	0	3
Length +	627.1	20	2
Null model	678.1	71	1
Monkfish			
Independent variables	AICc	ΔAICc	Weight
Length + Scenario	**193.9**	0	3
Length +	195.9	2	2
Null model	203.3	9.4	1

Table 4.6. Akaike's information criterion (AIC) estimated for each candidate model for haddock between day and night. Bold number is the lowest AIC specifies the selected model. * shows the AIC chosen as the simplest model between AIC values are similarly or not significant different.

Species	Scenario	Logit	Probit	Gomp.	Richard	DLogit	TLogit	Poly4	CLogit
Atlantic cod	Day	6251.3	6250.6	6227.2	6231.2	6207.2	**6191.6**	6226.5	6253.3
	Night	**939.9**	941.5	952.9	941.9	942.5	944.6	943.7	941.9
Haddock	Day	6060.6	6182.9	5925.4	5941.5	5603.9	**5601.4**	5660.9	6062.6
	Night	1765.4	1773.9	1703.9	1712.6	**1615.8**	1621.8	**1614.0***	1767.4
Whiting	Day	153.52	154.8	**148.5***	150.9	**147.2**	150.8	**148.2**	155.5
	Night	**264.1***	**264.0**	**264.3**	**263.9**	266.4	271.9	265.1	264.3
European plaice	Day	6967.4	6968.9	6964.7	6951.4	6952.2	6952.9	**6946. 8**	6951.4
	Night	1279.4	1280.0	1278.1	**1263.7**	1271.5	1277.4	14092.6	1267.5
American plaice	Day	1347.7	1347.6	1339.7	1342.6	1328.4	1334.4	**1327.3**	1349.7
	Night	**386.8***	**386.7**	**386.7**	388.7	**386.8**	388.9	390.2	388.8
Dab	Day	1006.5	1006.8	1004.4	1006.7	**975.3**	978.6	980.7	1008.5
	Night	439.5	440.4	438.1	435.3	425.5	431.5	**419.1**	431.2
Monkfish	Day	**194.8***	**194.6**	**194.3**	**196.4**	197.4	201.4	199.6	196.8
	Night	**59.1***	**59.2**	**59.8**	**61.0**	61.8	67.8	62.2	**61.0**

Table 4.7. Parameters of selected models estimated for roundfish between day and night. Values in () illustrate Efron percentile 95% CI. * is not applicable value.

	Atlantic cod		Haddock		Whiting	
Time	Day	Night	Day	Night	Day	Night
Model	TLogit	Logit	TLogit	Poly4	Gompertz	Logit
L50	48.7 (33.6-66.4)	63.5 (58.8-76.8)	12.1 (11.6-14.0)	17.4 (14.6-200.0)	23.0 (0.1-26.3)	48.5 (0.1-63.9)
SR	52.6 (39.7-77.6)	35.7 (27.7-52.1)	2.4 (1.3-7.4)	10.1 (8.1-64.3)	13.6 (7.8-48.0)	100 (13.3-100.0)
C1	0.6 (0.1-0.7)	*	0.1 (0.0-0.3)	*	*	*
C2	0.2 (0.1-0.7)	*	0.2 (0.1-0.8)	*	*	*
L501	69.0 (62.6-111.5)	*	22.8 (15.9-50.5)	*	*	*
SR1	42.8 (0.1-100.0)	*	0.1 (0.1-49.1)	*	*	*
L502	28.4 (25.9-71.0)	*	12.9 (11.6-28.0)	*	*	*
SR2	3.0 (0.1-100.00)	*	41.1 (0.1-58.2)	*	*	*
L503	9.6 (7.9-32.6)	*	11.9 (0.1-13.0)	*	*	*
SR3	0.3 (0.1-21.8)	*	1.5 (0.1-82.5)	*	*	*

p-value	0.001	0.166	0.782	0.377	0.499	0.065
Deviance	145.1	114.6	51.3	44.3	36.3	27.7
DOF	93.4	101	60	42	37	18

Table 4.8. Parameters of selected models estimated for flatfish and monkfish between day and night. Values in () illustrate Efron percentile 95% CI. * is not applicable value.

	European plaice		American plaice		Dab		Monkfish	
Time	Day	Night	Day	Night	Day	Night	Day	Night
Model	Poly4	Richard	Poly4	Logit	DLogit	Poly4	Logit	Logit
L50	200.0 (*-200.0)	83.1 (*-304)	200.0 (*-200.0)	24.8 (9.2-51.1)	13.7 (10.1-17.1)	*	92.2 (78.7-140.4)	168.7 (84.5-183.4)
SR	50.0 (*-50.0)	*	50.0 (*-50.0)	46.0 (23.5-100.0)	30.1 (21.9-187.9)	*	42.6 (22.0-100.0)	100.0 (17.5-100.0)
C1	*	*	*	*	0.4 (0.3-0.5)	*	*	*
L501	*	*	*	*	42.0 (33.2-200.0)	*	*	*
SR1	*	*	*	*	0.1 (0.1-48.0)	*	*	*

L502	*	*	*	*	12.3 (10.5-14.4)	*	*	*
SR2	*	*	*	*	2.2 (0.1-6.2)	*	*	*
p-value	0.013	0.179	0.376	0.237	0.056	0.238	0.913	0.993
Dev.	66.2	44.7	37	36.2	43.15	35.1	36.1	20.6
DOF	43	37	35	31	30	25.6	49	39

4.9 Figures

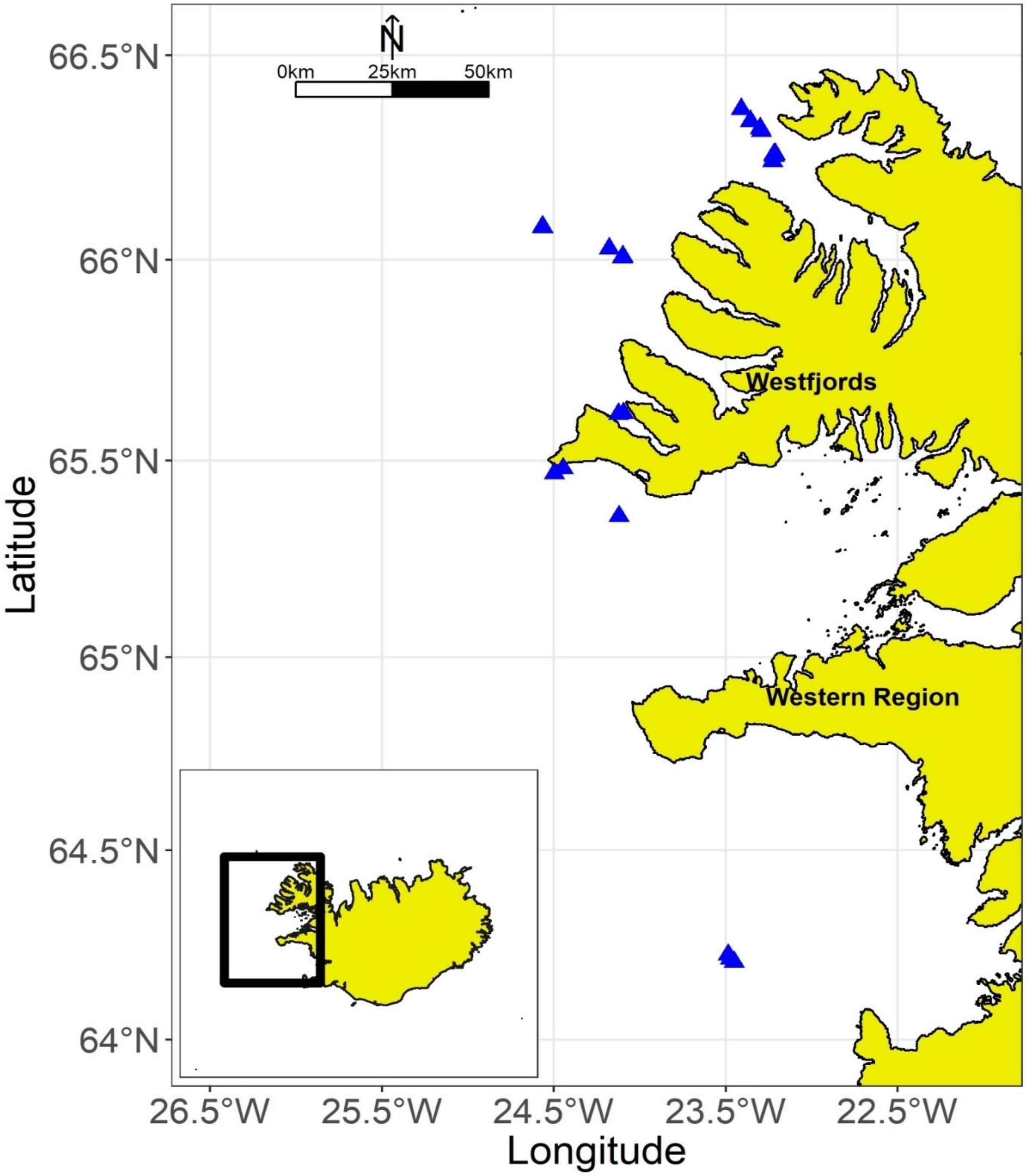


Figure 4.1. Map of the study area off western Iceland. The blue triangles showed all locations of hauls. Map is created using the data derived from global administrative areas (https://gadm.org/); license: GADM license.

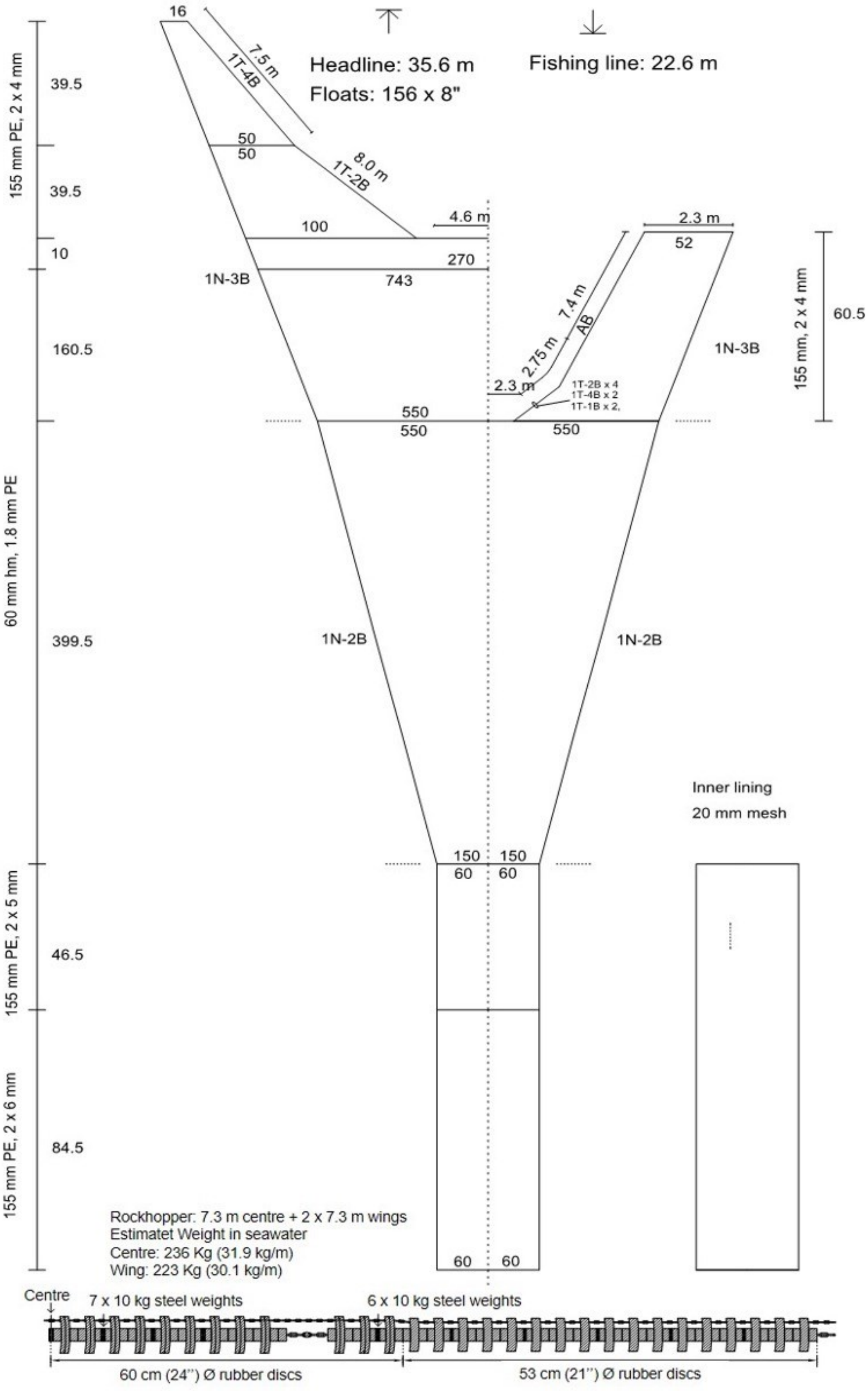
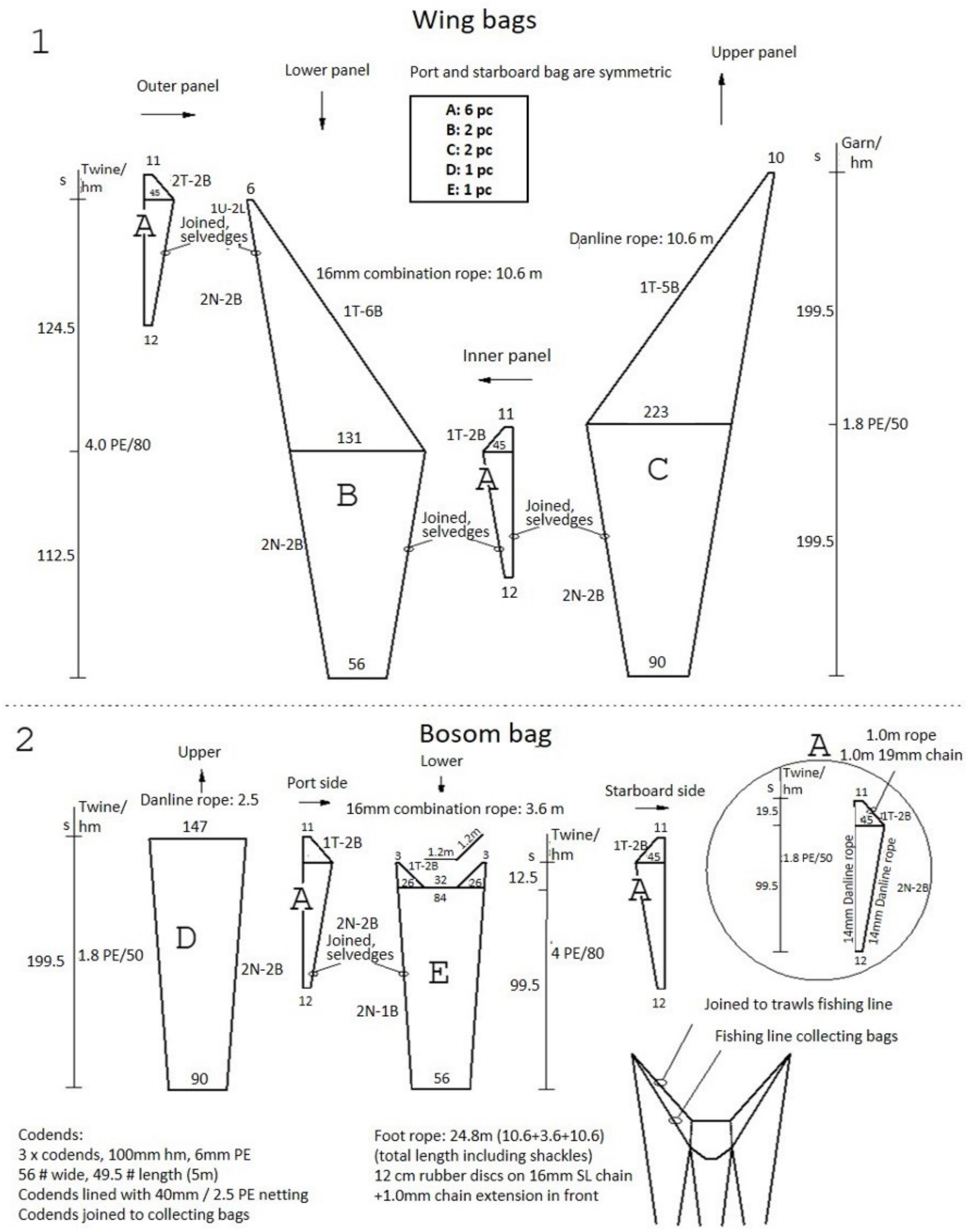


Figure 4.2. Net plan of the Gulltoppur trawl.



