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A catch comparison study on different codend designs to evaluate bycatch reduction in the North-East Atlantic deep-water shrimp (*Pandalus borealis*) fishery

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Master thesis in Resource Management, May 2020

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Hermann Magnus Hagen Pettersen

Abstract

Currently, there is a growing interest in the North-East Atlantic deep-water shrimp (*Pandalus borealis*) fishery with more actors expected to take part in the coming years. As the species and size of targeted shrimp varies globally, selectivity in this fishery is based on a grid system in front of a small mesh sized codend to avoid bycatch while simultaneously maintaining shrimp catches. However, small fish can still pass through the grid and risk being retained in the codend. Thus, the aim of this study was to analyze the selectivity of a modified shrimp trawl codend using shortened lastridges, an increased mesh size and a four panel codend in combination with the Nordmøre grid with the aim of reducing bycatch while simultaneously maintaining the retention of shrimp. This was carried out using a catch comparison analysis between the different treatment codends versus the compulsory two panel, 35 mm diamond mesh codend used in the fishery today. We found that applying shortened lastridge ropes, along with a four panel codend significantly improved the exclusion of redfish at approximately 50 % in length groups below 7.5 cm while simultaneously maintaining shrimp catches. However, a significant increase in catch efficiency for the Greenland halibut occurred. When all treatments were applied, a significant reduction in shrimp was observed as well as a significant reduction in both redfish and Greenland halibut. An additional experiment was undertaken observing the effect of shortened lastridge ropes while the baseline codends used were configured with four panels rather than two. This caused a significant reduction in shrimp as well as redfish and Greenland halibut in the treatment codend.

The results from this thesis demonstrates that applying 30% shortened lastridge ropes along with a four panel codend may be a potential solution for the industry in reducing bycatch, but further exploration regarding the exclusion of flatfishes is needed. Reducing the percentage of lastridge shortening may offer some more clarity for these species'.

Keywords: Lastridge ropes, 4-panel, mesh size, shrimp, fishery, bycatch, Nordmøre grid, treatment tree, codend, North-East Atlantic, Greenland halibut, redfish.

1. INTRODUCTION

1.1 Background

Shrimp is of great commercial interest in global fisheries and currently represents the second most traded fish commodity in terms of its value (FAO´s SOFIA, 2018). This helps generate substantial economic growth and benefits, particularly in developing countries which rely on fish for feed and as a main source of employment. The shrimp trawl fishery however has been associated with high bycatch rates, destruction of bottom fauna and poor management control, primarily in developing nations (Alverson, 1994; De Groot, 1984; Eayrs, 2007). The Food and Agriculture organization of the United Nations (FAO) estimates that approximately 9.1 million tonnes of fish bycatch is discarded each year and that globally, about 4.2 million tonnes of this is from bottom trawl fisheries (Roda et al., 2019). This poses a threat to shrimp fisheries as we are witnessing a paradigm shift in both the management style and society awareness surrounding the marine ecosystem and the food we eat. This shift is embodied by the development and implementation of more integrated approaches including tools to make fishing more sustainable, acceptable, profitable as well as ecosystem friendly (Gullestad et al., 2017). Research for the development of more sustainable fishing gears is important in order to reduce the negative impacts shrimp trawl fishing can have such as bycatch and the wasteful dumping of fish while still encouraging economic growth in this fishery.

I have chosen to refine this study towards reducing the negative impacts of the bottom trawl fishery for deep-water shrimp (*Pandalus borealis*) taking place in the North-East Atlantic (NEA). There is currently a growing interest for harvest in the NEA deep-water shrimp trawl fishery. It is expected that more Norwegian, Russian and third party vessels will take part in the deep-water shrimp fishery over the next years. The exploitation in the Barents Sea for this species is today far below the advice from the International Council for the Exploration of the Sea (ICES) which were around 61,000 tonnes in 2019 and 150.000 tonnes in 2020 (ICES, 2019). The total catch in 2019 was 43,000 tonnes[1]. This indicates that there is still a potential for increasing the harvest in the deep-water shrimp fishery. A central topic in the deep-water shrimp fishery in the NEA is the retention probability for juveniles bycatch of regulated and commercially important species of fish.

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[1] Norwegian Directorate of Fisheries- statistics bank, 2019.

The current regulations of the NEA-shrimp fishery allow retention of low numbers of fish from regulated species. The management authorities since 1984 have also implemented respective real time closures. For example, a fishing area is closed if a catch sample exceeds three Redfish (*Sebastes spp*.), three Greenland halibut (*Reinhardtius hippoglossoides*), eight Cod (*Gadus morhua)* and twenty Haddock (*Melanogrammus aeglefinus)* per 10kg of shrimps. Additionally, a shrimp catch can contain no more than 10 % by weight of undersized (i.e. < 15 mm carapace length) shrimps (Norwegian Directorate of Fisheries, 2018). These strict bycatch rules have led to frequent temporary closures of several large shrimp fishing grounds over the last 20 years (Gullestad et al. 2015; 2017) and have not been changed since 2005. Inefficient gear and bycatch reduction devices can lead to catches beyond these thresholds which in turn can lead to extended closures which often last for weeks or months. This forces the fishermen to change areas until bycatch levels fall below the threshold. As well as closures being a nuisance for the fishermen, bycatch of juvenile fish and undersized shrimps can also cause practical problems when sorting the catch on board the fishing vessels. Bycatch is defined as all of the non-intended fish, animals or non-living materials that are caught while fishing (Eayrs, 2007). Because of the small mesh size required in shrimp trawl fisheries, this fishery is one of the big solicitors when it comes to bycatch. Legislation and agreements have established bycatch limits due to the immense impact of this fishery on ecosystems, management and economic as well as social structures (Crowder & Murawski, 1998; Gullestad et al., 2017).

Biological differences between bycatch species in the NEA play a key role as to why the bycatch criteria differs. Redfish are a slow growing, long-lived species with a low natural mortality rate (Mayo, 1995). This make it an extra vulnerable species to fishing pressure as a population requires a longer recovery period than the codfishes for example, Cod and Haddock, which can endure much more fishing pressure while maintaining a strong population structure. Three species of redfish are commercially exploited in the NEA: *Sebastes norvegicus*, *Sebastes mentella* and *Sebastes viviparous*. Though these species differ in shape and appearance, it can be difficult to differentiate them unless examined carefully (Pampouile and Danielsdottir, 2008). *Sebastes norvegicus* and *Sebastes mentella* have been widely exploited in these areas over the last decades (Hermann et al., 2013), and it has been recommended by ICES (2018) that no exploitation of *Sebastes norvegicus* should occur in 2020. *Sebastes mentella* are currently in better condition, according to recent summaries given by ICES (2018). As these redfish species occupy the same areas in this fishery it can be difficult to differentiate between them, especially regarding individuals in the lower size groups.

As all *Sebastes* species are considered to be slow growing and long lived, a precautionary approach regarding the catch limits for these species is required. In comparison to redfish, the Greenland halibut is also a long lived, low productivity species, thus advice from ICES is to avoid high fishing pressure for this species (ICES, 2018). A low bycatch critera was set to 3 individuals per 10 kg of shrimp caught in order to avoid overexploitation. The stock is considered to be in a relatively stable state, however, surveys in the Barents Sea ecosystem have reported the number in sexed length samples of the species to be gradually decreasing each year (ICES, 2018). In comparison to cod and haddock for example, which have the ability to withstand higher fishing pressure, redfish and Greenland halibut represent the greatest challenge as bycatch species' in the NEA deep-water shrimp fishery.

The shrimp population in the NEA is also fluctuating in correlation with the cod stock (Berenboim et al., 2000), which means that the shrimp stock in the NEA is not only influenced by fishing pressure but also predation by cod (Garcia, 2007). This gives incentives for the production of more effective fishing gear in order to maintain a safe balance between these two stocks. The morphology difference between the species, example cod vs Greenland halibut, is also of importance, making it difficult to make use of effective selection gear that works for all species. The shrimp fishery in the NEA is MSC (Marine Stewardship Council) certified[2], meaning the stock is fished in a sustainable manner and according to the high standards set in order to be MSC-certified. However, it can be challenging to keep this certification if bycatch rates are high and large areas being closed. In 2016, a project was initiated "FHF 901303 optimization of a shrimp trawl fishery 2016-2019" where the goal was to find new solutions to the bycatch problem and to open up already closed areas. This project was funded by the Fisheries and Aquaculture Industry Research Fund (FHF) and the Norwegian Directorate of Fisheries.

1.2 Trawl methods

There are many different trawls configurations, and each of them are adapted to the fisheries and seas in which they are used (Valdemarsen & Suuronen, 2003). Trawling can be divided into different systems depending in which part of the water column trawling takes place.

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[2] Marine stewardship council (2020)

There is bottom trawling, which targets demersal species where the gear is towed along the seabed and the mouth of the trawl is held open by a pair of trawl doors (Seafish asset bank, 2020). Secondly, semi-pelagic trawling which involves the trawl being towed on or in very close proximity to the seabed while the trawl doors hang several meters above the seafloor. Lastly there is the pelagic trawl. This is designed to target pelagic species as the position of the trawl in the water column can be changed to suit the depth that the school of target species is located in. These trawling systems can either be hauled by a single vessel or two vessels, omitting the need for trawl doors. These systems can also be connected so that several trawls can be towed side by side. The methods most commonly used are the double and triple trawl configurations, but as many as twelve trawl configurations have been tested side by side by some fishermen in Denmark (Seafish asset bank, 2020).

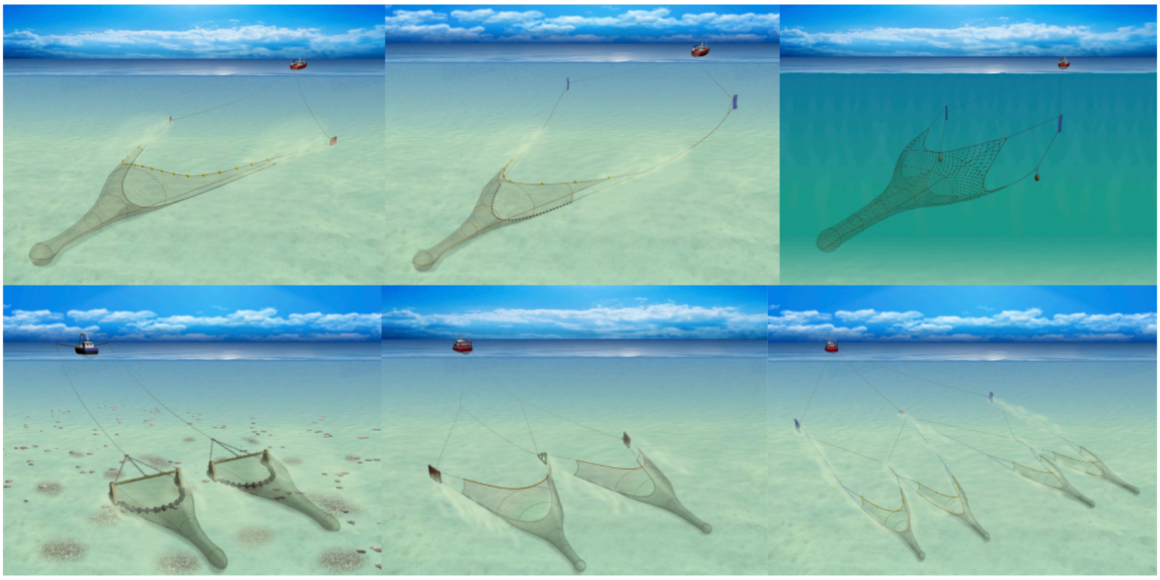

Figure 1: Showing different trawling methods (Seafish asset bank, 2020). Top left; bottom trawl, top middle; semi pelagic trawl, top right; pelagic trawl, bottom left; twin beam trawl, bottom middle; twin bottom trawl, bottom right; multi trawl.