Codends:
3 x codends, 100mm hm, 6mm PE
56 # wide, 49.5 # length (5m)
Codends lined with 40mm / 2.5 PE netting
Codends joined to collecting bags

Foot rope: 24.8m (10.6+3.6+10.6)
(total length including shackles)
12 cm rubber discs on 16mm SL chain
+1.0mm chain extension in front

Figure 4.3. The net plan of the collecting bags used to capture fish that escaped under the trawl. (1) illustrates the wing bags, and (2) illustrates the bosom bag.

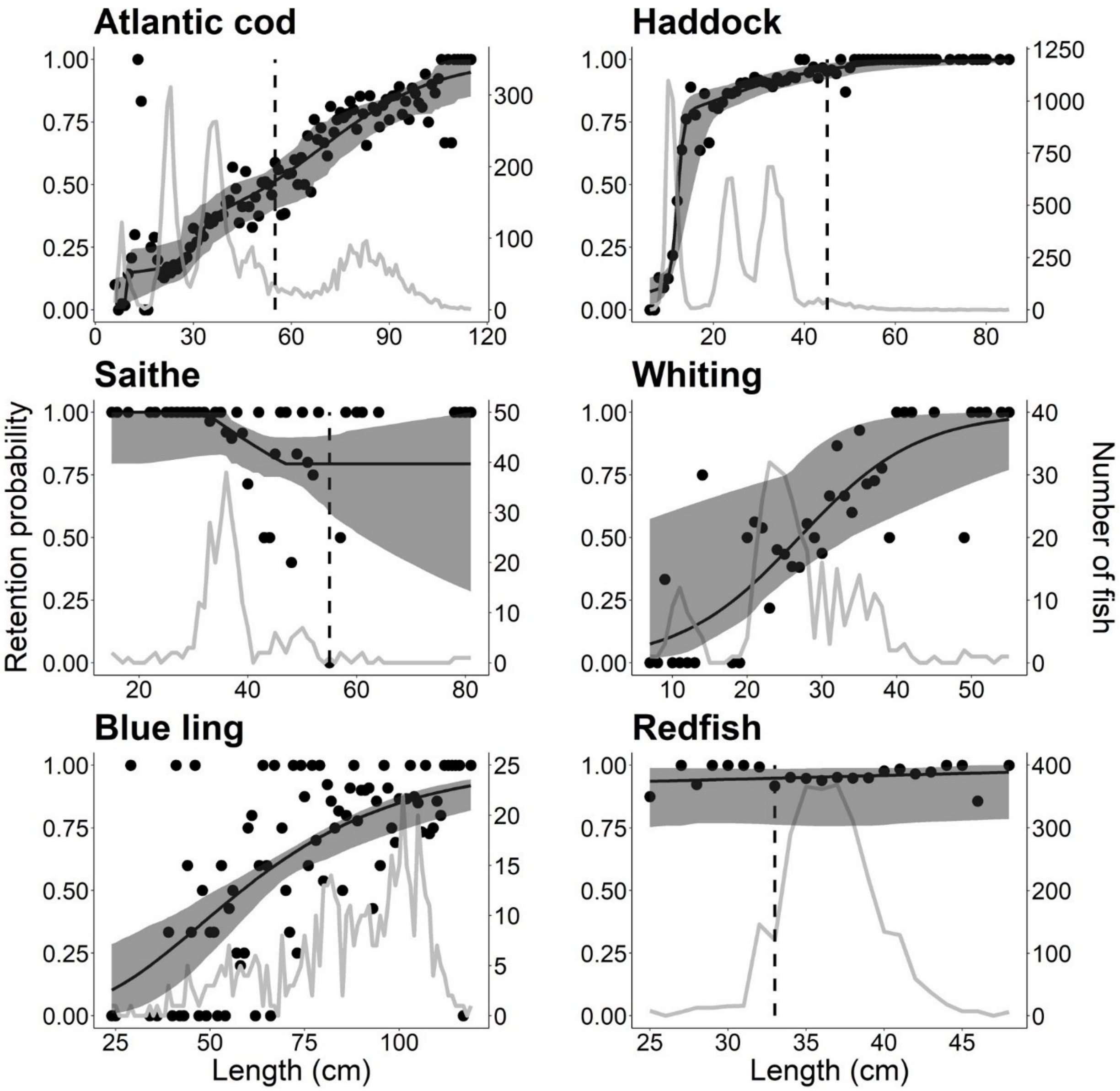


Figure 4.4. Size selection curves of roundfish. The thick black line represents the mean curve; the grey line is the size distribution of the population; black dots illustrate the experimental data; the black dashed vertical line is the minimum reference length for each species; the grey shaded areas are the 95% confidence bands.

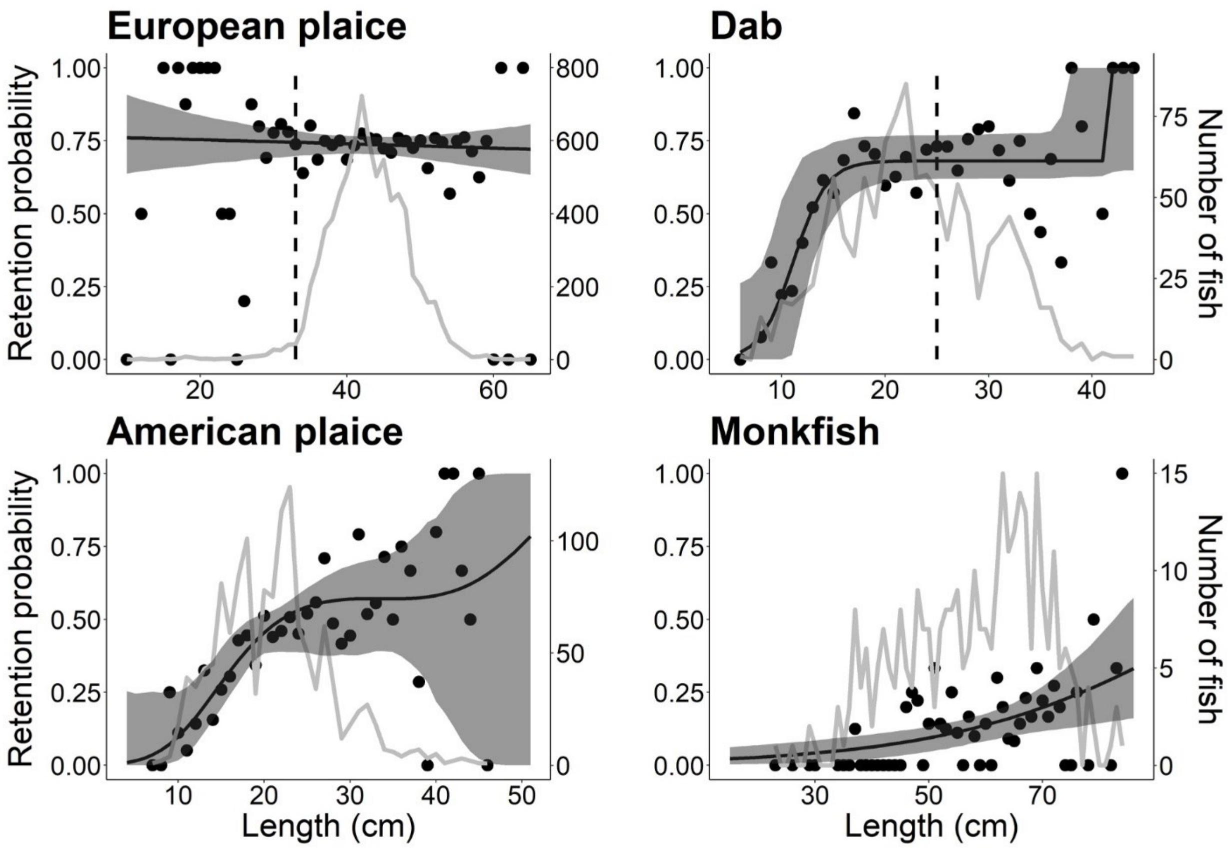


Figure 4.5. Size selection curve of flatfish and demersal fish. The thick black line represents the mean curve; the grey line is the size distribution of the population; black dots illustrate the experimental data; the black dashed vertical line is the minimum reference length for each species; the grey shaded areas are the 95% confidence bands.

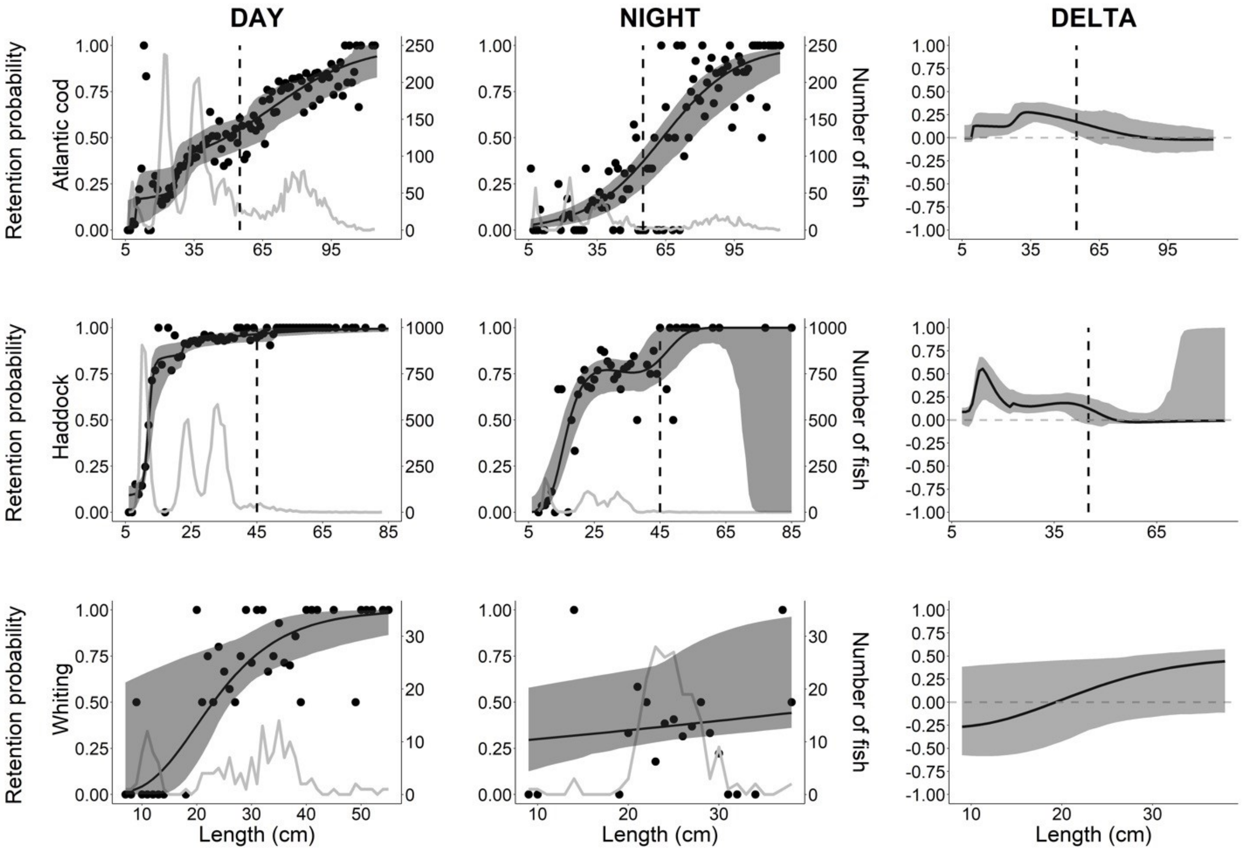


Figure 4.6. The selectivity curves of Atlantic cod, haddock, and dab during the day (left column) and the night (middle column) and delta curves (right column). In each size selectivity curve, the thick black line represents the mean curve; the grey line is the size distribution of the population; black dots illustrate the experimental data; the black dashed vertical line is the minimum length size for each species; the grey shaded areas are the 95% confidence bands. In each delta curve, the thick black curve is the fitted delta curve; grey shaded areas are the 95% confidence intervals; the vertical black dashed line represents the minimum reference length. The horizontal dashed line at 0.0 is to determine the difference in length-dependent retention probability between day and night. If the Delta curve is above 0.0 at a particular length, then the retention probability during the day is higher, if below 0.0, then retention was higher at night.

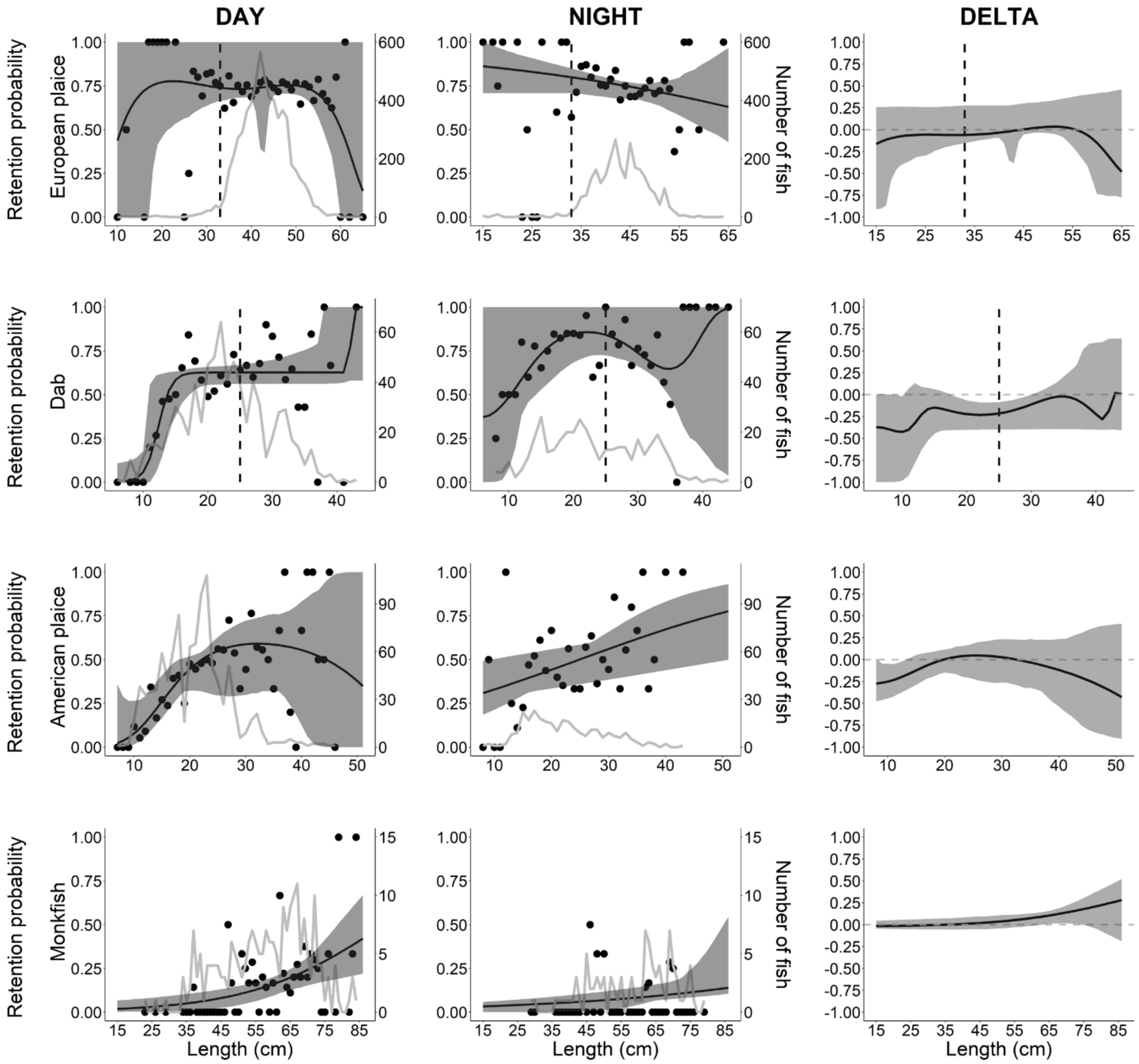


Figure 4.7. The selectivity curves of flatfish (European plaice, dab, and American plaice) and monkfish during the day (left column) and the night (middle column) and delta curves (right column). In each size selectivity curve, the thick black line represents the mean curve; the grey line is the size distribution of the population; black dots illustrate the experimental data; the black dashed vertical line is the minimum length size for each species; the grey shaded areas are the 95% confidence bands. In each delta curve, the thick black curve is the fitted delta curve; grey

shaded areas are the 95% confidence intervals; the vertical black dashed line represents the minimum reference length. The horizontal dashed line at 0.0 is to determine the difference in length-dependent retention probability between day and night. If the Delta curve is above 0.0 at a particular length, then the retention probability during the day is higher, if below 0.0, then retention was higher at night.

CHAPTER 5. Inferring fish behavior at the trawl mouth from escape location

5.1 Abstract

In this study, we used escape location underneath the trawl to understand groundfish herding behavior at the trawl mouth. Three collecting bags (port, center, starboard) were mounted under the trawl and behind the footgear to collect escapees. The escape-at-length of species that escaped into the center bag were compared to the two wing bags to infer fish response behavior, herding behavior, and swimming capacity at the trawl mouth. For roundfish, smaller-sized individuals escaped more in the center for both Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), < 20 and 11 cm, respectively, indicating that larger-sized fish were to a greater extent seeking to escape under the trawl at the wings, versus small fish being herded to the center and likely overrun due to reduced swimming capacity. For flatfish and monkfish (*Lophius piscatorius*), results varied. European plaice (*Pleuronectes platessa*), American plaice (*Hippoglossoides platessoides*), and monkfish were caught most often in the wings, though not significantly for American plaice. Catches of dab (*Limanda limanda*) between 18 and 27 cm were significantly higher in the center, with no difference for smaller and larger individuals. The differences between fish escape location likely result from a combination of varying herding behavior, size, and swimming capacity. Here, we were able to show how these size-dependent behaviors relate to fish response behavior, escape behavior, size, and likely swimming capacity.

5.2 Introduction

Fish reactions to trawl components could alter fish’s herding and escape patterns, directly affecting catch efficiency. Several investigations have revealed that most fish in front of the trawl are herded into the trawl path by visual cues and trawl components (doors, bridles, and footgear), thus becoming available for capture (Ryer, 2008; Wardle, 1993; Winger et al., 2010). Fish behavior during the herding process, particularly at the mouth of the trawl, is a critical process when considering how to improve and understand trawl selectivity (Engas and Godø, 1989; Godø and Walsh, 1992). During the herding process, fish react to the advancing trawl components in a way that is dependent on their swimming capacity and endurance, visual range, and physiological conditions, which can vary among species and differ according to size (Beamish, 1966; He, 1991; Winger et al., 1999). This leads to different behavioral patterns of fish at the trawl mouth, which in turn results in fish either falling back into the trawl net or escaping under the fishing line or over the headline of the trawl (Winger et al., 2010).

Roundfish reactions have been observed to approaching trawl components (Pitcher and Parrish, 1993; Wardle, 1993). These reactions include moving closer to the seabed and swimming away from trawl doors and bridles to keep the approaching threats within visual range, known as the "fountain maneuver" pattern (Wardle, 1993), which herds fish into the trawl path (Winger et al., 2010). Once fish reach the trawl mouth (i.e., trawl opening), they alter their course and swim in the opposite direction of the tow, in front of the trawl (Winger et al., 2010).

Several studies have shown that roundfish behavior in the trawl mouth varies among species. For example, Atlantic cod (*Gadus morhua*) maintain a position close to the seabed, where haddock (*Melanogrammus aeglefinus*) tend to rise in the water column (Main and Sangster, 1981; Godø and Walsh, 1992). Furthermore, the response of roundfish, such as Atlantic cod and haddock, at the trawl mouth was size-dependent. Valdemarsen et al. (1985) found that small cod and haddock entered the trawl at heights closer to the seabed than larger individuals. A follow-up study by Engås and Godø (1989) revealed length-dependent escape, where more small cod and haddock escaped underneath a survey trawl's fishing line than larger fish. Investigations supported this length-dependent behavior at the trawl mouth, where larger fish with greater swimming endurance can keep their station for long periods and find escape routes compared to small fish which tend to seek escape under the fishing line (Ingólfsson and Jørgensen, 2006; Ryer, 2008; Wardle, 1993).

Behavioral observations of flatfishes show that individuals respond to the advancing trawl at a shorter distance than roundfish, and reactions are characterized by an anti-predator strategy (Main and Sangster, 1981; Ryer, 2008). The initial reaction is to conceal themselves with camouflage, which combines burying themselves in sediment, cryptic coloration, and reducing activity to minimize their detection by a predator (Gibson, 2005). When the bridles of the trawl advance closer, fish either remain immobile, allowing the bridles to pass above them, or swim at a 90° angle into the trawl path (Main and Sangster, 1981; Ryer, 2008; Winger et al., 2010; Bryan et al., 2014). Some fish that swim slower than the speed of the advancing bridle are available to escape underneath, while others that swim equal to or greater than the coming bridle, can reach the trawl path and become available for capture (Main and Sangster, 1981; Ryer et al., 2010). At the trawl mouth, reactions in front of the groundgear are typically brief, often less than 1 min (Ryer, 2008), but can be greater than 5 min (Bayse et al., 2016), and then fish either flip and fall back into the net at the heights less than 1 meter from the seabed or escape under the groundgear (Bublitz, 1996; Bayse et al., 2016).

Different escape patterns underneath the trawl, between and within species, have been quantified using different methods. Starting in the 1980s, underwater camera technology was used to investigate fish behavior at the trawl mouth (Main and Sangster, 1981). Qualitative descriptions of fish behavior continued through the 1990s (Walsh and Hickey, 1993; Godø, 1999). Increasingly, quantitative techniques have been used to describe fish behavior at the trawl mouth that lead fish either escaping under or entering the trawl (Albert et al., 2003; Underwood et al., 2015; Bayse et al., 2016). Additionally, the use of underwater video in combination with the catch data has shown potential for quantifying fish behavior while herding (Godø, 1999; Weinberg and Munro, 1999; Larsen et al., 2018).

The bottom trawl includes a weighted groundgear at the bottom of the trawl mouth to keep the trawl in contact with the seabed and protect the netting from damage (Montgomerie, 2022). The form of groundgear is dependent on the type of bottom trawl, seabed, and targeted species. Recently, the rockhopper groundgear has been widely used in commercial trawl fisheries to allow fishing on rougher bottoms, reduce net damage, and can improve capture efficiency (Engås and Godø, 1989; Ingólfsson and Jørgensen, 2006). Additionally, rockhopper groundgear has been shown to be more effective in catching fish close to the bottom relative to traditional steel bobbins gear (Main and Sangster, 1985; Engås and Godø, 1989). By using bigger rubber spacers between the rockhopper discs, the inter-disc spaces can be increased to facilitate escape of small fish under the groundgear (Engås and Godø, 1989; Walsh, 1992). For instance, the escape rates of gadoid species have been observed to be length-dependent (Engås and Godø, 1989; Ingólfsson and Jørgensen, 2006).

The purpose of this study was to infer fish response behavior, herding behavior, and swimming capacity at the trawl mouth by comparing retained fish between collecting bags under the trawl. Fish escape was considered a consequence of fish behavior or response to the herding effect of the trawl (Walsh, 1992). Additionally, the effectiveness of fish behavior (i.e., ability to escape) at the trawl mouth may differ according to fish size, resulting in differences in length-based escape under the groundgear at particular locations. However, most works on fish behavior at the trawl mouth have focused on the center area, and less quantitative work has been focused on the wings. Here, we used escape-at-length comparison data to describe and quantify the extent to which fish behavior sets limits to fish escape ability along the groundgear. This study provides additional insights into the length-dependent behavior of fish at different areas of the trawl mouth during the herding process, which are currently unclear, and important for further development and understanding of bottom trawl selectivity and fish behavior.

5.3 Materials and Methods

5.3.1 Sea trials

Sea trials were conducted onboard the research vessel "Árni Friðriksson" (70 m, 4 × 1000 kW) from 7 to 13 September 2009. The fishing grounds were off the Westfjords and in Faxaflói Bay Iceland (Fig. 5.1). Fishing was carried out during day and night (between 22:20 (sunset) and 4:30 (sunrise), based on the local time zone of the study area during sea trials (see timeanddate.com)). Tow duration was defined from when the gear was on the bottom (estimated by echograph) till the start of haulback. Fishing locations were chosen in collaboration with the captain such that rough bottoms were avoided due to the vulnerability of the collecting bags to damage. Gear performance (towing velocity, duration, warp length, and door spread) was recorded for each tow.

5.3.2 Gear specifications

The trawl used was the "Gulltoppur", a design used by many Icelandic fishers (Fig. 5.2). The trawl doors were of the type of Poly-Ice no. 8, 2700 kg. Backstraps were 9 m long, sweeps 65 m, bridles 67 m and ground gear extensions 13 m. The total distance from doors to the ground gear was 154 m. A commercial rockhopper groundgear was used. It had 60 cm diameter discs at the center and the three rearmost discs of the wing. The rest of the wing had 53 cm discs. The gear weight in seawater was approximately 30 kg m^{-1}. Small mesh (20 mm) collecting bags were used to retain all the fish that escaped underneath the fishing line of the trawl (Ingólfsson and Jørgensen, 2006). Three collecting bags were attached to the groundgear, including a center bag, and two wing bags (Fig. 5.3). For each collecting bag, the headline of the collecting bag was joined to the fishing line of the trawl. The fishing line of the collecting bags had a groundgear made of 12 cm rubber discs threaded on a 24.8 m long 16 mm steel chain. A 1.0 m long chain extension, made of 19 mm steel, was used to connect the front ends of the gear to the front ends of the fishing line. There were no gaps between the bags.

5.3.3 Catch sampling

Catches from the collecting bags and codend were processed separately. Individuals were counted and measured to the nearest centimeter below total length. Subsampling was applied if a large number of a species was encountered. Tows that had less than 10 observations in collecting bags were removed from the analysis for the specific species.

5.3.4 Data analysis

This study compared the escape-at-length of each species that escaped between the center and wing sections of the groundgear. This escape-at-length comparison is performed using the *Center/(Center+Wing)* function, where *Center* is the number of fish measured in the center bag, and *Wing* is the number of fish measured in both wing bags, per length class (cm). The function estimates the proportion at length in catch from the center bag as a proportion of the total count at length from center and wing bags. As proportional data, it is considered binomial.

The escape-at-length data was modeled following procedures similar to Holst and Revill (2009) and Eighani et al. (2020). The curves of the proportions (logit; (*Center/Center+Wing*)) were modeled with low-order orthogonal polynomials (0 to 4th degree) using Generalized Linear Mixed Models (GLMMs) in R statistical software (R Development Core Team, 2009). The dependent variable was the logit (*Center/(Center+Wing)*; catch proportion at length), the independent variable was fish length (*MLL*), and the subsample ratio between *Center* and *Wing* was considered as an offset. The random effect of *Tow* was added on either or both intercept and slope of the models to account the variations in the escape-at-length data among tows due to the effects of extrinsic factors (i.e. environmental conditions, fish density, etc.) and/or intrinsic factors (i.e. differences in individual fitness of same length class between tows). The restricted maximum likelihood (REML) method was used to fit the models using the glmer function of the lme4 package (Bates et al., 2015). The model equation was therefore:

$$\text{Logit}\ (Center/(Center+Wing)) = \log\ (q_b/q_w) + \beta_0 + \beta_1 MLL + \ldots + \beta_k MLL^k + \varepsilon$$

where q_b and q_w are the subsampling ratios for *Center* and *Wing,* β_0 is the intercept. β values are the model parameters, increasing from 1 to k = 4, corresponding to increasing the polynomial order from linear polynomial to 4th degree polynomial. ε is the between haul random variable, where $\varepsilon \sim N(0, \sigma^2)$. For each model above a 1st degree polynomial, the independent variables were rescaled to prevent correlation from polynomial terms as orthogonal polynomials using the *poly* function in the stats package. A random effect was used originally on each polynomial term. However, if convergence problems or singularity were observed, the random effect was removed from the linear term to enable proper model fit. DHARMa was used to investigate model dispersion and residual diagnostics (Hartig, 2021).

The proportion values were estimated to be between 0 and 1 per length class. For example, a proportion of 0.5 means that the same retention rate was observed between the center and wings for a particular length class. Additionally, if a proportion of 0.75 was observed, it means 75% of individuals escaped in the center and 25% in the wings at a specific length. Model selection was based on the minimum Akaike information criterion value (Akaike, 1974) with a correction for small sample sizes (AICc). It was calculated using the AICctab function in the bbmle package (Bolker, 2021). The best model was chosen with the lowest AICc value. If there were multiple models within 2 AICc, the simplest model was considered as the best model. The best model selected for each species was then used to investigate the effects tows at day or night (diel effect) on the escape-at-length of species between locations if observed in at least 5 tows in each treatment (i.e. day and night tows). The diel effect was added in the model as the independent variable. If the diel effect significantly affected size selectivity was determined by a likelihood ratio test, where the test statistic (χ^2) determined the difference in deviance between the best model and the best model containing the diel effect at an α of 0.05.

The final model´s confidence intervals (CIs) were estimated using the bootMer mixed model bootstrapping function in lme4 and the boot.ci function in the boot package (Canty and Ripley, 2021) with 1000 simulations. The CIs were used to determine the significant difference in proportion at length retained between the center and wings. If the CIs included 0.5 at a particular length, there is no significant difference between escape locations.

This study was performed by the Marine and Freshwater Research Institute, which complies with the regulation imposed by the Icelandic “Food ministry”. This regulation allows the landing of all fish catch during sea trials.