Figure one shows some of the different trawl techniques used. Each of these methods is designed to be effective for the species and the seas where they are used. The twin beam trawl for example is intended for a large range of bottom living species and is criticized for poor selectivity and high potential for retention of non-targeted bycatch.

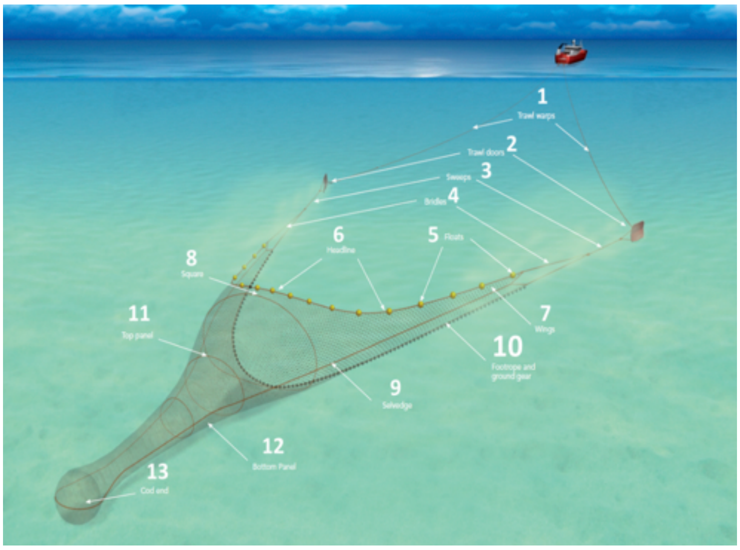

Figure 2: Outline of a single vessel bottom trawl (Seafish asset bank/Roger B. Larsen). 1: Trawl warps, 2: Trawl doors, 3: Sweeps, 4: Bridles, 5: Floats, 6: Headline, 7: Wings, 8: Square, 9: Selvedge, 10: Footrope and ground gear, 11: Top panel, 12: Bottom panel, 13: Codend.

Figure two shows the basic outline of a bottom trawl. In this paper the focus will be on this type of bottom trawl, as this is the trawling technique used in the shrimp fishery in the NEA. This trawl consists of a cone shaped belly section which is towed along the seabed and is funneled into a codend section, where the catch is retained. The trawl doors provide horizontal spread as well as stability and assist in sinking the trawl to ensure bottom contact. Wire sweeps and bridles connect the doors to the wing ends and the ground gear of the trawl net. These vary in length depending on the fishery. In the shrimp fishery in the NEA these sweeps and bridles are up to 70 meters long for single trawl systems and up to 30 meters long in double and triple trawl configurations.

The ground gear helps the trawl maintain contact to the seabed. Different types of ground gear are used depending on how rough the seabed is. These most often consist of chains, rubber discs or steel bobbins attached to the fishing line. These ground gears have different functions and in some cases can be used as a bycatch reduction device as demersal fish that swim close to the bottom can in some cases find escape routes by swimming under the gear (Engås & Godø, 1989). While the ground gear and trawl doors help maintain bottom contact, the headline aids in keeping the vertical opening of the net. This is achieved by attaching boyancy-like floats or hydrodynamic kites to the headline. In the NEA, the deep-water shrimp fishery primarily takes place at a depth of approximately 300m, and the fishing grounds consist mostly of soft muddy bottoms. Due to this species of shrimp's location and vertical distribution in the water column, the bottom trawl is the optimal gear type in this fishery.

While the amount of bycatch caught can by high in shrimp fisheries as many of the trawling methods used do not include modifications to exclude bycatch (Kennelly, 2007), several techniques to improve selectivity are available. These gear modifications are designed according to species-specific characteristics or behavior. According to Broadhurst (2000), these can be broken down into two categories:

1) Selective modifications that separate species by difference in behavior.

2) Selective modifications that mechanically exclude unwanted organisms according to their size.

1.3 Bycatch reduction devices commonly used in shrimp trawl fisheries

One of the devices which mechanically exclude unwanted organism according to their size and morphology is the Nordmøre grid. This design was first used to exclude jellyfish, but the revised version proved to also be efficient in excluding fish bycatch from the shrimp trawl (Isaksen et al., 1992). The grid system typically consists of a guiding funnel, a 45–50° angled grid, and a triangular fish outlet in the upper panel just in front of the grid (figure 3). This bycatch reducing device was introduced in the Norwegian inshore shrimp fishery in 1990 and it became compulsory in the NEA deep-sea shrimp trawl fishery in 1993. This design is used today in several other shrimp fisheries around the world (Suuronen and Sardá, 2007; He and Balzano, 2007; Garcia, 2007; Eyars, 2007; Frimodig, 2008).

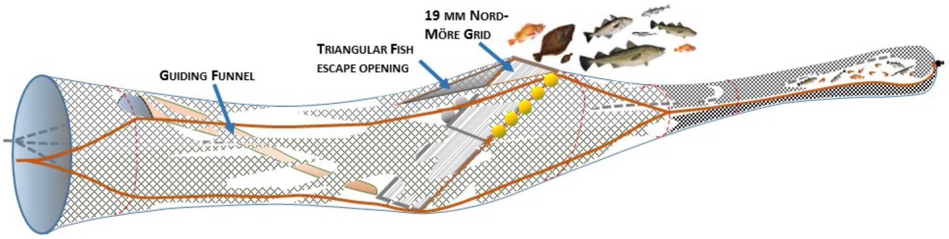

Figure 3: The bycatch excluder device system for shrimp trawls, i.e. the Nordmöre grid design (Roger B. Larsen).

Other techniques that utilize differences in behavior of species are the fisheye and the square-mesh window designs (figure 4). These bycatch reduction devices are commonly used in tropical waters and are designed for more powerful swimming fish (Eayrs, 2007). The fisheye consists of an oval steel or aluminum frame which provides an oval escape opening which the fish are able to swim through while the shrimp passively enter the codend (Frimodig, 2008). Placement of the fisheye can vary inside the codend, but wrong placement can have consequences on the composition of the catch. If it is placed too far in front of the codend, unintended catch may have difficulty escaping. If it is placed too far in the aft then there is a higher probability of losing more targeted catch. The square mesh window utilizes the differences in species behavior in the same way as the fisheye. The square mesh window is typically placed in the top panel and not to close to the back end of the codend, see figure 4. It consist of a panel of square meshes, which varies in size depending on the fishery and what species you want to exclude. In contrast to diamond meshes which tend to close under tension, these meshes remains open throughout hauling allowing fish to escape (Eayrs, 2007).

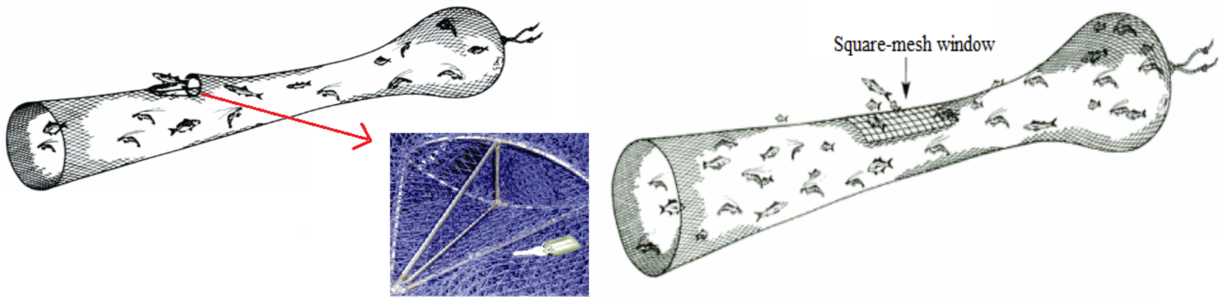

Figure 4: The fisheye (left) and the square mesh window (right) inside the codend (Eayrs, 2007).

Apart from rigid devices like the Nordmøre grid and the fisheye, soft excluder panels (sieve panels) are being used globally for improved bycatch reduction. The use of sieve panels is an old technique for selective shrimp-trawling, and one of the first selection devices tried out in the Norwegian shrimp fishery was a sieve panel placed vertically over the trawl opening (Strøm and Øynes, 1973; Rasmussen and Øynes, 1974). With varied results, this type of soft sorting system was further developed, and different soft sieve panels were tested in the section of the net between the trawl belly and the codend. Trials by Karlsen and Larsen in 1988 with the "HH-skillenett", which was a canted sieve panel placed between the trawl belly and the codend showed promise and became compulsory in some areas of the northern Norway shrimp fishery in the late 80s. The challenge with this sorting system surrounded its installation. A few errors in the installation of this device could lead to significant changes in its selective efficiency. The "HH-skillenett" also gave fishermen practical problems onboard with its handling. Some fishermen have even been known to cut a hole in the netting, because of clotting and loss of shrimp from poor installation of the net, allocating the blame on destruction occurring as a result of trawling when questioned by control authorities (pers, comm. Roger Larsen). The obstacles presented by the sieve panel designs were overcome with the development of the Nordmøre grid, a much more practical system for bycatch reduction in this fishery. It became the excluder device "everyone" wanted. Compared to the "HH-skillenett" and other mesh panels the Nordmøre grid was easy to install and with a bar spacing of 19mm the shrimp loss was considerably lower and had higher exclusion rates of fish (Isaksen et al,.1992). The grid became compulsory in the Norwegian shrimp fishery from 1. January 1990. The Russians shrimp fishery needed longer time on documentation on the grid and in early 1992 they had their results ready and on the first of January 1993 it became compulsory for the whole NEA. Subsequent investigations explored the potential for including sieve devices combined with the Nordmøre grid. For example, an experimental sieve panel mounted in front of the grid section of the trawl was tested by Jacques et al., 2019. When the sieve panel was used instead of the Nordmøre grid, the loss of commercial sizes of shrimp made the design unsuitable for commercial use. However, a more efficient bycatch reduction was obtained when the two devices were used in conjunction, but the associated exclusion of valuable target catch could not be simultaneously reduced to a level that would be acceptable to the industry.