5.4 Results

A total of 34 tows were made. Nine tows were removed due to sampling inconsistencies. Thus, 25 valid tows were used in the subsequent analyses, including 20 tows during the day and five at night. Tow speeds were 3.6 kn on average (range: 3.5-3.9 kn), and the average tow duration was 44 min (range: 23-79 min). The warp length was 207.0 m (range: 122.5- 484.6 m), and the door spread was 58.5 m (range: 43 to 96 m). Tows were conducted at depths ranging from 26 to 192 m, with a median depth of 73 m.

A total of 31 species were observed. However, six were found in sufficient abundance to be used in the analyses, including roundfish (Atlantic cod and haddock), flatfish (European plaice (*Pleuronectes platessa*), American plaice (*Hippoglossoides platessoides*) and dab (*Limanda limanda*) and monkfish (*Lophius piscatorius*). Atlantic cod was the most frequently occurring species and observed in 25 valid tows, including 19 day tows, five night tows, and one tow was carried out in both day and night. The second most frequent species were haddock and European plaice, observed in 23 (17 day tows, five night tows, and one tow was carried out in both day and night) and 22 (18 day tows and 4 night tows) valid tows, respectively, followed by American plaice, observed in 10 valid tows (seven day tows and three night tows). Dab and monkfish observed in 9 valid tows (six day tows and three night tows) (Table 5.1). One tow was subsampled on the port wing bag for Atlantic cod, haddock, and American plaice. Subsampling occurred on one tow, on the center bag for European plaice. For subsampling tows, at least 55% fish or more were measured, except for American plaice, whose subsampling was 25%. No tows were subsampled for dab and monkfish. For species that had at least 5 tows for day and night, no model showed a significant effect ($p > 0.05$) for fishing at night or day.

Atlantic cod

A total of 3796 Atlantic cod escaped into the collecting bags, 3794 measured for analysis; 1689 in the center, and 2105 in the wings (Table 5.1). Figure 5.4A shows the size structure observed for Atlantic cod, where lengths ranged between 6 and 109 cm; most individuals were less than 55 cm. By comparing AICc values in Table 5.2, the best model was the logit-cubic and the random effect *Tow* on the intercept and quadratic slope (Table 5.3). The results showed that more Atlantic cod escaped in the center at lengths < 20 cm than at the wings. Additionally, a large proportion (approximately 90%) of the smallest length classes escaped in the center. However, Atlantic cod > 27 cm escaped at the wings significantly more often than the center with the highest catch proportion of 85% at the 110 cm length class (Fig. 5.4B).

Haddock

A total of 3177 haddock escaped into the collecting bags, 3175 measured for analysis; 1585 in the center and 1590 in the wings (Table 5.1). Fish length ranged between 6 and 50 cm; but most individual escapees were less than 15 cm (Fig. 5.4C). The escape-at-length curve of haddock was best described by the logit-quadratic and the random effect *Tow* on intercept and quadratic slope (Table 5.2), and the model's parameters were shown in Table 5.3. The results show that haddock < 11 cm escaped more often in the center than the wings, with the highest escape proportion of 75% at the smallest length class observed (Fig. 5.4D). By contrast, fish greater than 14 cm escaped significantly more in the wings than the center, and escapees increased in the wings with increasing length at 35 cm and up (Fig. 5.4D). For escapees > 45 cm, large CIs were observed, attributing to the few individuals that escaped in the collecting bags and no significant difference was observed (Fig. 5.4D).

European plaice

A total of 2025 European plaice escaped into the collecting bags, 1958 measured for analysis; 739 in the center versus 1219 in the wings (Table 5.1). The size structure observed for European plaice is shown in Figure 5.5A, where lengths ranged between 10 and 65 cm; most individuals were between 30 and 55 cm (Fig. 5.5A). By comparing AICc values in Table 5.2, three models: logit-constant, logit-linear1, and logit-quadratic1, were within 2 AICc values, and the logit-constant model was then chosen since it was the simplest model (Table 5.3). The escape-at-length curve showed that significantly more (62.5%) European plaice escaped in the wings than in the center over all length classes (Fig. 5.5B).

American plaice

Out of the 1158 American plaice that escaped into the collecting bags, 685 were measured for analysis, including 279 in the center versus 406 in the wings (Table 5.1). The size structure observed for American plaice ranged between 7 and 46 cm; most individuals were between 10 and 30 cm (Fig. 5.5C). The AICc values in Table 5.2 showed that the logit-constant, logit-linear1, and logit-linear2 are good models to describe the experimental data, and the logit-constant model was then chosen since it was the simplest model (Table 5.3). The model indicated that American plaice escaped into the wings more often (55%) when compared to the center (45%), but these differences were not statistically significant as the CIs included 0.5 (Fig. 5.5D).

Dab

For dab, a total of 405 individuals escaped into the collecting bags, 220 in the center and 185 in the wings (Table 5.1). The fish lengths ranged from 6 to 41 cm, with 10 - 35 cm having a high frequency (Fig. 5.5E). Based on AICc values (Table 5.2), the logit-quadratic with the random effect *Tow* on the intercept was the best model (Table 5.3). The escape-at-length curve was inflated at lengths between 18 and 33 cm by a few tows with large numbers at those sizes in the center compared with the wings (Fig. 5.5F). However, a significant difference was only found in the lengths between 18 and 27 cm, where the center had a little over half (54% at 23 cm) of the escaping dab (Fig. 5.5F). For the lengths < 18 and > 27 cm, the wing bags caught more fish than the center; but these differences were not statistically significant (Fig. 5.5F).

Monkfish

The escape-at-length of monkfish was analyzed using 277 individuals escaping into the collecting bags during the experiment; 61 in the center and 216 in the wing (Table 5.1). Figure 5.6A shows the size structure of monkfish, where lengths ranged between 23 and 83 cm; most individuals were between 35 and 75 cm. Mixed models could not be used for this analysis due to singularity and convergence issues, likely due to the number of monkfish observed. Thus, generalized linear models were used as previously described with the random effect dropped and parametric CIs. The logit-constant model had the lowest AICc value (Table 5.2) and the model's parameters were shown in Table 5.3. The proportion curve of monkfish was under 25% over all of the length classes, meaning that monkfish escaped more often in the wings (approximately 80% on average) than the center (approximately 20% on average), and these differences were statistically significant (Fig. 5.6B).

5.5 Discussion

In this study, we quantified the length-dependent escape of fish at particular areas of the trawl mouth in terms of their response to herding effects, and swimming capacity. The analysis and results presented in this study were based on escape-at-length comparisons using the collecting bags method. Although the experimental design quantifies escapees under the fishing line, attaching the collecting bags potentially affects the fish´s behavior during the herding process. Collecting bags mounted behind groundgear might influence the gear geometry relative to standard commercial rigging. This could have affected fish behavior or response to the trawl components, particularly the groundgear. However, a previously published observation with a similar design revealed no abnormality in the door spread and headline height when attaching the collecting bags to the trawl (Ingólfsson and Jørgensen, 2006). In addition, Krag et al. (2010) tested a similar type of collecting bag system in a flume tank prior to their application in field research. Thus, the experimental trawl was assumed to be similar to the commercial trawl in trawl geometry, and the effects of collecting bags were regarded as negligible.

The escape-at-length analysis revealed a similar length-dependent escape under the trawl for Atlantic cod and haddock at different locations. The length-dependent escape by which smaller-sized individuals escaped more in the center for both Atlantic cod and haddock, < 20 and 11 cm, respectively, whereas larger-sized fish (Atlantic cod > 27 cm and haddock > 14-46 cm) escaped more at the wings. If these escape-at-length curves were interpreted solely as a function of fish behavior and/or swimming capacity at the trawl mouth, our study suggests that larger-sized fish likely were seeking to escape under the trawl at the wings, versus small fish being herded to the center and likely overran.

Main and Sangster (1981) initially observed that Atlantic cod remain close to the seabed in response to the approaching trawl components. However, recent observations have suggested that Atlantic cod probably swam or rose over the groundgear as they passed through the net rather than remain close to the seabed (Pol and Eayrs, 2021; Thomsen, 1993). Combined with swimming capacity, these observations could explain the difference in escape behavior of Atlantic cod in the trawl mouth based on sizes found between locations (center or wings). When aggregating in the center section, large Atlantic cod with greater swimming ability may rise above the fishing line, whereas small fish try to make escape attempts through spaces between rockhoppers of the groundgear (Ingólfsson and Jørgensen, 2006; Pol and Eayrs, 2021; Ryer, 2008). An alternative explanation for the differing escape behavior could be that if Atlantic cod react to the advancing trawl components late, they show erratic swimming, particularly near the trawl's wings. This induces fish to be either run over by the groundgear of the trawl or suddenly dart away by using a kick and glide gait (Brinkhof et al., 2017; Kim and Wardle, 2003). This response may lead to large fish escaping underneath the fishing line at the wing sections.

These results provided additional insights into Atlantic cod behavior at the trawl mouth compared with prior studies. The escape behavior of Atlantic cod related to the herding effect of the groundgear was quantified by Walsh (1992), Ingólfsson and Jørgensen (2006), and in a more recent study by (Krag et al., 2010). These studies used the mean catch data collected by the collecting bag method to compare the escape behavior of Atlantic cod between center and wing areas of the groundgear. The authors suggested that Atlantic cod more often escape the trawl from the center area rather than the wing areas as they aggregated in the front of the center part of the groundgear in response to the herding effect (Wardle, 1993). In this study, we further found the escape rates at several particular lengths of Atlantic cod and compared those between escape locations, which could not be verified in previous studies.

Compared to Atlantic cod, the behavioral tendency of haddock at the trawl mouth has been observed to rise at heights above the fishing line as they entered the trawl net, confirming previous studies (Godø and Walsh, 1992; Main and Sangster, 1981). At least 74% of haddock escapees were less than 15 cm in length. This might indicate that the heights at which individuals rise at the trawl mouth depended on the individual's swimming capacity, which differs according to the fish sizes. When herding at the center of the trawl mouth, small haddock (< 11 cm) with poor swimming capacity may be seeking the spaces under the fishing line for escape relative to large individuals (> 14 cm), or were simply run over by the trawl due to fatigue. This could be a plausible explanation that more small individuals were escaping from the center than the wings. In addition, a relatively high proportion of haddock > 14 cm escaped through the wing areas, indicating that these haddock may illustrate an erratic response when they react to the approaching trawl components. Like Atlantic cod, the erratic response of haddock is represented by sudden darting away, kicking and gliding, or running over the groundgear, leading to an increase in the number of large individuals escaping at the wings compared to the center.

The behavioral difference between Atlantic cod and haddock has played a vital role in developing separator trawls to separate Atlantic cod from the catch of haddock (Krag et al., 2010; Brinkhof et al., 2017; Larsen et al., 2018). Increasing spaces between the fishing line and the seabed can increase the escape of Atlantic cod under the trawl, therefore reducing bycatch of Atlantic cod from haddock-directed fisheries (Krag et al., 2010). Our results provided additional insights in which Atlantic cod > 27 cm more often escaped at the wings. These results could potentially be used to develop new groundgear to avoid capture of large Atlantic cod and small haddock.

The escape patterns of flatfish and monkfish between locations varied among species, and was less related to fish length. European plaice and monkfish were likely seeking to escape at the wings other than the center, and escape rates were uniformed over length, indicating that the behavior of European plaice was not related to fish length. Similarly, the slightly higher number of American plaice were likely attempting to escape at the wings rather than the center over the length, even though the difference was not statistically significant. In contrast, the escape of dab under the trawl was related to fish length, where a considerable proportion of fish > 27 cm escaped more often in the center. These differences in escape patterns are probably due to behavioral differences, including escape behavior and fish response to the herding effect of the trawl.

Most European plaice that escaped underneath the trawl was greater than 30 cm, including many commercial sizes (33 cm Minimum Conservation Reference Size). Their escape was observed more often at the outer groundgear areas. This implied that the herding effect was not efficient to herd European plaice into the center of the groundgear as flatfish herding behavior was described by earlier studies (Bublitz, 1996; Main and Sangster, 1981). Bublitz (1996) observed that most flatfish left the substrate when oncoming nets approached and were generally herded into the center of the trawl mouth at different heights. The potential explanation for these differences may be the combination of response behavior and swimming characteristics driven by fish densities (Godø et al., 1999). At low densities, when the groundgear is reached, flatfish, particularly medium and large individuals, swim ahead for a short distance in a zigzag pattern or swim laterally across the trawl mouth and then escape through the gaps under the wing sections of the groundgear (Godø et al., 1999; Winger et al., 2004; Bayse et al., 2016). Of note, the similar escape pattern observed for fish < 30 cm should be considered with caution as the number of these fish were observed at a relatively low amount. Small European plaice with poorer swimming capacity become fatigued quickly during herding and are positioned still on the seabed when groundgear passes above them (Ryer, 2008). This leads to a plausible consideration that the herding behavior of small individuals did not differ between particular areas of the groundgear.

Observations have shown that most American plaice escaping under groundgear were less than 30 cm, and their escape was not significantly different between particular regions of the groundgear (Winger et al., 1999; 2004). These observations were consistent with the escape behavior of American plaice found in the current study. The length-frequency analysis indicated that most American plaice escaped into collecting bags were smaller than 30 cm (Fig. 5.5C). The escape-at-length analysis could not reveal differences in escape behavior of American plaice between locations along the groundgear over observed lengths. These escape behaviors are likely explained based on the swimming capacity of fish, where small individuals with poor swimming capacity might prefer to bury in the substrate to escape rather than herd toward the center of the groundgear (Winger et al., 1999; 2004).

In contrast, the escape behavior of dab was described by a slight bell-shaped escape-at-length comparison curve, where medium individuals (between 18 and 25 cm) escaped more often into the center of the groundgear. More fish > 12 cm escaped at the center than the wings, but a significant difference was found only between 18 and 25 cm (based on the lower CIs; Fig. 5.5F). This implied that the large individuals with greater swimming capacity likely exhibited a chain of behaviors involving swimming away and settling and were likely herded more often towards the center of the groundgear than the wings. This finding is similar to Bayse et al. (2016), who observed flatfish reactions to the groundgear at the center area. The authors considered that likely large individuals may be overtaken by the trawl and probably escaped under the groundgear. This escape behavior was similar to the typical flatfish behavior observed by Bublitz (1996) and reviewed by Ryer (2008).

Monkfish in the current study were observed to escape more often in the wings than the center over all length classes, confirming that monkfish were not herded into the center of groundgear. This would suggest that there may be a camouflage behavior of monkfish in relation to the gear during the herding process. It is similar to a flatfish response to the herding effect of the trawl described by Gibson (2005) and Winger et al. (2010). Monkfish likely have poor swimming ability and may swim less than the speed of advancing sweeps, remain in their positions on the seabed briefly, or bury in the substrate. This strategy may allow monkfish to keep their positions close to the wing sections rather than herding into the center of the groundgear.

Our findings provide more details on the size-specific behavior of fish at the trawl mouth compared with previous studies. Most recorded video projects have directly interpreted fish behavior mainly in the narrow area at the center of the groundgear (Kim and Wardle, 2003; Winger et al., 2004; Underwood et al., 2015; Bayse et al., 2016). Here, our study quantified the extent to which fish react to the groundgear between the center and outer areas (wings) with a length-based approach. This analysis provides higher precision to fish behavior in the trawl when compared to Walsh (1992) and Ingólfsson and Jørgensen (2006), who quantified differences in escape behavior between different regions of the groundgear using an analysis that combined the catch of all areas under the trawl. Based on the results obtained, the fish behavior at the center of groundgear in this study was generally consistent with those quantitatively described by underwater video analysis. This supports that the escape-at-length comparison method used in this study can be employed to infer fish behavior in relation to the herding effect of the trawl. Future analysis of fish behavior at the wing areas could include different combinations of this method with underwater cameras to improve understanding of the complex behavior sequence of fish that lead to fish escaping under the trawl at the wing areas. Additionally, this method would be useful for studies where cameras are not an option due to low visibility or extremely rough seabeds.