Another study done to improve the size selectivity of juveniles and small size fish in the NEA tested a double grid selection system (Larsen et al., 2018b). Here, the effect of adding an additional release grid with a 9 mm bar spacing behind the Nordmøre grid was investigated. The results showed an increase in escapement for the smallest shrimp and smallest juveniles but concluded that more improvements to the design of the release grid needed to be made in order to further reduce catches of small shrimp and juvenile bycatch. To ensure these populations are protected, select fishing grounds in the NEA are still closed for periods of time when bycatch levels become too high. This can introduce practical problems to fishermen as well as losses in income and valuable fishing time. Research and development to solve this issue has increased in the last decade, while the only legislation on size selective systems currently in the NEA is the requirement for a 19 mm bar spacing and 35 mm mesh size in the codend (Norwegian Directorate of Fisheries, 2018).

Most commonly used codends consist of diamond meshes, but research done in the Icelandic shrimp fishery (Thorsteinsson, 1992) showed that by replacing these in the codend with square meshes drastically reduces the bycatch of juvenile fish. However, this led to a loss of approximately 10-20% of the smallest shrimp. But at the time, this loss of the target catch was acceptable for fishers due to the small numbers of shrimp lost as these could not be utilized and sold for a higher price. Further research regarding square mesh codends (Bahamon et al., 2006) in the Mediterranean Sea showed some improvements in selectivity for some species. However, it was concluded that the square mesh codend would not be efficient for the multispecies fishery it was conducted in and it would yield relatively high economic losses as the escape of species with relatively high commercial value would occur, and these losses would most likely be met with resistance from the fishing industry to accept square mesh codends. In comparison, the NEA shrimp fishery has a lower diversity of species with a few key commercially important species which are central for consideration when discussing implementation of bycatch reduction devices in this area.

While the square mesh codend can contribute to a reduction in juvenile bycatch of fish species (Karlsen and Larsen, 1989; Thorsteinsson, 1992; Broadhurst and Kennelly, 1996; Bahamon et al., 2006; Silva et al., 2012), a study carried out in the NEA (Herrmann et al., 2019) concluded that there was not any improvement in cod selectivity between diamond meshes and square meshes, but the uncertainties was big in the study which could be the reason for lack of significance difference. Furthermore, fishermen may be reluctant to implement square meshes due to the risk of losing a proportion of the smaller shrimp. Rather than using square meshes, shortening of the lastridge ropes to increase the opening of the meshes in the codend may help to counter the challenges of selectivity in the NEA shrimp fishery. Opening up the diamond meshes while hauling may enable more escapement of juvenile fish that have passed through the Nordmøre grid and would otherwise be retained in the codend. This process is depicted in figure 5. Shortening the lastridges by 30% (red dotted line in figure 5) results in the meshes holding more of a square shape. Figure 6 portrays the slack in the codend with 30% shortened lastridges compared to the regular codend. Trawls use these lastridges as a supportive element if the codend should get stuck and tear while trawling, to avoid the risk of losing the entire codend (Isaksen and Valdemarsen, 1990). Applying lastridges ropes to the codend will cost very little as the principle is relatively simple and can be easily adapted to the shrimp fleet. It will also for control purpose's be easy to check and enforce.

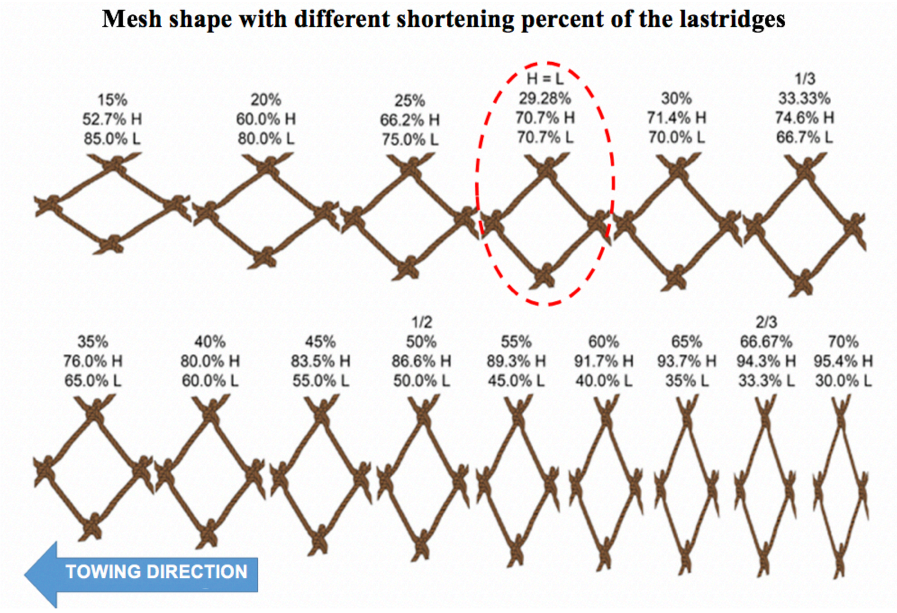

Figure 5: The change in mesh shape with increased shortening percentages of the lastridge ropes (Roger B. Larsen).

Figure 6: Two codends, (lower) with 30% shortened lastridges, (upper) no shortening of the lastridges.

Codends used in the NEA consist of two panels, an upper panel and a lower one. This two panel codend has an internal opening which is restricted, giving the fish limited space to move around. When the codend fills up it expands into an oval shape. For a diamond mesh trawl this makes the codend more closed and in turn difficult for efficient selectivity to happen. A four panel codend, which consists of an upper, lower and two side panel, allows the codend to remain more open with a more rounded square shape as it fills. As it is more open, the flow of water through the trawl to the codend is also improved giving fish more space to move in the net. This enables the catch to have a higher quality as stress on the fish is reduced and provides better conditions for selectivity to occur (Seafish Asset Bank, 2020). A four panel codend in combination with a Nordmøre grid and shortened lastridges may have the potential to be an effective bycatch reduction technique.

1.4 Regulation and Governance

Since the introduction of the Exclusive Economics Zones (EEZ) in 1976, Norway and Russia (until 1991 the Soviet Union) have commenced management of their shared marine resources in the NEA, including deep-water shrimp in the joint Norwegian-Russian Fisheries Commission (JNRFC) (Kvalvik, 2003). This commission collaborates within the fields of regulation, research and compliance control in the NEA. The history of this collaboration has been a long and interesting one, developing through shifting political climates, depletions of stocks and changes in the ecosystem. This commission has undertaken several comprehensive tasks such as closing and opening fishing grounds, setting regulations for fishing practices and a co-ordinated introduction of the selection grids (Hønneland, 2000). Despite a lot of resistance throughout, this joint collaboration regime has been recognized by the Food and Agriculture organization as being very successful and an example to be followed by others (Gillett, 2008).

Compliance control is conducted by the military coast guard at sea while the Fisheries Directorate controls the landings. All vessels are also monitored by the central office in Bergen, who keep track of the remaining quota of foreign vessels. Inspectors from the Directorate at landing sites check the landings and at sea, the coast guard inspects the fishing gear i.e mesh size, grids as well as the catch and bycatch interference. The closing and opening of fishing grounds are conducted by the Control Section, which is a branch of the Norwegian Directorate of Fisheries stationed in Tromsø. If an area has suspected high bycatch rate, an inspector from the control section joins or rents a trawler and then counts the bycatch by conducting tows in the area, and after an area is held closed for some time, data from new trawl tows are collected and a decision is then made whether the area should remain closed or allowed to be opened (Breivik et al., 2016). The fishermen on a national level in particular in Norway, place a high importance on both trust and mutual respect between the stakeholders and management. Studies conducted (Hønneland, 1998; Hoel et al., 1996) showed that most fishermen comply with the management regulations most of the time.

Annual scientific catch advice for stocks in the NEA is provided by ICES. The JNRFC uses this annual advice in negotiations and makes decisions based on this for setting catch limits for each of the commercially important species. The main tool used in management for controlling the fishery is the total allowable catch (TAC). This describes how much of a stock by volume can be sustainably fished in a fishing area. The TAC advice for shrimp in the NEA provided from ICES for the year 2020 was 150 000 tonnes (ICES, 2019). This is a clear indication for the health of this particular stock. Despite the good condition of the stock (ICES, 2019), the problem for the shrimp fleet remains to be the strict bycatch rules and the subsequent risk of closed areas which would force the fleet to move on to other fishing grounds.

These bycatch rules are thoroughly discussed each year when the JNRFC meets to discuss new TACs and rules in the fisheries. The criteria set for bycatch in the shrimp fishery is today based upon a bioeconomic method described by Veim et. al. (1994) where methodology for calculating acceptable levels for inclusion of juveniles in the shrimp catches is provided. The method calculates the current value of the shrimp catches and expected present value of the bycatches. Based on this method, an area is to be kept open if the shrimp catch collectively gives a higher present value than the bycatch and closed if preserving the juveniles presents a higher present value. While this method is being used, the rule itself is determined through deliberations and negotiation within the JNRFC. Currently the acceptable bycatch levels allowed in this fishery have remained unchanged since 2005, despite pressures from Norwegian management authorities to loosen the levels for selected bycatch species such as redfish (Anne Kjos Veim, pers. comm.[3]). While the Nordmøre grid functions in excluding bycatch of larger size, it is evident today that the compulsory technical regulation of a minimum codend mesh size of 35 mm and the 19 mm bar spacing of the Nordmøre grid are not enough to avoid excessive retention of juvenile and small fish.

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[3] Anne Kjos Veim, Section chief, development section -Norwegian Directorate of Fisheries

1.5 Theoretical framework

In the 1970s the deep sea fishery for Northern shrimp developed rapidly in Norway. Major criticism followed from other sides of the fisheries sector when large quantities of commercially important species were caught along with the shrimp as bycatch (Roger B. Larsen, pers. comm.[4]). This put pressure on the JNRFC to find solutions to the problem in the fishery and so throughout the late 70s and 80s different techniques with mesh panels and grids were tested with varied results (Strøm and Øynes, 1973; Rasmussen and Øynes, 1974; Karlsen and Larsen, 1988; Isaksen et al.,1992). The Nordmøre grid proved to be the most successful design tested and became compulsory North of 62° in Norway first of January 1990 and in 1993 became compulsory for the whole NEA shrimp fishery.

Without an effective bycatch separator, it is likely that the shrimp fishery in the NEA would have been shut down in the mid-1990s in order to protect the strong juvenile year-classes of cod in the area. A primary reason for these drastic changes to the shrimp fishery were due to the NEA cod crises at the end of the 1980s with record low TACs being set (Armstrong et al., 2014). The coastal fishermen targeting cod (*Gadus morhua*) had a strong political standing, and had it not been for the introduction of the Nordmøre grid and its ability to exclude bycatch, the NEA off-shore shrimp fishery would probably have been history. Since the Nordmøre grid's development and subsequent mandatory implementation, further research and development has been conducted through co-operation between management, industry and research institutions. The bycatch of juvenile fish has remained to be an ongoing problem in recent years for the ecosystem, fishermen and other stakeholders. Several different studies of different selection techniques have been carried out (Jacques et al. 2019, Larsen et al. 2018abcd) with varied results in order to alleviate this problem. The use of shortened lastridge ropes has shown promise (Isaksen et al., 1990; Reeves et al., 1992; Ingolfsson and Jørgensen, 2020) as well as the use of four panel codends and increased mesh sizes. Both management bodies and stakeholder groups have a significant interest in these selective gears and are thus the reason behind this study.

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[4] Roger B. Larsen, UiT The Arctic University of Norway

1.6 Research question

This study addresses this issue within the context of the NEA bottom trawl shrimp fishery as bycatch in other fisheries and in shrimp trawling globally remains to be an ongoing problem.

The aim of this study is to analyze the selectivity of a modified shrimp trawl codend using shortened lastridges, increased mesh size and four panel codends. When these gears are combined with the regular Nordmøre grid configuration it was investigated whether exclusion of unwanted and illegal bycatch species could be increased in the NEA shrimp trawl fishery. If successful findings from this study is presented, it may be used to motivate a solution to be used by the industry. This can also help to give the fishery an improved image from the public in terms of the products overall sustainability and the degree of security that fishermen feel as members of this industry. Thus, the following research question is investigated in this study:

1) Can shortened lastridges, increased mesh size and four panel codends in comparison to the regular two panel diamond mesh codend help reduce bycatch in the NEA shrimp fishery?

In 2005 the JNRFC set bycatch limits of eight cod, twenty haddock, three Greenland halibut and three redfish per 10 kilos of shrimp caught based on the biological precautionary approach. These limits have since remained unchanged, leading to areas being closed because the bycatch remains too high. Therefore, in addition to the gears tested as outlined above, talks were conducted in order to gain more insights regarding the decisions driving legislation and their thoughts surrounding the future of the NEA deep-water shrimp fishery. These talks were made with members of Norwegian fisheries management institutions as well as with a selection of shrimp fishermen. These talks will be addressed in the discussion section of this thesis.

2 MATERIALS AND METHODS

2.1 Time, Vessel and area

Data collection was conducted aboard the double-rigged ocean shrimp trawler FV "Arctic Viking" with 17 crew members onboard. This commercial fishing trawler, equipped with full commercial processing facilities, was built in 1986 and is sailing under the Faroese flag. The vessel is 58 meters long and 13 meters wide with a 4090 HP engine but reduced to generate 3700 HP. As well as other renovations since its building date, in 2019 She had a new 4600 HP engine installed. Today the trawler is considered to be modern and efficient in its operations for the catch and production of shrimp. The research cruise took place from the 12 – 26th of September 2018 in a closed shrimp fishing area on the northeastern side of Svalbard near "Kvitøya" situated at 80.09°N, 32.35° Ø.

2.2 Fishing gear

The trawl deck onboard was arranged with two trawl paths and during the trials it was rigged with two identical Vonin shrimp trawls (2700#) (figure 7). These were mounted with a pair of Sea Hunter trawl doors, each weighing 6 tonnes with a size of 13.2 m^2. The trawls used had a 68.50 m fishing line with a rock hopper ground gear composed of rubber discs with a diameter of 53 cm, a 16 mm chain and five steel bobbins with a diameter of 53 cm attached. This trawl accomplished good ground contact at a towing speed of 1.5 to 2.5 knots. The materials used for the netting twine in the front section of the trawl were polyethylene (PE) and Polyethylene terephthalate (PET) with Premium twine in the aft (belly) section. The belly consisted of 5 panel sections which had a total length of 50 meters. Each of the two trawls had the same net design up to this point (figure 8).

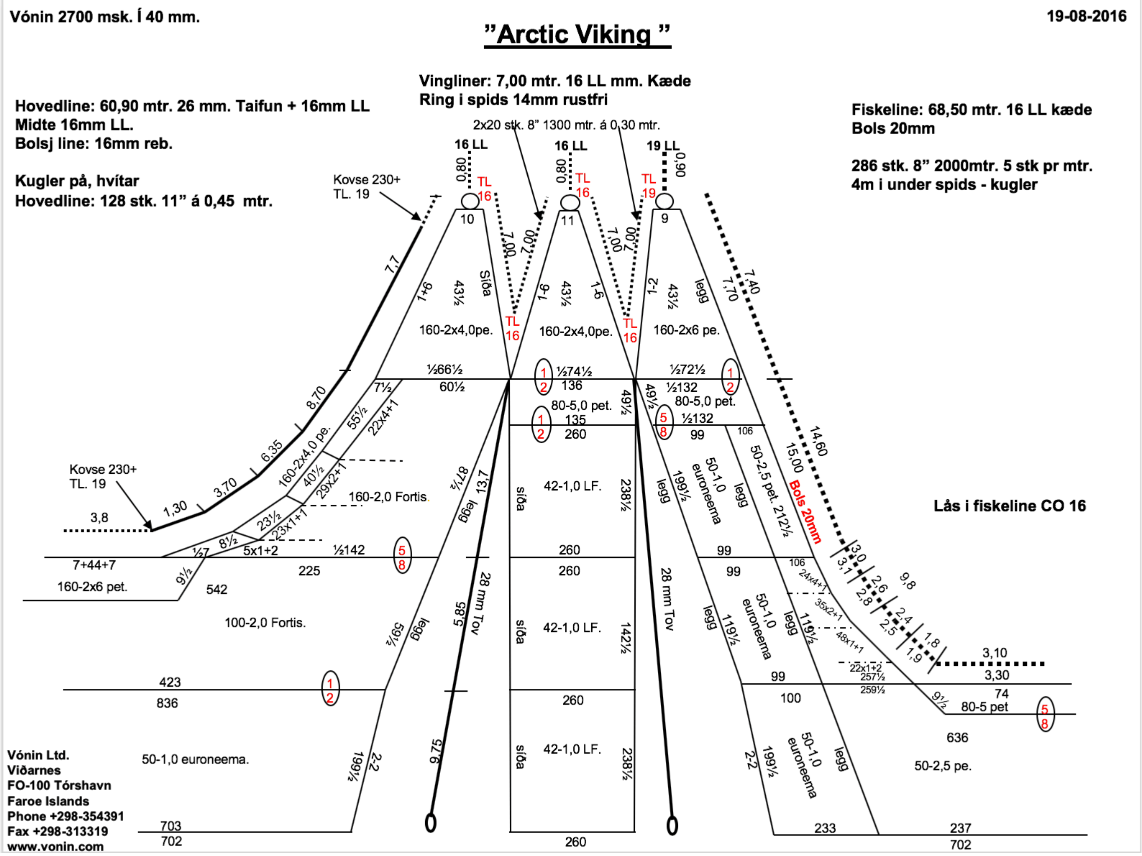

Figure 7: The front sections of the Vonin 2700# shrimp trawl used during the trial (Bjarni Petersen)[5].

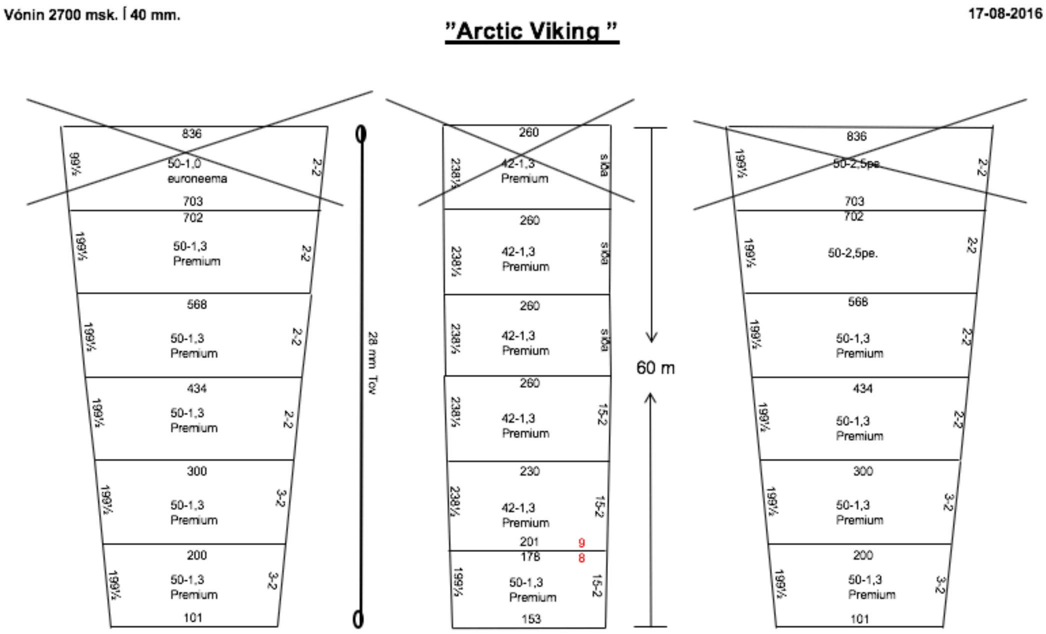

Figure 8: Aft (belly) section of the Vonin 2700# shrimp trawl used during the trial (Bjarni Petersen).

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[5] Bjarni Petersen, Captain of the M/Tr «Arctic Viking».

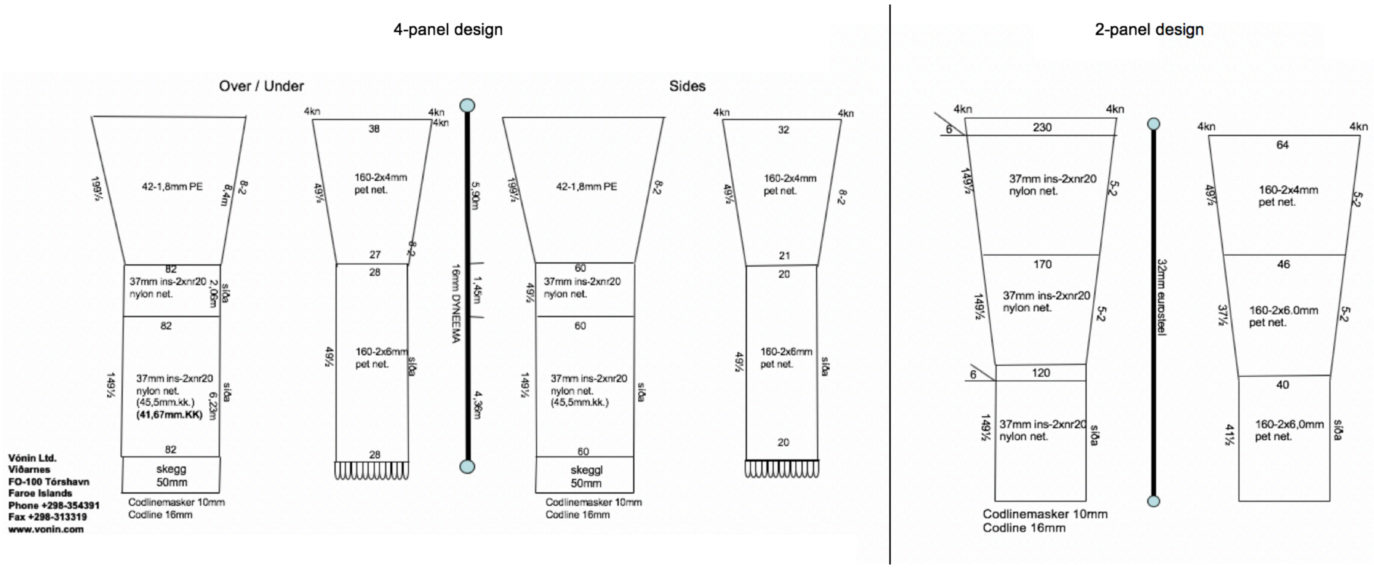

Figure 9: Codends used during the trial with the four-panel design(left) and the two-panel design (right) (Bjarni Petersen).