This study used the escape-at-length comparison method to infer fish behavior at different escape locations under the groundgear of a trawl. Overall, fish behavior was characterized by escape behaviors, herding response, and swimming capacity, which varied among species and differed according to fish size. The behavior of roundfish such as Atlantic cod and haddock quantified in the current study is length-dependent and agrees with previous observations. Flatfish reaction at the trawl mouth showed more variation with species-specific results than roundfish. While the escape behavior of dab found in this study was similar to common flatfish's behavior observed by previous underwater observations (Bayse et al., 2016; Bublitz, 1996; Ryer, 2008), some flatfish such as European plaice and American plaice exhibited contrary results. These unexpected results need further observations to improve the understanding of how fish respond to the herding effect of the trawl.

Developing the groundgear of a trawl to improve the trawl's selectivity based on fish escape under the fishing line can be one of the important options available for fisheries management (Engås and Godø, 1989; Walsh, 1992; Ramakrishnan, 2018). The rockhopper groundgear is both effective at catching fish close to the seabed while also allowing the escape of small gadoid fish (Engås et al., 1988; Ingólfsson and Jørgensen, 2006). Small fish have been observed to actively search the escape opening along the groundgear under the fishing line between rockhopper rollers (Engås et al., 1988). Fish behavior inferred in this study is in line with those observations while providing new findings of small gadoid fish escaping more often in the center area. This suggests that modifications to the groundgear regarding increasing spaces between the fishing line and the bottom at particular locations might increase the escape of undersized fish and flatfish, which generally enter the trawl at heights less than 1 m. Alternatively, increasing escaping spaces may reduce fish encounters with the groundgear, which is considered to be a cause of mortality of fish when escaping under the trawl (Ingólfsson and Jørgensen, 2006).

5.6 Acknowledgements

We would like to thank the crew of the research vessel "Árni Friðriksson" for their assistance. This research was funded by the MFRI project. Student salary and travel was provided by the Canada First Research Excellence Fund's OFI (Module H.3).

5.7 References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control 19, 716–723. https://doi.org/10.1109/TAC.1974.1100705

Albert, O.T., Harbitz, A., Høines, Å.S., 2003. Greenland halibut observed by video in front of survey trawl: behavior, escapement, and spatial pattern. Journal of Sea Research 50, 117–127. https://doi.org/10.1016/S1385-1101(03)00063-7

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software 67. https://doi.org/10.18637/jss.v067.i01

Bayse, S.M., Pol, M.V., He, P., 2016. Fish and squid behavior at the mouth of a drop-chain trawl: factors contributing to capture or escape. ICES Journal of Marine Science 73, 1545–1556. https://doi.org/10.1093/icesjms/fsw007

Beamish, F.W.H., 1966. Swimming endurance of some Northwest Atlantic fishes. Journal of the Fisheries Board of Canada 23, 319–340.

Bolker, B., R Development Core Team, 2020. bbmle: Tools for General Maximum Likelihood Estimation.

Brinkhof, J., Larsen, R.B., Herrmann, B., Grimaldo, E., 2017. Improving catch efficiency by changing ground gear design: Case study of Northeast Atlantic cod (*Gadus morhua*) in the Barents Sea bottom trawl fishery. Fisheries Research 186, 269–282. https://doi.org/10.1016/j.fishres.2016.10.008

Bryan, D.R., Bosley, K.L., Hicks, A.C., Haltuch, M.A., Wakefield, W.W., 2014. Quantitative video analysis of flatfish herding behavior and impact on effective area swept of a survey trawl. Fisheries Research 154, 120–126. https://doi.org/10.1016/j.fishres.2014.02.007

Bublitz, C.G., 1996. Quantitative evaluation of flatfish behavior during capture by trawl gear. Fisheries Research 25, 293–304. https://doi.org/10.1016/0165-7836(95)00431-9

Canty, A., Ripley, B.D., 2021. boot: Bootstrap R (S-Plus) Functions. R package version 1.3-28. https://cran.r-project.org/web/packages/boot/boot.pdf.

Eighani, M., Bayse, S.M., Paighambari, S.Y., Broadhurst, M.K., 2020. Mono- *vs* multifilament gillnets: effects on selectivity of narrow-barred Spanish mackerel *Scomberomorus commerson* in the Persian Gulf. Journal of the Marine Biological Association of the United Kingdom 100, 285–290. https://doi.org/10.1017/S0025315419001243

Engås, A., Godo, O.R., 1989. Escape of fish under the fishing line of a Norwegian sampling trawl and its influence on survey results. ICES Journal of Marine Science 45, 269–276. https://doi.org/10.1093/icesjms/45.3.269

Engås, A, Jacobsen, J.A., Soldal, A.V., 1988. Catch comparison between rockhoppers and bobbins ground gear on the Norwegian bottom sampling trawl, In: ICES C.M. 1988/B:

31. Presented at the Fish Capture Committee, International Council for the Exploration of the Sea, 12p.

Gibson, R.N., 2005. The behavior of flatfishes. In Gibson, R.N. (Ed.), Flatfishes: Biology and Exploitation. Blackwell Science, Ltd., Oxford, UK. 84, pp. 213–239.

Godø, O.R., Walsh, S.J., 1992. Escapement of fish during bottom trawl sampling - implications for resource assessment. Fisheries Research 13, 281–292.

Godø, O.R., Walsh, S.J., Engås, A., 1999. Investigating density-dependent catchability in bottom-trawl surveys. ICES Journal of Marine Science 56, 292–298. https://doi.org/10.1006/jmsc.1999.0444

Hartig, F., 2021. DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models.

He, P., 1991. Swimming endurance of the Atlantic cod, *Gadus morhua* L., at low temperatures. Fisheries Research 12, 65–73. https://doi.org/10.1016/0165-7836(91)90050-P

Holst, R., Revill, A., 2009. A simple statistical method for catch comparison studies. Fisheries Research 95, 254–259. https://doi.org/10.1016/j.fishres.2008.09.027

Ingólfsson, Ó.A., Jørgensen, T., 2006. Escapement of gadoid fish beneath a commercial bottom trawl: Relevance to the overall trawl selectivity. Fisheries Research 79, 303–312. https://doi.org/10.1016/j.fishres.2005.12.017

Kim, Y.-H., Wardle, C.S., 2003. Optomotor response and erratic response: quantitative analysis of fish reaction to towed fishing gears. Fisheries Research 60, 455–470. https://doi.org/10.1016/S0165-7836(02)00114-5

Krag, L.A., Holst, R., Madsen, N., Hansen, K., Frandsen, R.P., 2010. Selective haddock (*Melanogrammus aeglefinus*) trawling: Avoiding cod (*Gadus morhua*) bycatch. Fisheries Research 101, 20–26. https://doi.org/10.1016/j.fishres.2009.09.001

Larsen, R.B., Herrmann, B., Brinkhof, J., Grimaldo, E., Sistiaga, M., Tatone, I., 2018. Catch efficiency of groundgears in a bottom trawl fishery: A case study of the Barents Sea haddock. Marine and Coastal Fisheries 10, 493–507. https://doi.org/10.1002/mcf2.10048

Main, J., Sangster, G., 1981. A study of the fish capture process in a bottom trawl by direct observation from a towed underwater vehicle. Scottish Fisheries Research Report 23, 1–23.

Main, J., Sangster, G.I., 1985. Report on the direct observation experiments with the chalut 28.90/37.1m JCB trawl during July 3–23, 1984. ICES CM 1985/B: 9/Ref K 19.

Montgomerie, M., 2015. Basic fishing methods. A comprehensive guide to commercial fishing methods. SEAFISH, 103p.

Pitcher, T.J., Parrish, J.K., 1993. The functions of shoaling behavior. In: Pitcher, T.J. (Ed.), The Behavior of Teleost Fishes, 2nd ed. Chapman and Hall, London, pp. 363–439 715 p.

Pol, M., Eayrs, S., 2021. Behavior in a bottom trawl: moving forward to limit catches of Atlantic cod. ICES Journal of Marine Science 78, 2317–2324. https://doi.org/10.1093/icesjms/fsab106

R Development Core Team, 2009. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Ramakrishnan, M., 2018. A Review of Trawl Selectivity Studies carried out along Indian Coast. Fishery Technology 55, 1–18.

Ryer, C.H., 2008. A review of flatfish behavior relative to trawls. Fisheries Research 90, 138–146. https://doi.org/10.1016/j.fishres.2007.10.005

Ryer, C.H., Rose, C.S., Iseri, P.J., 2010. Flatfish herding behavior in response to trawl sweeps: a comparison of diel responses to conventional sweeps and elevated sweeps. Fishery Bulletin 108:145–154.

Thomsen, B., 1993. Selective flatfish trawling. ICES Marine Science Symposia 196, 161–164.

Underwood, M.J., Winger, P.D., Fernö, A., Engås, A., 2015. Behavior-dependent selectivity of yellowtail flounder (*Limanda ferruginea*) in the mouth of a commercial bottom trawl. Fishery Bulletin 113, 430–441. https://doi.org/10.7755/FB.113.4.6

Valdemarsen, J.W., Engås, A., Isaksen, B., 1985. Vertical entrance into a trawl of Barents Sea gadoids as studied with a two level fish trawl, in: ICES C.M. 1985/B: 46. Presented at the Fish Capture Committee, International Council for the Exploration of the Sea, p.16

Walsh, S.J., 1992. Size-dependent selection at the footgear of a groundfish survey trawl. North American Journal of Fisheries Management 12, 625–633.

Walsh, S.J., Hickey, W.M., 1993. Behavioral reactions of demersal fish to bottom trawls at various light conditions. ICES Marine Science Symposia 196, 68–76.

Wardle, C., 1993. Fish behavior and fishing gear. In: Pitcher, T.J. (Ed.), Behavior of Teleost Fishes. Chapman and Hall, London, pp.607-643.

Weinberg, K., Munro, P.T., 1999. The effect of artificial light on escapement beneath a survey trawl. ICES Journal of Marine Science 56, 266–274. https://doi.org/10.1006/jmsc.1999.0442

Winger, P., He, P., Walsh, S.J., 1999. Swimming endurance of American plaice (*Hippoglossoides platessoides*) and its role in fish capture. ICES Journal of Marine Science 56, 252–265. https://doi.org/10.1006/jmsc.1999.0441

Winger, P.D., Eayrs, S., Glass, C.W., 2010. Fish behavior near bottom trawls, In: He, P. (Ed.), Behavior of Marine Fishes: Capture Processes and Conservation Challenges. Wiley-Blackwell, Oxford, UK, pp. 65–103. https://doi.org/10.1002/9780813810966.ch4

Winger, P.D., Walsh, S.J., He, P., Brown, J.A., 2004. Simulating trawl herding in flatfish: the role of fish length in behavior and swimming characteristics. ICES Journal of Marine Science 61, 1179–1185. https://doi.org/10.1016/j.icesjms.2004.07.015

5.8 Tables

Table 5.1. Overview of valid tows observed for each species.

Measurement	Cod	Haddock	European Plaice	American Plaice	Dab	Monkfish
No. of fish in bosom bag	1689	1585	739	279	220	61
No. of fish in wing bags	2105	1590	1219	406	185	180
Total no. of fish measured	3794	3175	1958	685	405	241
No. of tow	25	23	22	10	9	9
Min. length (cm)	6	6	10	7	6	23
Max. length (cm)	109	50	65	46	41	83

Table 5.2. AICc values were estimated for each candidate model for each species

The bold number is the lowest AICc specifies the selected model. * shows the AICc chosen as the simplest model between AICc values are similar or within 2 AICc. NA is not applicable

Model	Independent variable and random effect	Atlantic cod	Haddock	European plaice	American plaice	Dab	Monkfish
Logit-constant	1	2580.3	1357.9	1127.0	443.8	337.0	**245.7**
Logit-constant	1 + (1|*Tow*)	2419.9	1143.9	**1093.4***	**434.5***	337.5	NA
Logit-linear *1*	*MLL* + (1|*Tow*)	2381.2	943.4	**1092.9**	**435.2**	339.5	NA
Logit-linear *2*	*MLL* + (*MLL*|*Tow*)	2337.8	960.2	1096.8	**435.6**	NA	NA
Logit-quadratic *1*	*MLL.orth.1* + *MLL.orth.2* + (*1*|*Tow*)	2299.0	924.9	**1093.9**	436.8	**334.5**	NA
Logit-quadratic *2*	*MLL.orth.1* + *MLL.orth.2* + (1+*MLL.orth.1*|*Tow*) + (1+*MLL.orth.2*|*Tow*)	2246.5	**910.0**	1126.3	438.2	NA	NA
Logit-cubic *2*	*MLL.orth.1* + *MLL.orth.2* + *MLL.orth.3* + *(*1+*MLL.orth.1*|*Tow) +* *(*1+*MLL.orth.2*|*Tow) +*	**2221.7**	NA	1105.5	442.8	NA	NA

Table 5.3. GLMM parameters for escape-at-length comparison. SE is the standard error of the estimate; estimate is the value of intercept or slope.

Species	Model	Parameter	Estimate	SE	*z*-value	*p*-value
Atlantic cod	Logit-Quadratic *2*	β_0	-0.325	0.098	-3.303	< 0.001
		β_1	5.727	1.647	-3.476	< 0.001
		β_2	11.947	3.328	3.590	< 0.001
Haddock	Logit-Quadratic *2*	β_0	- 0.842	0.097	-8.672	< 0.001
		β_1	-13.521	1.607	-8.413	< 0.001
		β_2	6.806	2.512	2.709	0.011
European plaice	Logit-constant	β_0	-0.522	0.107	-4.887	< 0.001
Dab	Logit-Quadratic *1*	β_0	0.156	0.152	1.026	0.304
		β_1	-0.245	1.409	-0.174	0.861
		β_2	-3.563	1.358	-2.624	0.009
American plaice	Logit-constant	β_0	-0.241	0.157	-1.540	0.123
Monkfish	Logit-Quadratic *2*	β_0	-1.294	0.191	-6.783	< 0.001
		β_1	-0.371	2.258	-0.164	0.870
		β_2	-2.774	2.860	-0.970	0.332