Figure 9 shows the four panel 35mm mesh size test codend used (left) and the two panel 35mm mesh size baseline codend (right) that was used during the trials. Series 2 and 3 used the same type of codend only difference was the mesh size of 40 mm.

The grids we used were a Canadian design with outer dimensions of 170 cm X 240 cm (Figure 10). The frame of the grid was made out of nylon while the bars were a combination of plastic and fiberglass. This construction made the grid easier to handle on deck compared to grids made of steel. The bars had a rectangular profile, i.e. a width of 1 cm and a depth of 2 cm and if the bars became damaged, they could be replaced.

Figure 10: The grids used in the sea trials (Photo: Hermann Pettersen).

2.3 Experimental setup

The experimental designs for these trials were made in collaboration between the Norwegian Directorate of Fisheries and UiT, The Arctic University of Norway. The research was part of a four year project funded by the Aquaculture Industry Research Fund (FHF) and the Fisheries Directorate. All designs tested in this trial were discussed with both management and stakeholder groups prior to the research being carried out. The experimental setups were comprised of four series:

Series 1: Baseline: 35 mm mesh standard codend (2-panel)
Test: 35 mm mesh codend and 30% shortened lastridges (4-panel)

Series 2: Baseline: 35 mm mesh standard codend (2-panel)
Test: 40 mm mesh codend and 30% shortened lastridges (4-panel)

Series 3: Baseline: 35 mm mesh standard codend (2-panel)
Test: 40 mm mesh codend (4-panel)

Series 4: Baseline: 35 mm mesh codend (4-panel)
Test: 35 mm mesh codend and 30% shortened lastridges (4-panel)

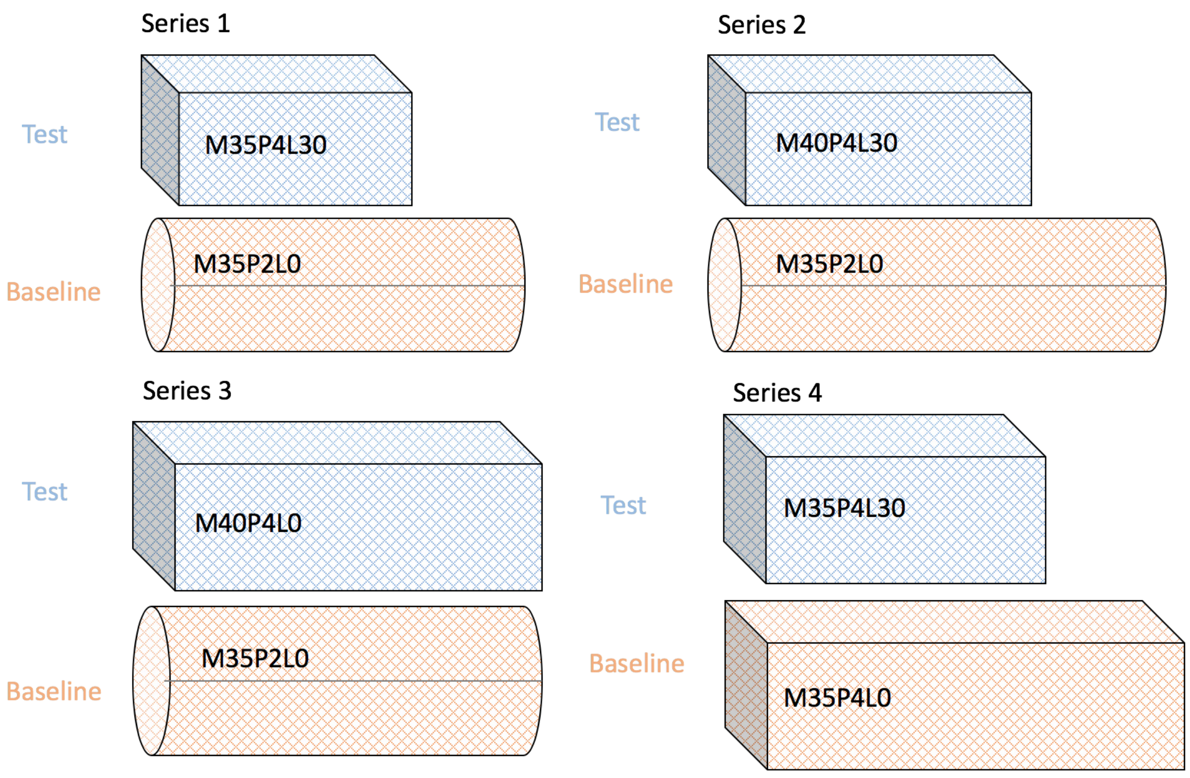

Figure 11: The experimental setup for each series and the treatments applied. M=mesh size, P=panel and L=lastridges.

Series 1

The series 1 configuration was applied to this trial to test the combined effect of applying two treatments, the effect of the number of panels and shortening of the lastridge ropes. Specifically, this series tests a four panel 35 mm mesh size codend with 30% shortened lastridges (M35P4L30) against the baseline 35 mm mesh size two panel codend with no shortening of the lastridges (M35P2L0) (figure 11). The shortening of lastridges by 30% (L30) was selected as it was the level most likely to ensure a more open mesh shape (figure 5) compared to the opening in a two-panel standard diamond mesh codend. Therefore, series 1 investigates the potential for reducing bycatch without changing the codend mesh size.

Series 2

Series 2 investigated the full effect of applying all three treatments to the codend design including increasing the mesh size, changing to four panels in the codend and shortening the lastridge ropes compared to the regular (M35P2L0) configuration used in the fishery today. This design thus will indicate how far we can reduce the bycatch with all available treatments simultaneously (under the assumption that they all affect the selectivity in the same direction).

Series 3

Series 3 tests the combined effect of making the codend a four-panel construction (treatment P2->P4) while simultaneously increasing the mesh size (treatment M35->M40). This series was investigated in order to test the hypothesis that a four panel codend will provide an increased effect when combined with an increased mesh size as a more homogeneous distribution of the meshes will be enabled and thus openness of them in the codend. This was hypothesized to enable a reduction in catch efficiency for juvenile fish species.

Series 4

Series 4 differs from the first three series' as the baseline codend used is not that of the standard fleet design. The baseline and the test here are configured with a four-panel codend (treatment P2-P4) and the effect of introducing shortened lastridges (treatment L0->L30) is tested. This will allow the shortening of the lastridges to be investigated against a four panel codend with no shortened lastridges, and thus see the effect of shortened lastridges if a four panel codend is used or is implemented in the fishery.

2.4 Data collection

Prior to testing the four series, a test haul was made using two identical trawls setup in the same manner as they are used in the commercial sector; a 2-panel design with 35 mm meshes in the codend. This was done in order to verify that the selectivity between the two trawls were equal and to give the research team a closer look into the operation on deck and within the factory in order to make any final preparations before the first data collection. Further north from 79.25°N, 30.56°E to 80,16°N, 36.16°E, the testing of series 1, 2 and 3 was conducted while series 4 took place further south-east at 76.08°N, 40.26°E.

In order to not corrupt any of the data the catches from each of the codends were kept separate throughout processing. For series 1 a total of 12 hauls were made with this setup, as well as one additional haul to include video recordings using artificial light. After 7 hauls the test and baseline codends were switched to opposite sides of the trawl deck in order to reduce the effect of differences in catch efficiency between the trawl sides. Series 2 included a total of 10 hauls. Again, the trawls were interchanged half way through the series in order to account for port/starboard side variation. Series 3 consisted of 10 hauls. Due to a lack of time while testing series 4, only 5 hauls rather than the 10 hauls planned were possible to complete.

After each haul across all series’, the starboard codend was processed first, i.e. all of the bycatch was sorted from the shrimp, the shrimp catch was processed and then the port side codend was processed and sorted so that no contamination could occur between the two catches. All of the bycatch was sorted by species and measured to the nearest centimeter below. From each successful haul approximately 1 kilo of shrimp was subsampled from the total catch and length measured. The carapace length was then measured for each shrimp in the subsample using calipers measuring to the nearest millimeter below. The 1 kg subsample of shrimp was considered adequate in order to provide a size distribution that was representative for the shrimp in each of the codends. Since some hauls contained large amounts of redfish bycatch, it was necessary to take a random sample (subsample) of this species in some of the hauls. All subsampling was taken out of the total population from each of the codends before any sorting took place. The total weight of shrimp from both codends was also taken, as well as the total weight of Greenland halibut, redfish, cod and haddock. Length measurements to the nearest centimeter below were also taken for all individuals of Greenland halibut, cod and haddock. The total catch of other bycatch species was also registered and weighed.

2.5 Modeling

The statistical software SELNET (SELection in trawl NETting) were used for the analysis of the catch data. This software is a tool developed by Prof. Bent Herrmann for the analysis of size selectivity and catch data from towed fishing gears (Sistiaga et al. 2010; Herrmann et al. 2012; 2016). Using the catch data collected we wanted to examine whether there was a significant difference in catch efficiency between the treatment made to the codends (shortened lastridges, increasing mesh size and the number of panels) against the baseline trawl codend for each of the series. By following the method described in Herrmann et al. (2017) based on comparing the catch data between two trawls, we can assess the length-dependent catch comparison rates (CC) and the catch ratio rates (CR) to interpret the results. Table (1) summarizes the catch data for each of the species used for the catch comparison analysis described below.