5.9 Figures

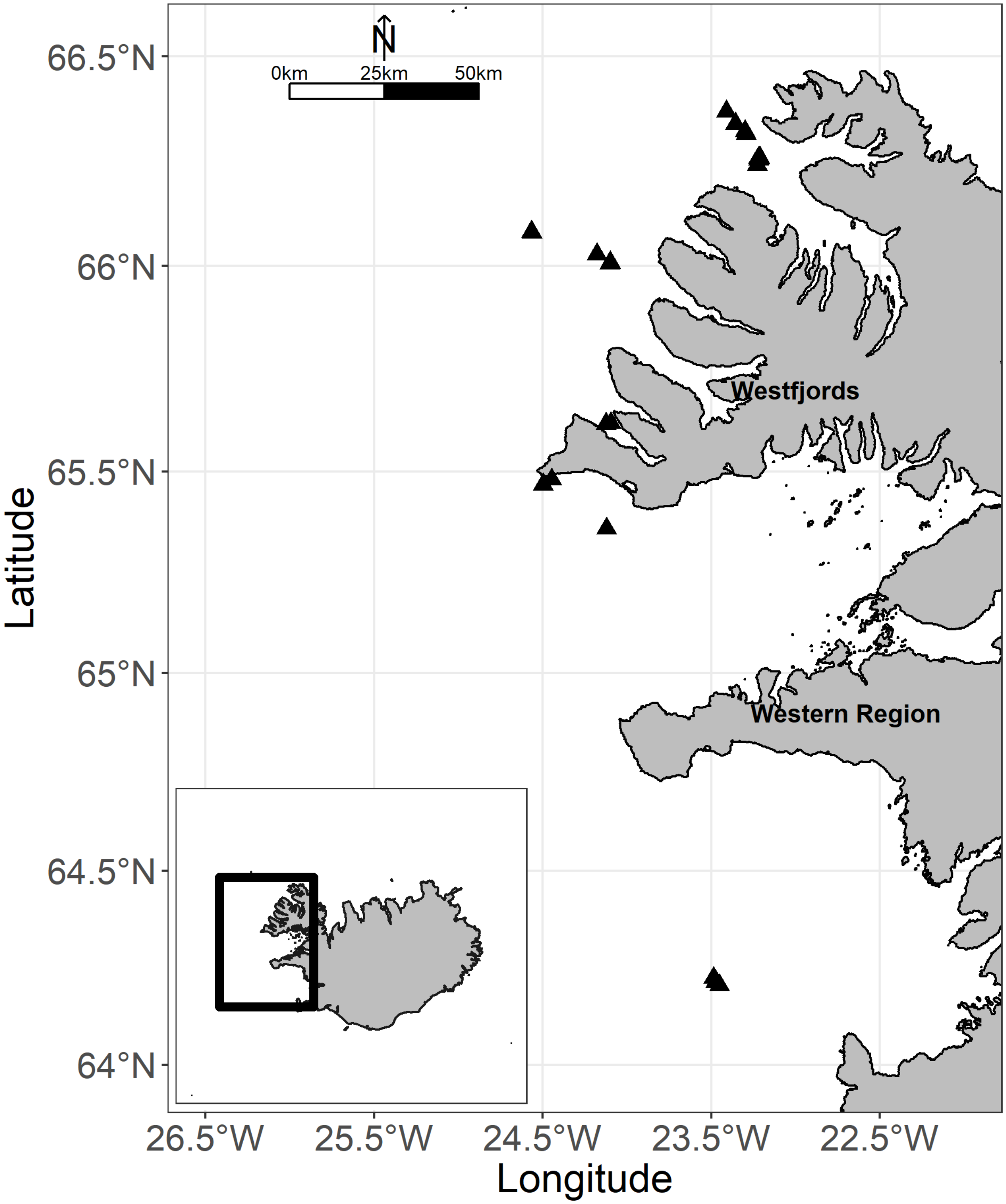


Figure 5.1. Map of the study area off western Iceland. The black triangles showed all locations of tows. Map credit: global administrative areas (https://gadm.org/); license: GADM license.

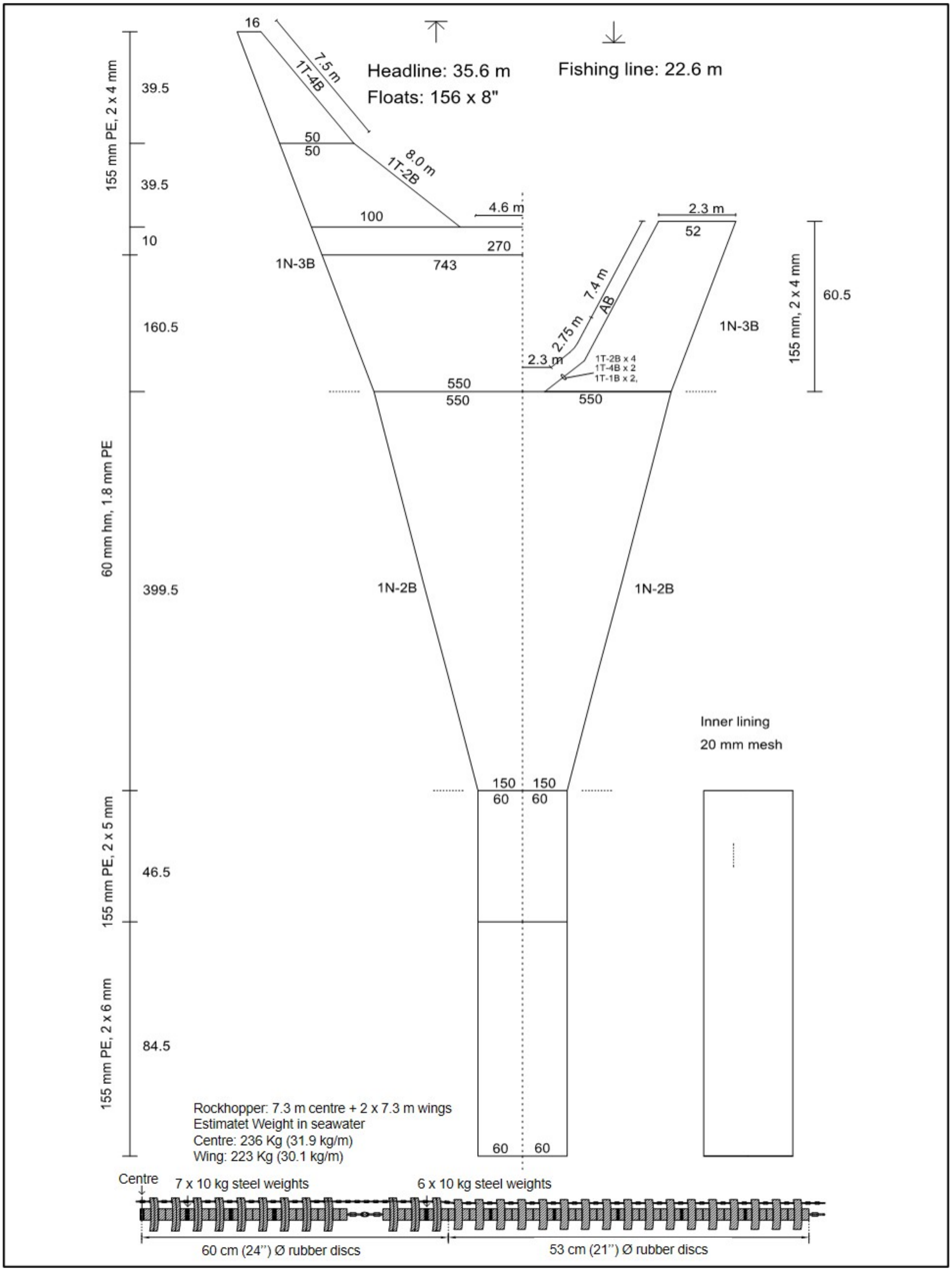
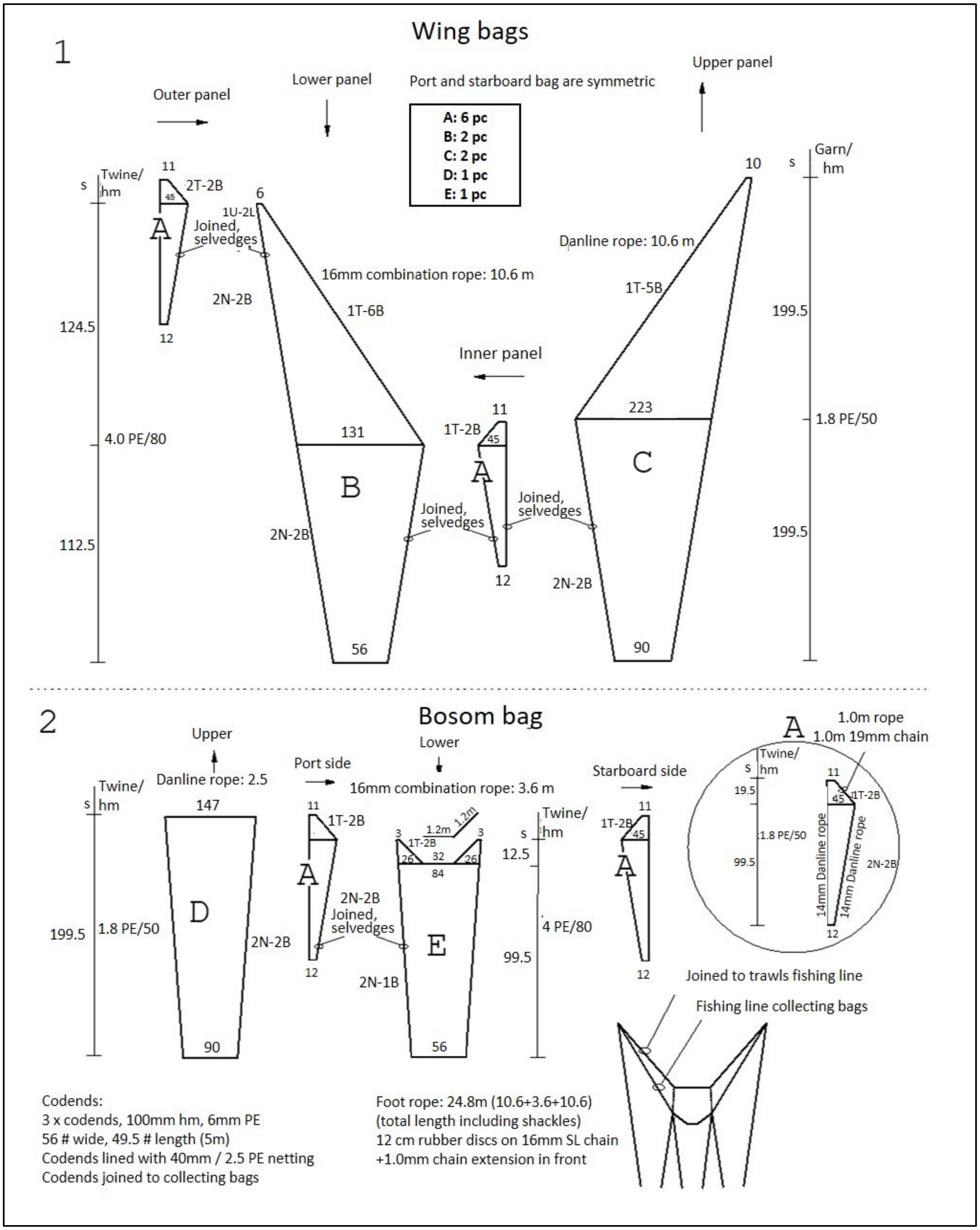


Figure 5.2. Net plan of the Gulltoppur trawl.



Codends:
3 x codends, 100mm hm, 6mm PE
56 # wide, 49.5 # length (5m)
Codends lined with 40mm / 2.5 PE netting
Codends joined to collecting bags

Foot rope: 24.8m (10.6+3.6+10.6)
(total length including shackles)
12 cm rubber discs on 16mm SL chain
+1.0mm chain extension in front

Figure 5.3. The net plan of the collecting bags used to capture fish that escaped under the trawl. (1) illustrates the wing bags, and (2) illustrates the bosom bag.

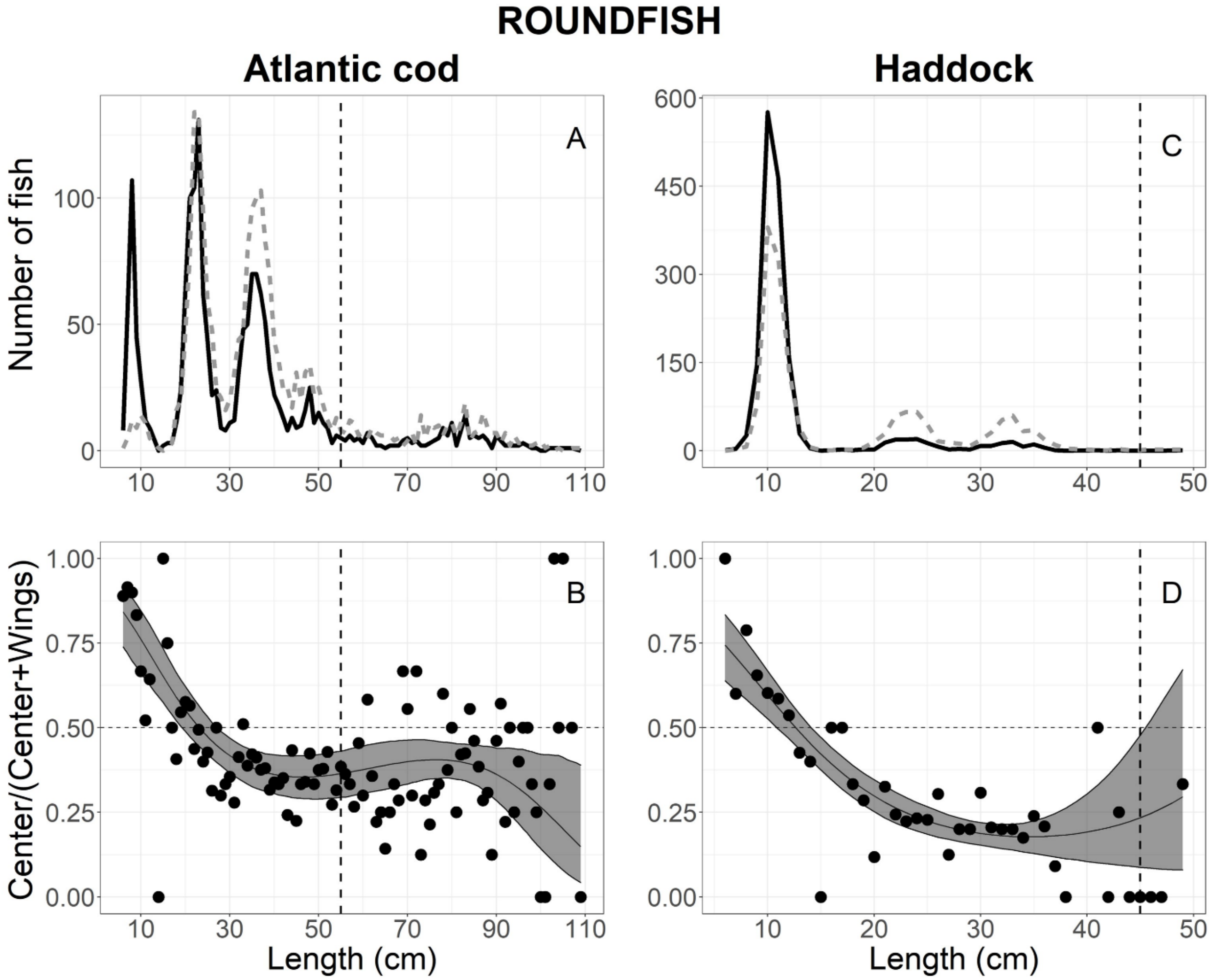


Figure 5.4. The length frequency and escape-at-length curves of roundfish. (A) and (C) are the length-frequency curves of Atlantic cod and haddock. The black line and grey dashed line represents the length frequencies of individuals in the bosom and both wing bags, respectively. (B) and (D) are the proportion curves at each length class for Atlantic cod and haddock. The black line represents the mean curves, and the grey shaded areas are the 95% confidence bands determined by bootstrap simulation. The vertical dashed line in each panel represents each fishery's minimum reference length size. A value of 0.5 indicates an even split between collecting bags for the specific length.