2.5.1 Modeling Catch Comparison

The method mentioned above models the length dependent catch comparison rate (CC_l) summed over hauls in this manner:

$$CC_l = \frac{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}+\frac{nb_{lj}}{qb_j}\right\}} \quad (1)$$

Here the nb_{lj} and the nt_{lj} is the numbers of shrimp or fish length measured in each length class *l* for both the treatments codends (*t*) and baseline codends (*b*)with the parameters qb_j and qt_j as the related subsampling factors (the fraction of the shrimp or fish caught being length measured), and *m* describing the number of hauls carried out with the treatment and baseline trawl. From here a functional form $CC(l, \boldsymbol{v})$ is estimated from the experimental data, which is common practice in fishing gear catch comparison trials (Grimaldo et al. 2018; Karlsen et al. 2018; Lomeli et al. 2018ab:2019). This functional form gives us a smooth length dependency curve, which is less influenced by observation error for each individual length class than expressed in equation 1. The functional form for the catch comparison rates were obtained by using a maximum likelihood estimation by minimizing the following equation:

$$-\sum_l\left\{\sum_{j=1}^{m}\left\{\frac{nb_{lj}}{qb_j}\times ln[1.0-CC(l,\boldsymbol{v})]\right\}+\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\times ln[CC(l,\boldsymbol{v})]\right\}\right\} \quad (2)$$

The $\boldsymbol{v}$ in the catch comparison curve $CC(l, \boldsymbol{v})$ is a vector that represents the parameters which describe the curve. When catch efficiency of both the baseline and treatment trawl codends are equal, the expected value for the catch comparison rate should be 0.5 meaning that each of the trawls are catching the same amount. Therefore, this baseline can be used to infer if there is a different in catch efficiency between the two trawl codends. We modeled the experimental CC_l by using the function $CC(l, \boldsymbol{v})$ on the following form:

$$CC(l,\boldsymbol{v}) = \frac{exp[f(l,v_0,\ldots,v_k)]}{1+exp[f(l,v_0,\ldots,v_k)]} \quad (3)$$

Here the *f* is a polynomial of order *k* with coefficients v_0 to v_k. We considered *f* of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Former studies including Krag et al. (2015) and Sistiaga et al. (2018) have shown that this provides a model that is sufficiently flexible to describe the catch comparison curves between fishing gears i.e. the treatment codends vs baseline codends. Leaving out one or more of the parameters $v_0 \ldots v_4$, at a time resulted in 31 additional candidate models for the catch comparison function *CC(l,v)*. Among these models, the catch comparison proportion was estimated using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017). Specifically, the models were ranked and weighted in the estimation according to their AICc values (Burnham and Anderson 2002). The AIC (Akaike Information Criterion) is a number that measures how well a model fit the dataset, while the AICc includes a correction for small sample sizes in the data. The AICc is calculated as the AIC (Akaike, 1974) to address potential overfitting in small sample sizes. Models that resulted in AICc values within +10 of the value of the model with lowest AICc value ($AICc_{min}$) were considered for the estimation of *CC(l,v)* following the procedure described in Katsanevakis (2006) and in Herrmann et al. (2015). We use the same combined model for the result of this multi-model averaging and calculated it using Eq. 4:

$$CC(l,\boldsymbol{v}) = \sum_i w_i \times CC(l,\boldsymbol{v}_i)$$
$$with$$
$$w_i = \frac{exp\left(0.5\times\left(AICc_i - AICc_{min}\right)\right)}{\sum_j exp\left(0.5\times\left(AICc_j - AICc_{min}\right)\right)} \qquad (4)$$

where the summations are over the models with an AICc value within +10 of $AICc_{min}$.

The ability of the combined model to describe the experimental data was evaluated based on the p-value, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct. Therefore, this p-value, which was calculated based on the model deviance (D) and the degrees of freedom (DOF), should be >0.05. Specifically, D has an approximate

χ^2 distribution when the model is correct, and the p-value is therefore calculated for a χ^2 distribution with D and DOF as parameters (Wileman et al. 1996; Lomeli et al., 2020). For DOF we use the number of length classes in the experimental data minus the number of parameters

$\boldsymbol{v}$ in the model $CC(l,\boldsymbol{v})$. However, lack of fit as indicated by large D compared with DOF, which corresponds to $p < 0.05$ does not necessarily imply that the fitted combined catch comparison curve is not a good model for the length-dependent catch comparison data (Wileman et al. 1996; Lomeli et al., 2020). If a plot of the modeled curve against the experimental rate shows no clear structure regarding influence of length, then the lack of fit can be assumed to be due to overdispersion in the data (McCullagh and Nelder, 1989). Therefore, in case of $p < 0.05$, we checked for patterns in deviation between modeled catch comparison curve and the experimental CC_l.

2.5.2 Modeling Catch Ratio

Since catch comparison analysis does not give us the direct relative value of catch efficiency between fishing with the treatment codends and the baseline codends we have to estimate the catch ratio (CR). This was done from the catch comparison function $CC(l,\boldsymbol{v})$ which allowed us to obtain the relative catch ratio $CR(l,\boldsymbol{v})$ with the following:

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{[1-CC(l,\boldsymbol{v})]} \quad (5)$$

This gives us the direct relative value of catch efficiency between fishing with a treatment and baseline trawl codend. This means that if the catch efficiency of both the trawls are equal the $CR(l,\boldsymbol{v})$ should be 1.0. A $CR(l,\boldsymbol{v})$ at 1.5 for instance would mean that the treatment trawl codend is catching 50 percent on average more than the baseline codend for individuals of length *l*. Respectively, a $CR(l,\boldsymbol{v})$ at 0.5 would mean that the treatment trawl codend is catching only 50 percent of what the baseline trawl codend does. The Efron percentile 95% Confidence limits (Efron, 1982) were also estimated for both the catch comparison curves and the catch ratio curves to show if the experimental data showed any significant change in catch efficiency between the treatment codends vs the baseline codends. This was done by using the double bootstrapping method for paired trawl catch data using SELNET and running 1000 bootstrap repetitions. The bootstrapping method accounts for uncertainties in the experimental dataset from in between haul variation as well as the size structures in each individual haul.

We estimated directly from the experimental catch data an overall value for the catch ratio using Eq. 6:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \left\{ \frac{nt_{lj}}{qt_j} \right\}}{\sum_l \sum_{j=1}^{m} \left\{ \frac{nb_{lj}}{qb_j} \right\}} \qquad (6)$$

The outer summation in (6) is over all length classes in the experimental data sets. However (6) was also used summing over only respectively undersized individuals and targeted sizes to obtain values $CR_{average-}$ and $CR_{average+}$. Contrary to for $CR(l,\boldsymbol{v})$ is the results for $CR_{average-}$ and $CR_{average+}$ dependent on the population length structures fished during the cruise and cannot be extrapolated to situations with very different population structures fished.

2.5.3 Treatment Tree

In this section it is outlined how other combinations of the three treatments can be investigated without specifically testing them at sea. In order to do this a novel nomenclature was developed and expressed in a treatment tree (Figure 12).

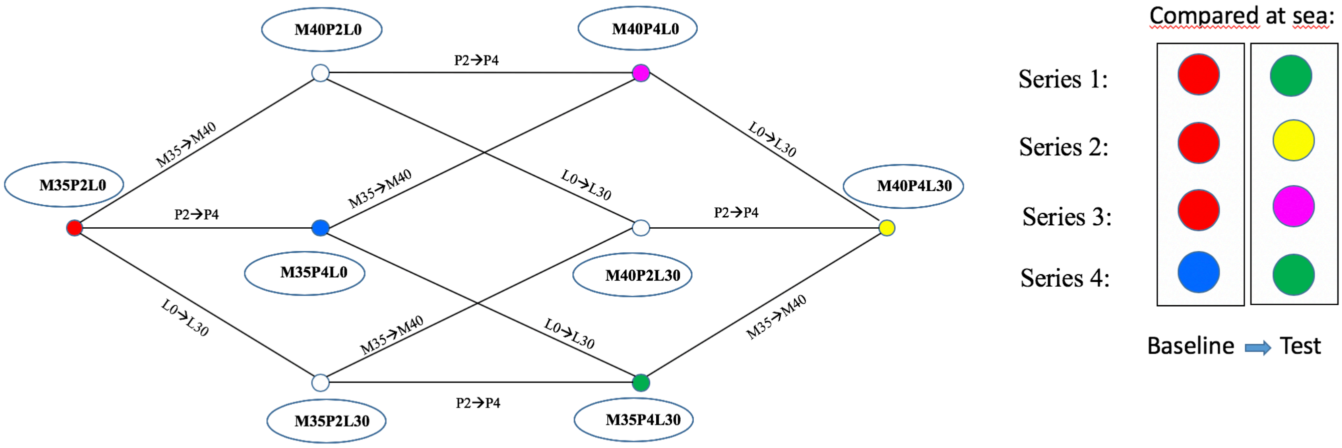

Figure 12: Treatment tree showing the paths for each series. The colours show the series we compared at sea, with the colour red being the baseline codend of M35P2L0 for series 1,2 and 3. The corresponding colors for each series show the test codend. The blue colour in series 4 shows the baseline codend of M35P4L0 with the corresponding green as the test codend.

This tree shows each of the treatments used in the trials and the different paths each took. For example series 1 expressed the changes from a regular two panel codend with 35 mm mesh size and no shortened lastridges (red dot) to the four panel codend with 35 mm mesh size and 30% shortened lastridges (green dot). To estimate the relative catch efficiency between two trawls (Ta) and (Tb) not fished simultaneously we used the formulation described below:

$$CR(l)_{Ta\_Tb} = \frac{CR(l)_{Ta}}{CR(l)_{Tb}} \quad (5)$$

where $CR(l)_{Ta}$, and $CR(l)_{Tb}$ are the length-dependent catch ratios for respectively the treatment trawl (Ta) against the baseline trawl B and the treatment trawl (Tb) against the baseline trawl B. We also obtained the 95% confidence interval limits (Efron, 1982) for $CR(l)_{Ta\_Tb}$ based on the two bootstrap populations of results (1000 bootstrap repetitions in each) for, respectively, $CR(l)_{Ta}$, and $CR(l)_{Tb}$ as they are obtained independently (Herrmann et al., 2018). This allowed the possibility of calculating branches in the tree that we did not test in the trials at sea.

3 RESULTS

3.1 Catch data

During the ten day fishing trial, 37 successful hauls were made in total. Each codend in each haul contained shrimp, redfish and Greenland halibut, except for the area where series 4 was conducted, thus no analysis for Greenland halibut could be made for that series. Catches of cod and haddock throughout the hauls were not large enough to enable analysis to be carried out in this study for these species. A total of 13935 shrimps, 30906 redfish and 7621 Greenland halibut were length measured (table 1). As the ship operated with a twin trawl system, two codends had to be processed after each tow, summing to 74 instances for data collection, thus subsampling for the redfish was required in 41 of the cases while subsampling of shrimp was consistently done in each instance throughout the trial. No subsampling was done for the Greenland halibut. The catches of shrimp were machine sorted and processed into four size categories; industrial size, which were blocked frozen, as well as small, medium and large sizes, which were cooked and frozen in five kilo containers. The number of shrimp per kilo from each of the codends was registered. Industrial shrimp were not counted, but the total weight for each haul and codend was recorded.

Table 1: Length data used for the catch comparison analysis. Numbers in front of parentheses are the total number measured and values in parentheses are the sampling factors (percentage of total catch that were length measured) for each species in each haul across all series for both the treatment codend and the baseline codend.