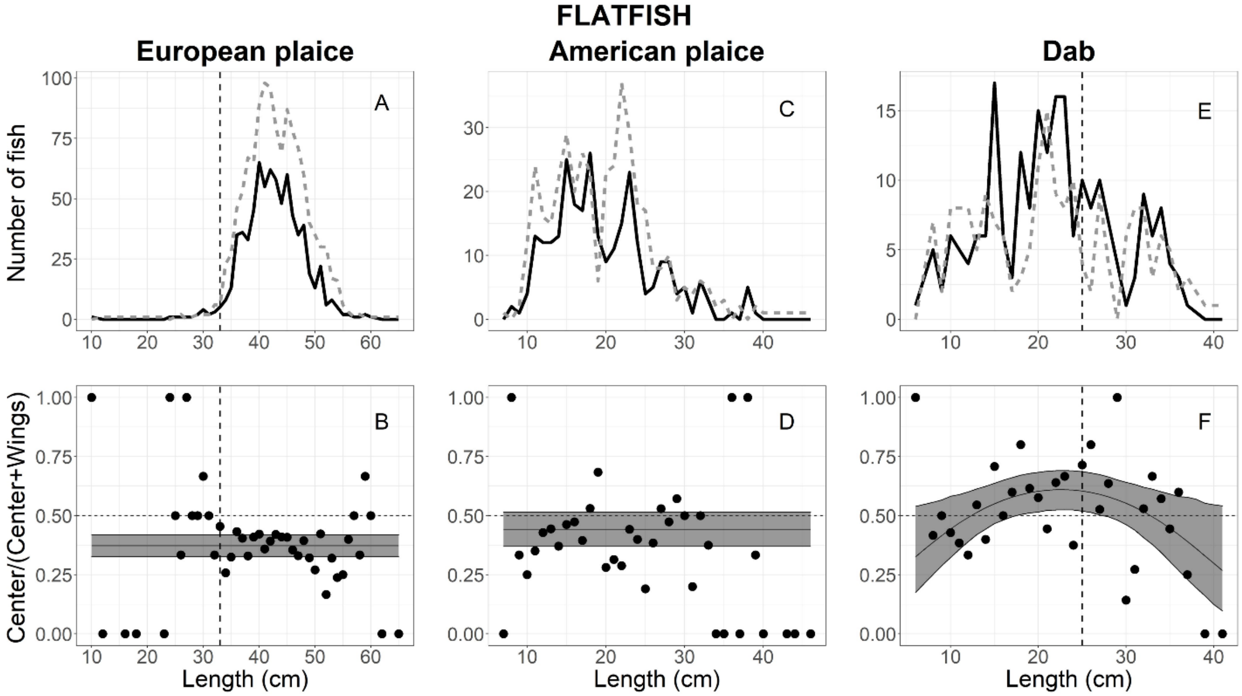


Figure 5.5. The length frequency and escape-at-length curves of flatfish. (A), (C) and (E) are European plaice, American plaice, and dab length-frequency curves. The black line and grey dashed line represent individuals length frequencies in the bosom and both wing bags, respectively. (B), (D) and (F) are the proportion curves at each length class for European plaice, American plaice, and dab. The black line represents the mean curves, and the grey shaded areas are the 95% confidence bands determined by bootstrap simulation. The vertical dashed line in each panel represents the minimum length size of each fishery. A value of 0.5 indicates an even split between collecting bags for the specific length.

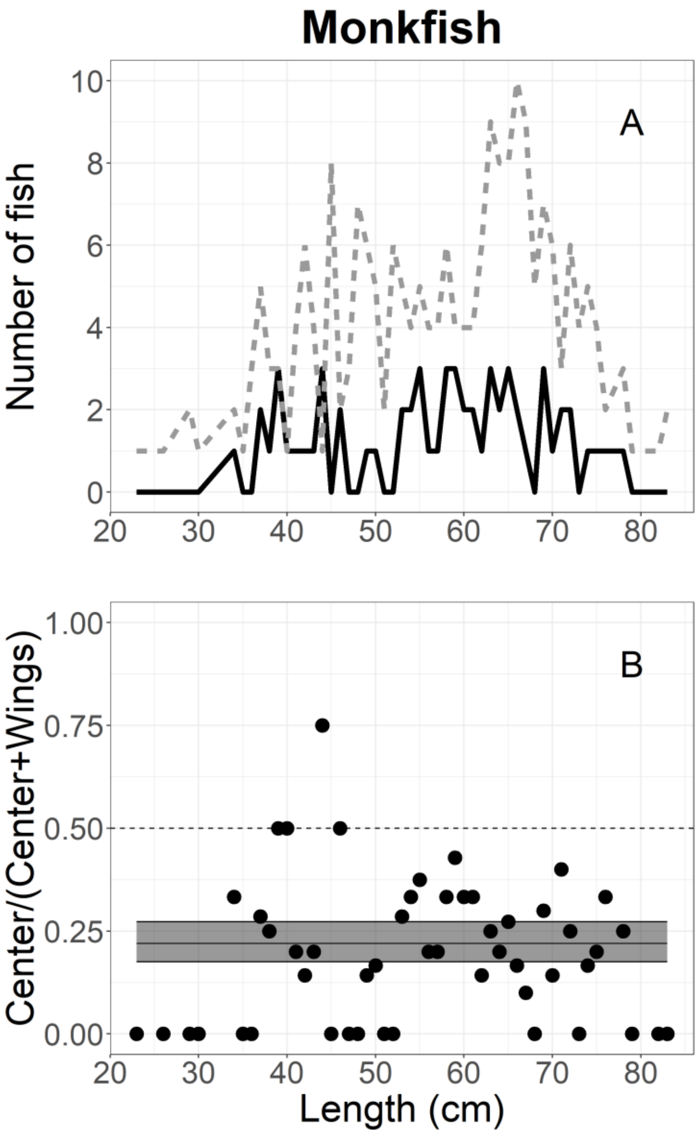


Figure 5.6. The length frequency and escape-at-length curves of roundfish. (A) is the length-frequency curves of monkfish measured in collecting bags. The black line and grey dashed line represent individuals length frequencies in the bosom and both wing bags, respectively. (B) illustrates the proportions of escape at each length class estimated for monkfish. The black line represents the mean curves, and the grey shaded areas are the 95% confidence bands determined by bootstrap simulation. A value of 0.5 indicates an even split between collecting bags for the specific length.

CHAPTER 6. General conclusions

Bottom trawling is one of the most versatile fishing practices, capturing a wide range of target species living on or near the seabed at varying depths. Bottom trawling is currently used as the main fishing practice in groundfish fisheries in the North Atlantic, contributing a high proportion of the fisheries production. In Canada, for example, groundfish bottom trawls provide about two-thirds of the total harvest (by weight) for groundfish fisheries (Charles, 1997; DFO, 2018). Similarly, Iceland groundfish fisheries mainly use the bottom trawl to capture groundfish species, contributing 75-80% of the total catch value (Arnason, 1996; Halliday and Pinhorn, 1996; Nielsen et al., 2018). However, besides those high contributions, bottom trawls are also considered the main contributors of bycatch, with a high proportion of undersized fish and unwanted species in the catch (Pálsson, 2003; Woods et al., 2015). These bycatch issues have been considered the key factor of the decline in biomass.

The decline in biomass of redfish in the Canadian redfish (*Sebastes* spp.) fishery and groundfish in Iceland groundfish fisheries are examples of the influence of bycatch issues on North Atlantic fisheries. The decline in the redfish fishery in the Gulf of St. Lawrence was mainly caused by overfishing and a high proportion of undersized redfish captured in the catch of the trawl by using the 90 mm diamond mesh codend (Duplisea, 2018; DFO, 2020). However, recent strong recruitment events provide a large biomass of redfish in the Gulf of St. Lawrence, leading to a reopening of the commercial fishery. Thus, avoiding the capture of small redfish has been addressed in terms of technical measures to develop the emerging sustainable redfish fishery. In the line of technical measures, using the T90 codend (diamond mesh is rotated 90° in the transverse direction) has been more effective in reducing the capture of small redfish relative to the conventional codend (Cheng et al., 2020). However, considering that the T90 codend still captures small redfish, further investigations on bycatch reduction are needed. Additionally, the bycatch of unwanted species in the catch of redfish is also a large concern in developing an emerging redfish fishery. Atlantic cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), white hake (*Urophycis tenuis*), and silver hake *(Merluccius bilinearis)* have been observed to co-occur with redfish, therefore becoming the main bycatch species of the redfish fishery (Simpson et al., 2018; DFO, 2021a). Thus, technical measures to reduce bycatch species in the catch of redfish should be addressed.

Similarly, the bycatch of undersized fish in the catch is also an significant challenge in Icelandic groundfish fisheries. These fisheries mainly use the multi-species bottom trawl to capture mixed species, resulting in a large number of small fish species retained in the codend, therefore, bycatch (Pálsson, 2003 Woods et al., 2015). Bycatch of undersized fish led to the closing of some areas around Iceland to trawling, causing reductions in the total landings of groundfish fisheries over the last two decades . Recent attempts to mitigate bycatch have been conducted, including technical measures (increasing the mesh size of the diamond mesh codend) and fisheries management aspects (i.e., increasing the minimum fish size and closing fishing areas, where the trawl retains extremely high proportions of small fish in the catch). These attempts remain difficult due to the differences in body shape of mixed species entering the codend. Ideally, the selection process could be carried out at earlier stages of the capture process, such as at the trawl mouth, where small individuals of some species (i.e., gadoid) escaped under the groundgear more often than large individuals.

This thesis developed two fishing techniques with the aim of advancing bycatch reduction in the Canadian redfish fishery and examined the groundgear selectivity of a bottom trawl and fish behavior at the trawl mouth in Icelandic groundfish fisheries. These works were built upon previous work, as reviewed in Chapter 1. Trawl designs were developed based on knowledge of fish behavior at particular stages of the capture process (i.e., in the codend and at the trawl mouth), and recent gear innovations have been conducted with different degrees of success (i.e., the shaking codend, semi-pelagic trawl, etc.). Trawl designs were completed through appropriate steps, from building the scale model of the gear, and testing in a flume tank, to evaluating the catch efficiency of full-scale models in commercial fishing settings. The flume tank test validates the scale of the gear designs and provides accurate predictors of full-scale performance (Winger et al., 2006). Within this thesis, I developed two fishing techniques, including the shaking codend (Chapter 2) and semi-pelagic trawl (Chapter 3), using a flume tank test to validate the full-scale model of gears for commercial settings to evaluate the effectiveness of the gears designed. A commercial fishing experiment is a critical step to complete a trawl design. This step was applied to evaluate the selectivity of trawl designs through all chapters (Chapters 2 through 5) of the thesis, and its sample sizes (i.e., the trawl experiment designs and the number of hauls deployed) were set based on the selectivity method used for evaluations.

The selectivity of gear designs was evaluated based on the selectivity techniques described in Chapter 1. Three size selectivity methods, including the absolute size selectivity, the relative size selectivity, and underwater observations, were applied for Chapters 2 through 5. As I described, the absolute size selectivity is required if the selection process takes place in which the selectively experimental design can retain all size compositions of target species in the sampled population (Pope et al., 1975; Wileman et al., 1996). The absolute size selectivity therefore estimates accurate measures of selectivity. Within this thesis, this absolute method was applied for evaluating the selectivity of the shaking codend, where the covered codend method was used as the non-selective gear to retain all fish that escaped from the codend (Chapter 2) and the selectivity of the groundgear of an Icelandic bottom trawl, where the collection bag method was applied to retain all fish escaped under the fishing line (Chapter 4). Otherwise, if the selection process takes place where the trawl selection experiments do not meet the non-selective assumption (the non-selective trawl does not retain all fish enter the trawl), the relative size selectivity method is required (Wileman et al., 1996; Kotwicki et al., 2017). This method was applied in Chapter 5 to describe fish behavior along the groundgear. Finally, since the above methods are based on the catch data, underwater observations using camera technologies could be utilized to produce further information on how fish respond to the gear during the selection process. This method was applied to describe and quantify how fish behavior at the trawl mouth influences the efficiency of the trawl design (Chapter 3).

The shaking codend developed in this thesis is in line with research developing the trawl codend's selectivity and increasing the level of success of previous attempts. As discussed in Chapter 1, the shaking codend (the codend attached by an elliptical-shaped piece of canvas) was previously successful at reducing the capture of juvenile fish (Kim, 2013; 2015). Chapter 2 is the first known study to develop the shaking codend using the T90 codend (A diamond mesh codend rotated 90˚ in the transversal direction) in commercial use and evaluate its selectivity using the absolute size selectivity method. Comparisons between the selection curve of the shaking codend and non-shaking codend (the T90 codend without canvas) validated the effectiveness of the shaking codend at reducing the capture of small redfish while maintaining the capture of marketable redfish. The absolute size selectivity was suitable to describe the experimental data despite the low number of hauls deployed for the shaking codend (4 hauls), compared with 11 hauls for the non-shaking codend. However, these variations could lead to some cautions in interpreting the results, as discussed in Chapter 2. Further, although the applied selectivity models estimated the higher proportion of redfish in the shaking codend contact with codend meshes for escape, redfish response within the codend and approach to the codend panels were unknown. Future research with appropriate sample sizes between codends combined with underwater observations placed within the shaking codend would provide stronger evidence for using the shaking codend technique to improve the selectivity of the trawl for the emerging redfish fishery.

The absolute size selectivity method was also applied for examining the length-dependent escape of fish under the groundgear of a trawl. Unlike Chapter 2, which used the covered codend experiment to evaluate the codend selectivity, Chapter 4 used the collection bag experiment to evaluate the selectivity of the groundgear. As described in Chapter 4, the collection bag experiment used small mesh bags mounted under the fishing line to capture all fish escaping under the trawl, while the trawl net was constructed with the same small mesh size to retain all fish entering the trawl. Thus, the experimental data can be adequately analyzed using the absolute size selectivity technique. However, compared with the shaking codend, evaluating the groundgear selectivity in Chapter 4 needed a high sample size having all size compositions of the sampled population. Thus, the number of sampled hauls deployed in Chapter 4 were higher than those deployed for the shaking codend (Chapter 2).

As I reported in Chapter 4, ten fish species escaped under the groundgear totaling 27,296 fish measured in the trawl codend (16,499) and collection bags (10,797) during 27 hauls. Modeling the length frequency of these fish species revealed distinct escape patterns among species. For example, markedly length-dependent escape was found for most species, including gadoid fish, such as Atlantic cod, haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), and blue ling (*Molva dypterygia*) and flatfish, such as American plaice

(*Hippoglossoides platessoides*) and dab (*Limanda limanda*). These findings, like previous studies are successful at describing the length-dependent escape of fish under the groundgear of bottom trawls using the absolute size selectivity technique (Ingólfsson and Jørgensen, 2006). Concerning that large fish with greater swimming capacity may rise over the headline or to the left or right of the wings for escape. This is probably considered a factor that could influence the results of this study. Future observations are needed to account for these escaping fish, only at this point can the fish escape under the trawl be fully evaluated.

Chapter 4 also furthered the escape pattern of fish species at varying fishing conditions (i.e., day and night trawling). Fish response to the upcoming trawl differed according to variations in light intensities, which vary between day and night. Previous observations indicated that fish exhibited the optomotor response to trawl components in front of the trawl during high light conditions, becoming available to capture, compared with the dark conditions, where fish erratically respond to the approaching gear (Glass and Wardle, 1989; Walsh and Hickey, 1993; Krag et al., 2010). By comparing the length-dependent escape of fish between day and night hauls, Chapter 4 demonstrated variations in escape patterns between and within selected species. For example, small individuals of Atlantic cod, haddock escaped more often during night hauls, compared with dab, whose medium-sized individuals tended to escape during day hauls.

Another fishing technique this thesis developed for the Canadian redfish fishery is the semi-pelagic trawl (Chapter 3). Compared with the shaking codend, which focused on reducing the capture of small fish, the semi-pelagic trawl intended to capture redfish off the seabed efficiently. My review in Chapter 1 documented a diel vertical migration by redfish (see Gauthier and Rose, 2005), making the bottom trawl less efficient (Duplisea, 2018). Attempts to increase the catch of redfish at these conditions may increase the capture of bycatch species, which co-occur with redfish in the Gulf of St. Lawrence (Duplisea, 2018). The performance of the semi-pelagic trawl was validated through a flume tank testing and full-scale sea experiments (Chapter 3). Examining the interaction between the trawl groundgear and the seabed during sea experiments revealed that the semi-pelagic trawl could fish dynamically at varying water levels clear of the seabed, and as reported in Chapter 3, this dynamic fishing can be controlled by changes in warp length and tow speed. The comparative fishing design failed to compare the capture of redfish and bycatch between on-seabed trawling (conventional trawl) and off-seabed trawling (semi-pelagic trawl) during the sea experiments. However, assessing catches of redfish and major bycatch species through the low number of hauls deployed for both trawling on and off the seabed would prove that the semi-pelagic trawl is at least capable of capturing a commercial quantity of redfish and ability to avoid capturing bycatch species related to the seabed.