		Shrimp		**Redfish**		**Greenland Halibut**	
		Length range (8.5-31.5mm)		Length range (3.5-16.5cm)		Length range (7.5-29.5cm)	
Series	**Haul**	**Test**	**Baseline**	**Test**	**Baseline**	**Test**	**Baseline**
1	1	278 (0.063)	280 (0.0419)	9 (1.0000)	120 (1.0000)	9 (1.0000)	13 (1.0000)
	2	150 (0.0009)	150 (0.0008)	408 (0.2464)	371 (0.1875)	89 (1.0000)	68 (1.0000)
	3	253 (0.0014)	307 (0.0016)	297 (0.1612)	400 (0.1164)	166 (1.0000)	113 (1.0000)
	4	200 (0.0006)	175 (0.0004)	390 (0.1533)	324 (0.0855)	152 (1.0000)	120 (1.0000)
	5	169 (0.0019)	167 (0.0016)	323 (0.1849)	309 (0.0598)	84 (1.0000)	48 (1.0000)
	6	178 (0.0005)	192 (0.0005)	364 (0.1442)	358 (0.0693)	73 (1.0000)	72 (1.0000)
	7	178 (0.0005)	189 (0.0005)	330 (0.1274)	315 (0.1298)	44 (1.0000)	12 (1.0000)
	8	164 (0.0004)	165 (0.0004)	336 (0.1201)	368 (0.0749)	22 (1.0000)	27 (1.0000)
	9	173 (0.0004)	183 (0.0004)	343 (0.0932)	305 (0.0391)	9 (1.0000)	4 (1.0000)
	10	148 (0.0005)	148 (0.0006)	399 (0.1694)	382 (0.0848)	2 (1.0000)	2 (1.0000)
	11	175 (0.0003)	153 (0.0003)	449 (0.1727)	333 (0.0502)	20 (1.0000)	26 (1.0000)
	12	174 (0.0007)	155 (0.0007)	387 (0.3940)	3419 (1.0000)	15 (1.0000)	6 (1.0000)
2	1	159 (0.0006)	153 (0.0005)	1193 (1.0000)	531 (0.0827)	22 (1.0000)	25 (1.0000)
	2	163 (0.0009)	210 (0.0009)	796 (1.0000)	556 (0.1652)	98 (1.0000)	121 (1.0000)
	3	185 (0.0007)	144 (0.0006)	596 (0.5609)	522 (0.1019)	101 (1.0000)	80 (1.0000)
	4	139 (0.0036)	251 (0.0044)	128 (1.0000)	905 (1.0000)	21 (1.0000)	19 (1.0000)
	5	165 (0.0026)	162 (0.0017)	163 (1.0000)	472 (0.2518)	155 (1.0000)	183 (1.0000)
	6	169 (0.0111)	153 (0.0067)	150 (1.0000)	366 (1.0000)	216 (1.0000)	188 (1.0000)
	7	161 (0.0017)	213 (0.0013)	110 (1.0000)	607 (1.0000)	140 (1.0000)	135 (1.0000)
	8	125 (0.0031)	174 (0.0028)	168 (1.0000)	444 (0.4908)	57 (1.0000)	56 (1.0000)
	9	115 (0.0075)	113 (0.0067)	207 (1.0000)	446 (0.0875)	-	2 (1.0000)
	10	172 (0.002)	185 (0.0015)	144 (1.0000)	469 (0.6148)	121 (1.0000)	125 (1.0000)
3	1	149 (0.006)	179 (0.0063)	631 (1.0000)	467 (0.4034)	487 (1.0000)	369 (1.0000)
	2	135 (0.0258)	129 (0.0227)	512 (0.1707)	454 (0.0896)	273 (1.0000)	298 (1.0000)
	3	172 (0.0018)	213 (0.0013)	324 (1.0000)	455 (0.3785)	115 (1.0000)	95 (1.0000)
	4	192 (0.0014)	176 (0.0011)	403 (1.0000)	451 (0.3924)	270 (1.0000)	254 (1.0000)
	5	188 (0.0014)	241 (0.0014)	241 (1.0000)	831 (1.0000)	241 (1.0000)	201 (1.0000)
	6	173 (0.0039)	221 (0.0037)	142 (1.0000)	434 (0.3901)	37 (1.0000)	27 (1.0000)
	7	117 (0.0047)	181 (0.0046)	461 (1.0000)	481 (0.3995)	47 (1.0000)	35 (1.0000)
	8	160 (0.0014)	217 (0.0013)	311 (1.0000)	443 (0.2306)	272 (1.0000)	287 (1.0000)
	9	176 (0.0015)	212 (0.0017)	279 (1.0000)	469 (0.3756)	225 (1.0000)	280 (1.0000)
	10	182 (0.0012)	213 (0.0012)	647 (1.0000)	335 (0.1893)	468 (1.0000)	279 (1.0000)
4	1	146 (0.0494)	181 (0.0355)	72 (1.0000)	91 (1.0000)		
	2	203 (0.0028)	286 (0.003)	90 (1.0000)	120 (1.0000)		
	3	259 (0.0022)	287 (0.0019)	163 (1.0000)	185 (1.0000)		
	4	229 (0.0024)	320 (0.003)	174 (1.0000)	271 (1.0000)		
	5	274 (0.0013)	309 (0.0014)	455 (0.6261)	493 (0.5773)		
Total no.		13935		30906		7621	

3.2 Species comparison

In the continuation of this sub-chapter, the catch comparison results are described for each species; shrimp, redfish and Greenland halibut. All analysis was done using SELNET, and the length data presented in Table 1. Since time only allowed for five hauls in series 4, some caution should be taken into account during interpretation as a lack of data can not provide the same amount of certainty as a complete data set. The results will be presented in terms of catch comparison curves and catch ratio curves for each species analyzed.

A catch ratio curve is used to illustrate the differences between the test-and baseline codends and is often used to supplement a catch comparison curve as it provides a direct measure for the relative catch efficiency. A catch ratio curve of 1.0 implies that both codends fish with the same efficiency. For instance, if there are 50 individuals in the test-codend and 50 individuals in the baseline codend the result = 50/50 = 1, meaning they fish with the same efficiency. To obtain the catch ratio one need first to estimate the catch comparison rate and then use the general relationship between those (equation 5). A catch ratio below 1.0 implies a reduced catch efficiency in the test codend compared to the baseline codend in the respective length class.

3.2.1 Shrimp

Shrimp, which is the targeted species in question is included in the analysis to investigate the potential for any of the treatments tested having any effect on reducing the catch efficiency compared to the baseline trawl, i.e. the codend used today in this fishery. Table 2 shows the fit statistics, which describe how well a model fits the observations. An indication of a well fitted curve can be found from expecting the deviance, which is a goodness-of-fit- statistic for a selected model, vs the degrees of freedom (DOF), which determines the critical value at whether you accept or reject a hypothesis. If the margin between the two are high, the respected P-value, which indicates how likely it is that the results occurred by chance alone, will be low. Thus, it can be determined that the probability of retention is not a coincidence. The fit statistics are based on the catch comparison (CC) curves and the catch ratio (CR) curves.

Table 2: Fit statistics for the selected model. CRaverage- value is the percentages of what is retained in the test codend compared to the baseline codend below the MLS. CRaverage+ is above the MLS. Values inside the parentheses are the 95% confidence limits.

Length	**Series 1**	**Series 2**	**Series 3**	**Series4**
8.5	0.052 (0.003 - 1.039)	-	-	-
9.5	0.103 (0.009 - 1.017)	0.365 (0.002 - 2.678)	0.071 (0.003 - 6.93E+08)	0.102 (0.003 - 1.048)
10.5	0.179 (0.027 - 1.013)	0.339 (0.006 - 1.714)	0.1 (0.009 - 0.897)	0.172 (0.013 - 0.902)
11.5	0.279 (0.066 - 1.076)	0.336 (0.016 - 1.4)	0.138 (0.021 - 0.445)	0.267 (0.047 - 0.846)
12.5	0.396 (0.135 - 1.124)	0.349 (0.035 - 1.156)	0.189 (0.041 - 0.477)	0.385 (0.135 - 0.801)
13.5	0.518 (0.236 - 1.126)	0.377 (0.063 - 1.053)	0.253 (0.105 - 0.475)	0.516 (0.272 - 0.794)
14.5	0.634 (0.367 - 1.105)	0.418 (0.107 - 1.016)	0.331 (0.191 - 0.658)	0.647 (0.442 - 0.843)
15.5	0.735 (0.498 - 1.114)	0.47 (0.171 - 0.957)	0.421 (0.289 - 0.766)	0.763 (0.579 - 0.908)
16.5	0.815 (0.617 - 1.102)	0.533 (0.247 - 0.95)	0.519 (0.393 - 0.796)	0.852 (0.693 - 0.959)
17.5	0.875 (0.704 - 1.1)	0.604 (0.341 - 0.946)	0.617 (0.475 - 0.822)	0.909 (0.766 - 0.999)
18.5	0.916 (0.768 - 1.11)	0.68 (0.438 - 0.966)	0.709 (0.539 - 0.856)	0.934 (0.79 - 1.038)
19.5	0.942 (0.809 - 1.115)	0.756 (0.541 - 0.984)	0.79 (0.654 - 0.936)	0.935 (0.783 - 1.073)
20.5	0.958 (0.837 - 1.127)	0.827 (0.643 - 1.008)	0.855 (0.732 - 1.001)	0.924 (0.735 - 1.105)
21.5	0.969 (0.855 - 1.134)	0.888 (0.733 - 1.051)	0.906 (0.784 - 1.119)	0.911 (0.683 - 1.139)
22.5	0.977 (0.861 - 1.135)	0.933 (0.785 - 1.097)	0.942 (0.803 - 1.16)	0.91 (0.662 - 1.185)
23.5	0.987 (0.865 - 1.144)	0.96 (0.806 - 1.166)	0.967 (0.795 - 1.191)	0.935 (0.665 - 1.23)
24.5	0.998 (0.866 - 1.142)	0.968 (0.811 - 1.238)	0.983 (0.792 - 1.249)	1.005 (0.69 - 1.407)
25.5	1.011 (0.874 - 1.17)	0.958 (0.802 - 1.302)	0.992 (0.781 - 1.313)	1.151 (0.723 - 1.926)
26.5	1.027 (0.864 - 1.232)	0.933 (0.754 - 1.376)	0.996 (0.763 - 1.374)	1.429 (0.727 - 3.545)
27.5	1.041 (0.83 - 1.355)	0.9 (0.669 - 1.512)	0.997 (0.543 - 1.342)	1.967 (0.692 - 8.413)
28.5	1.052 (0.739 - 1.56)	0.862 (0.548 - 1.776)	0.995 (0.506 - 1.289)	3.062 (0.613 - 28.386)
29.5	1.054 (0.628 - 1.914)	0.828 (0.407 - 2.188)	0.991 (0.378 - 1.308)	5.517 (0.522 - 138.893)
30.5	1.04 (0.494 - 2.525)	0.802 (0.256 - 2.963)	0.986 (0.309 - 1.323)	-
31.5	-	-	0.981 (0.225 - 1.35)	-
$\text{CR}_{\text{average-}}$	37.83 (12.13 - 112.00)	33.71 (5.81 - 101.62)	21.35(7.72 - 47.98)	50.18 (26.09 - 81.52)
$\text{CR}_{\text{average+}}$	94.49 (84.52 - 105.25)	82.43 (69.93 - 94.05)	81.28(72.00 - 89.74)	90.54 (81.00 - 96.03)
P-value	<0.0001	<0.0001	<0.0001	<0.0001
Deviance	164.56	182.6	177.75	60.38
DOF	18	17	18	16

Due to the high subsambling factors for the shrimp the p-value is low, and the deviance, which describes the goodness-of-fit which may be interpreted as being a poor model fit. In this case it is more likely to be a case of over dispersion in the data as visual inspection of the fit shows no indication of length dependent patterns in the deviations between the catch data and the treatment codends selection curves for the shrimp. Therefore, the model was assumed to be legitimate. The $\text{CR}_{\text{average-}}$ in the table indicates that the test codend in series 1 retains 37.83 % of individuals below the MLS (minimum landing size) line than what the baseline codend would retain. $\text{CR}_{\text{average+}}$ is what is retained above the MLS line.