Video observations have been effective at evaluating the selectivity of bottom trawls. A combination of video observations with the fishing experiment approaches would be very useful in determining the effectiveness of a trawl design (e.g., Bayse, 2015). By explicitly describing fish response to the trawl designs, video analysis would complement the length analysis from comparative fishing. Additionally, recent attempts used video analysis alone to quantify the interaction between fish and trawl designs and how these interactions drive the capture outcome of the trawl (Underwood et al., 2015; Bayse et al., 2016). Chapter 3 is an example of using only video analysis to quantify fish behavior at the center area of the trawl mouth. The semi-pelagic trawl was developed to lift the trawl net higher in the water column to capture redfish as they move off the seabed. This technical principle is difficult to apply to fishing experiments (i.e., using the collection bag method) to evaluate the effectiveness of the trawl, thus video analysis was required.

Chapter 3 described redfish behavior at the center of the trawl mouth and its effect on the capture outcome (i.e. enter the trawl or escape under the fishing line) of the semi-pelagic trawl. Video analysis indicated that over half of redfish at the trawl mouth enter the trawl, and the capture outcome depends on where fish are distributed at the trawl mouth and how fish swim in relation to the vertical plane (i.e., swimming upward, swimming down, and no change in swimming direction). For example, redfish are highly capable of entering the trawl when distributing above the fishing line and/or swimming upward. Otherwise, redfish behavior aids in relatively high escape under the trawl (i.e., redfish either appeared under the fishing line or swam down to seek the escape openings under the fishing line). Underwater videos also provided valuable information on how fish react to and escape through the spaces between rollers of the groundgear.

Redfish behavior at the trawl mouth quantified in Chapter 3 complemented the escape pattern of redfish described in Chapter 4. Chapter 4 demonstrated that most redfish aggregated at the trawl mouth tended to enter the trawl rather than escape under the fishing line. Most fish that escaped capture were small individuals. By using video analysis, Chapter 3 detailed how redfish react to the gear components at the trawl mouth in a way that leads to fish escaping under the trawl. This valuable information gave direct guidance on how to move forward from the results of fish behavior at the trawl mouth and its escape pattern under the trawl. If further knowledge can lead to a way of encouraging small redfish swimming behavior that avoids capture, the trawl designs would be more selective.

Applying the semi-pelagic trawl is an important option that meets the fisheries management point of view, as it can capture redfish off the seabed and can be desirable from the fisher's perspective, as it can reduce the cost for future redfish fishers in the Gulf of St.

Lawrence. Redfish are impacting the ecosystem as they are considered as a predator of Northern shrimp (*Pandalus borealis*). A massive return of redfish in the area reduced the Northern shrimp stock, exacerbating the decline in the Northern shrimp fishery, which may lead to this fishery in moratorium or operating under very low quotas (Blais, 2021; DFO, 2021b; Cadigan et al., 2022). Switching to another fishery is considered the best way to adapt to the harsh economics that shrimp fishers could suffer from the decline. The scenario that transitions all shrimp vessel fleets (*n* = 114) to the future redfish fishery can be beneficial. This transition would reduce the fishing pressure on Northern shrimp stock that meets the fisheries management aspects in stock resilience. Otherwise, these shrimp's fishing vessels are appropriate with the groundgear bottom trawl which is used to develop the semi-pelagic trawl in this study. Since, the semi-pelagic trawl developed in this thesis is considered promising for the future redfish fishery in the Gulf of St. Lawrence, this fishing technique can be simply adapted to the shrimp trawl fishing fleet regarding fishing redfish clear of the seabed. Alternatively, transitioning the shrimp fishing fleet to future redfish fishery would reduce the purchase cost for future redfish fishers. Regarding capturing redfish off the seabed, pelagic trawling is also considered as an effective technique. However, as discussed in Chapter 3, pelagic trawling would be excessively expensive (large trawl, new sensors, new doors, etc.) and/or need a more powerful vessel compared with the semi-pelagic trawl developed in this thesis. Applying the semi-pelagic trawl with a relatively simple modification in the current redfish and Northern shrimp fishing fleet could be a cost-effective solution.

Fish escape under the trawl quantified in Chapter 4 could be considered as a consequence of how the fish responds to groundgear, which was attributed to vary along the groundgear (i.e., center and wing areas) and differ according to fish size. Within the trawl mouth, fish behavior at the center area has been well-known using underwater observations (described in Chapter 3), compared with wing areas, where underwater observations are limited because setting cameras is difficult in these areas. Chapter 5 quantified fish behavior at wing areas in relation to those at the center area using the catch comparison method (the relative size selectivity). Compared with Chapter 3, Chapter 5 sets limits to how fish respond to the upcoming trawl that leads to fish escaped under the fishing line along the groundgear. Comparing escape-at-length data retained in the center bag with those in wing bags during 27 hauls revealed that fish behavior at the trawl mouth varied among areas in relation to fish size, and these differences are species-specific. For example, most large gadoid fish with greater swimming capacity rise above the fishing line when aggregating at the trawl mouth and seeking escape openings at wing areas. Other species, such as European plaice (*Pleuronectes platessa*), reacts to the groundgear late, allowing groundgear to pass over rather than being herded into the center area. This behavior was not consistent with that quantified for American plaice and dab. Additionally, variations in fishing conditions (i.e., day and night) did not influence how fish respond to the herding effect of the trawl at different locations of the trawl mouth.

As discussed in Chapter 1, fish behavior at several stages of the capture process plays a key role in developing gear designs to improve the selectivity of the bottom trawl. At the trawl mouth, fish behavior drives the capture outcome of the trawl, directly influencing the trawl selectivity (Ryer, 2008; Wardle, 1993; Winger et al., 2010; Bayse et al., 2016). Since most of the underwater camera observations to date have focused on the trawl mouth, how fish react to the trawl components at wings remains unclear. Thus, fish response to the herding effect of the trawl at wing areas inferred in this thesis is novel, directly contributing to the knowledge gaps of the length-based fish behavior along the groundgear. Since examination of fish escape under the trawl indicated that small individuals tend to actively search escape openings under the fishing line. Investigations of fish behavior at different locations of the trawl mouth detailed how these small fish species react to the groundgear for escape and where they escape most often along the groundgear. These valuable new findings are necessary for developing gear designs to improve the selectivity of the multi-species trawl in Icelandic groundfish fisheries regarding earlier stages of the capture process.

In conclusion, this thesis furthered fishing techniques for the Canadian redfish fishery and improved our current knowledge of groundgear selectivity and fish behavior in the trawl in Icelandic groundfish fisheries. Following the suggestions from Chapter 1, the shaking codend method and the semi-pelagic trawl could be applied to advance bycatch reduction in the redfish fishery. The full-scale shaking codend was evaluated and considered an effective technique for reducing the bycatch of undersized redfish during commercial operations. A semi-pelagic trawl effectively captured redfish at heights clear of the seabed and had the potential for bycatch reduction. The valuable new knowledge of fish behavior at the center of the trawl mouth and under the groundgear was also aided. Within fish behavior categories at the trawl mouth, some altered the capture outcome of the trawl. Additionally, the thesis addressed the knowledge gaps of fish escape under a multi-species bottom trawl in Icelandic groundfish fisheries, providing information on the length-dependent escape of most target species, and these escape patterns differed according to fishing conditions. This thesis also furthered the knowledge of fish behavior at the different locations along the groundgear. This valuable new information not only provides direction for future development of trawl selectivity in Icelandic groundfish fisheries but also aids in the knowledge gaps of fish behavior, which directly drives escape patterns of fish under the trawl.

References

Arnason, R., 1996. On the ITQ fisheries management system in Iceland. Reviews in Fish Biology and Fisheries 6, 63–90. https://doi.org/10.1007/BF00058520

Bayse, 2015. Observing fish behavior and evaluating gear design to reduce bycatch of small mesh trawl fisheries in New England (Doctoral dissertation). University of Massachusetts Dartmouth.

Bayse, S.M., Pol, M.V., He, P., 2016. Fish and squid behavior at the mouth of a drop-chain trawl: factors contributing to capture or escape. ICES Journal of Marine Science 73, 1545–1556. https://doi.org/10.1093/icesjms/fsw007

Blais, M., 2021. Chemical and biological oceanographic conditions in the Estuary and Gulf of St. Lawrence during 2020. Canadian Science Advisory Secretariat (CSAS), Ottawa, ON.

Cadigan, N.G., Duplisea, D.E., Senay, C., Parent, G.J., Winger, P.D., Linton, B., Kristinsson, K., 2022. Northwest Atlantic redfish science priorities for managing an enigmatic species complex. Canadian Journal of Fisheries and Aquatic Sciences 79, 1572–1589. https://doi.org/10.1139/cjfas-2021-0266

Charles, A.T., 1997. Fisheries management in Atlantic Canada. Ocean and Coastal Management 35, 101–119. https://doi.org/10.1016/S0964-5691(97)00028-8

Cheng, Z., Winger, P.D., Bayse, S.M., Kebede, G.E., DeLouche, H., Einarsson, H.A., Pol, M.V., Kelly, D., Walsh, S.J., 2020. Out with the old and in with the new: T90 codends improve size selectivity in the Canadian redfish (*Sebastes mentella*) trawl fishery. Canadian Journal of Fisheries and Aquatic Sciences 77, 1711–1720. https://doi.org/10.1139/cjfas-2020-0063

DFO, 2020. Redfish (*Sebastes mentella* and *S. fasciatus*) stocks assessment in Unit 1 and 2 in 2019. DFO Canadian Science Advisory Secretariat Science Advisory Report 019.

DFO, 2021a. Impact of an expanding Redfish (*Sebastes* spp.) fishery on southern Gulf of St. Lawrence White Hake (*Urophycis tenuis*). DFO Canadian Science Advisory Secretariat Science Advisory Report 2021/033, 25.

DFO, 2021b. Assessment of Northern Shrimp stocks in the Estuary and Gulf of St. Lawrence in 2021 (Science Advisory No. 2022/006), Canadian Science Advisory Secretariat. Fisheries and Oceans Canada, Canada.

DFO, 2018. Integrated Fisheries Management Plan (IFMP). 4VWX5 groundfish - Maritimes Region.

Duplisea, D.E., 2018. Fishermen's historical knowledge leads to a re-evaluation of redfish catch. Marine and Coastal Fisheries 10, 3–11. https://doi.org/10.1002/mcf2.10006

Gauthier, S., Rose, G.A., 2005. Diel vertical migration and shoaling heterogeneity in Atlantic redfish: effects on acoustic and bottom-trawl surveys. ICES Journal of Marine Science 62, 75–85. https://doi.org/10.1016/j.icesjms.2004.10.001

Glass, C.W., Wardle, C.S., 1989. Comparison of the reactions of fish to a trawl gear, at high and low light intensities. Fisheries Research 7, 249–266.

Halliday, R.G., Pinhorn, A.T., 1996. North Atlantic fishery management systems: A comparison of management methods and resource trends. Journal of Northwest Atlantic Fishery Science 21, 3–135. https://doi.org/10.2960/j.v20.a1

Ingólfsson, Ó.A., Jørgensen, T., 2006. Escapement of gadoid fish beneath a commercial bottom trawl: Relevance to the overall trawl selectivity. Fisheries Research 79, 303–312. https://doi.org/10.1016/j.fishres.2005.12.017

Kim, Y.-H., 2015. Escape response of juvenile fish in a shaking codend determined from tank experiments. Fisheries Research 161, 273–279. https://doi.org/10.1016/j.fishres.2014.08.012

Kim, Y.-H., 2013. Shaking motion characteristics of a cod-end caused by an attached circular canvas during tank experiments and sea trials. Fisheries and Aquatic Sciences 16, 211–220. https://doi.org/10.5657/FAS.2013.0211

Krag, L.A., Holst, R., Madsen, N., Hansen, K., Frandsen, R.P., 2010. Selective haddock (*Melanogrammus aeglefinus*) trawling: Avoiding cod (*Gadus morhua*) bycatch. Fisheries Research 101, 20–26. https://doi.org/10.1016/j.fishres.2009.09.001

Kotwicki, S., Lauth, R.R., Williams, K., Goodman, S.E., 2017. Selectivity ratio: A useful tool for comparing size selectivity of multiple survey gears. Fisheries Research 191, 76–86. https://doi.org/10.1016/j.fishres.2017.02.012

Nielsen, M., Asche, F., Bergesen, O., Blomquist, J., Henriksen, E., Hoff, A., Nielsen, R., Viðarsson, J.R., Waldo, S., 2018. The myth of the poor fisher: Evidence from the Nordic countries. Marine Policy 93, 186–194. https://doi.org/10.1016/j.marpol.2018.04.003

Pálsson, Ó.K., 2003. A length-based analysis of haddock discards in Icelandic fisheries. Fisheries Research 59, 437–446. https://doi.org/10.1016/S0165-7836(02)00017-6

Pope, J.A., Margetts, A.R., Hamley, J.M., Akyuz, F., 1975. Manual of methods for fish stock assessment. Pan 111. Selectivity of fisbing gear. FAO Fisheries Technical Paper 41, 65p.

Ryer, C.H., 2008. A review of flatfish behavior relative to trawls. Fisheries Research 90, 138–146. https://doi.org/10.1016/j.fishres.2007.10.005

Simpson, M.R., Miri, C.M., Mello, L.G.S., Colbourne, E., H Rockwood, 2018. Assessment update of White Hake (*Urophycis tenuis*, Mitchill 1815) in NAFO Division 3P. Canadian Science Advisory Secretariat (CSAS) Research Document 2018/060, 29.

Underwood, M.J., Winger, P.D., Fernö, A., Engås, A., 2015. Behavior-dependent selectivity of yellowtail flounder (*Limanda ferruginea*) in the mouth of a commercial bottom trawl. FB 113, 430–441. https://doi.org/10.7755/FB.113.4.6

Wardle, C., 1993. Fish behavior and fishing gear. In: Pitcher, T.J. (Ed.), Behavior of Teleost Fishes. Chapman and Hall, London, pp.607-643.

Walsh, S.J., Hickey, W.M., 1993. Behavioral reactions of demersal fish to bottom trawls at various light conditions. ICES Marine Science Symposia 196, 68–76.

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Cooperative Research Report 215. XXp

Winger, P.D., DeLouche, H., Legge, G., 2006. Designing and testing new fishing gears: The value of a flume tank. Marine Technology Society Journal 40, 44–49. https://doi.org/10.4031/002533206787353240

Winger, P.D., Eayrs, S., Glass, C.W., 2010. Fish behavior near bottom trawls, In: He, P. (Ed.), Behavior of Marine Fishes: Capture Processes and Conservation Challenges. Wiley-Blackwell, Oxford, UK, pp. 65–103. https://doi.org/10.1002/9780813810966.ch4

Woods, P.J., Bouchard, C., Holland, D.S., Punt, A.E., Marteinsdóttir, G., 2015. Catch-quota balancing mechanisms in the Icelandic multi-species demersal fishery: Are all species equal? Marine Policy 55, 1–10. https://doi.org/10.1016/j.marpol.2015.01.004