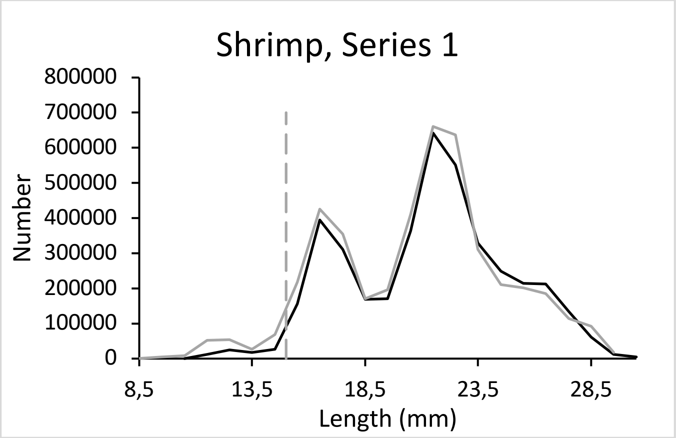

Figure 13: Catch frequency of shrimp series 1 for test codend(black) and Baseline codend(gray), grey striped line shows the MLS(minimum landing size) of 15 mm for shrimp.

Figure 13 shows the catch frequency of shrimp caught for series 1, which shows that we have strong catch data for this species around 20 mm, thus giving us narrow confidence bands and can present the results with high certainty.

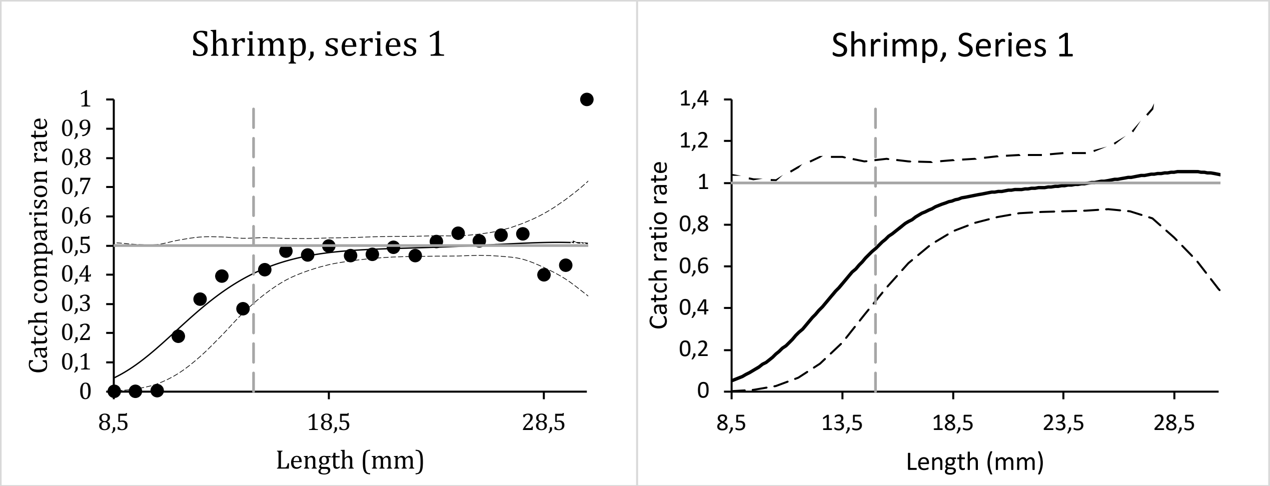

Figure 14: Catch comparison and catch ratio curve for shrimp in series 1 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends, while the grey dashed vertical line shows the MLS (Minimum landing size) of 15 mm.

Figure 14 shows the CC and CR curve for the shrimp in series 1. In this series we tested the effect of adding a four panel 35 mm mesh sized codend with 30 % shortened lastridges against the regular two panel 35 mm mesh size codend. From figure 14, we can see that there is an indication of a reduction in catch efficiency for the test codend below the MLS line, but with the upper confidence band not going under the 0.5 line for the catch comparison curve or below 1.0 for the catch ratio curve implies that the reduction is not proved significant. Thus, it cannot be ruled out that both codends may have the same capture efficiency.

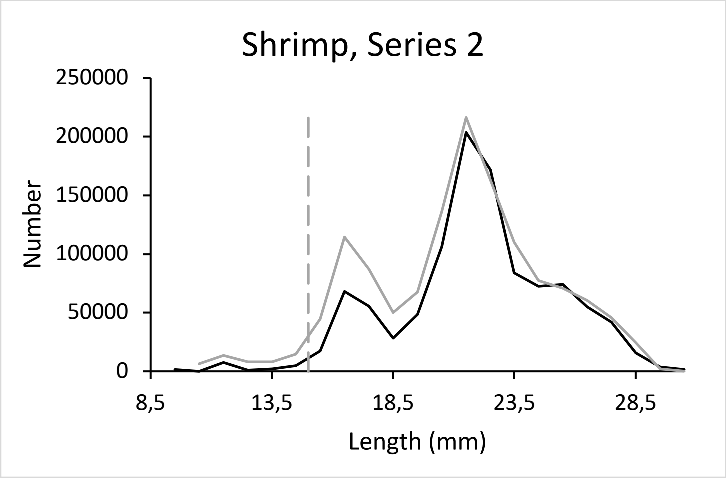

Figure 15: Catch frequency of shrimp series 2 for test codend(black) and Baseline codend(gray), grey striped line shows the MLS(minimum landing size) of 15 mm for shrimp.

Figure 15 shows the catch frequency of shrimp caught for series 2. Here we see that the catch frequency of shrimp for both codends is highest at around 20 mm, with the baseline codend having a slightly higher catch frequency at 16 mm.

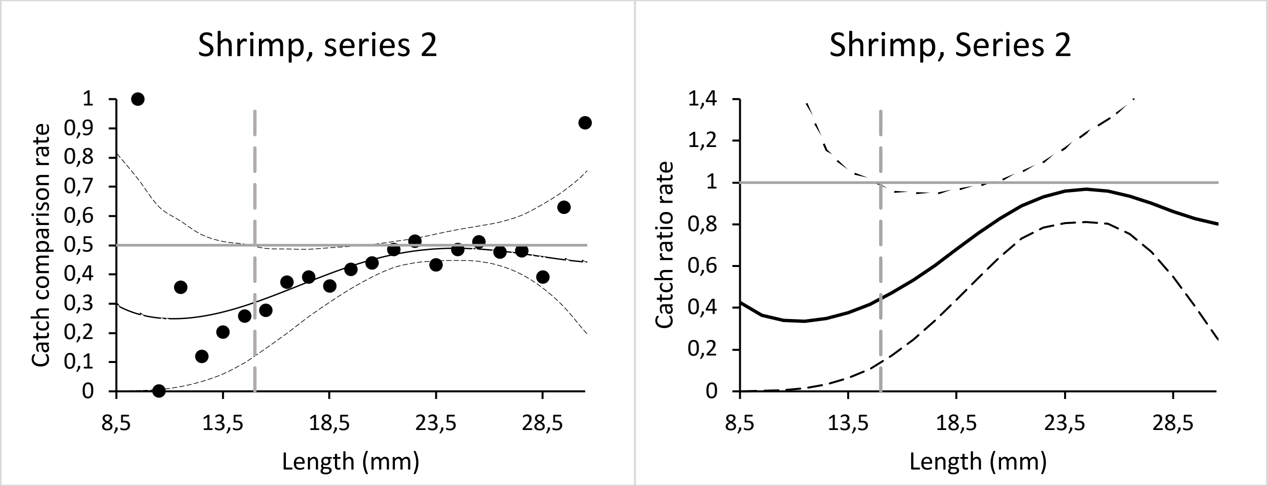

Figure 16: Catch comparison and catch ratio curve for shrimp in series 2 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends, while the grey dashed vertical line shows the MLS (Minimum landing size) of 15 mm.

Figure 16 shows the CC and CR curve for the shrimp in series 2. In this series we tested the effect of increasing the mesh size from 35 mm to 40 mm, increasing the panels from two to four and shortening the lastridges by 30%. Figure 16 demonstrates a significant reduction in shrimp catch between 15 mm and 19 mm in carapace length. This prove that we have a reduction in catch efficiency in the test codend for shrimp in these length classes. This is supported by the upper confidence band dropping below the 0.5 line. From the supplemented CR curve, we see a significant drop in catch efficiency. Implementing all three treatments would lead to lower catches of shrimp in length classes between 15 mm and 19 mm carapace length.

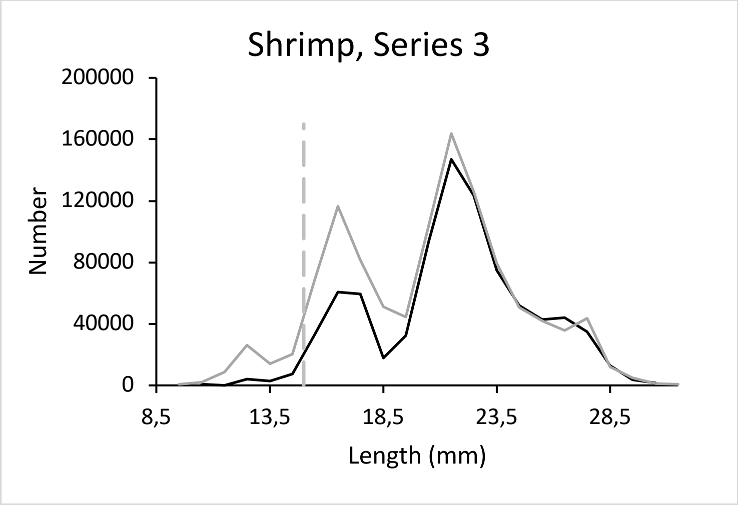

Figure 17: Catch frequency of shrimp series 3 for test codend(black) and Baseline codend(gray), grey striped line shows the MLS(minimum landing size) of 15 mm for shrimp.

Figure 17 visualize the catch frequency of shrimp caught in series 3. We can see that the catch frequency is highest at 21 mm for both codends, but with the baseline codend having a slightly higher catch frequency at 16.5 mm and 12.5 mm carapace length.

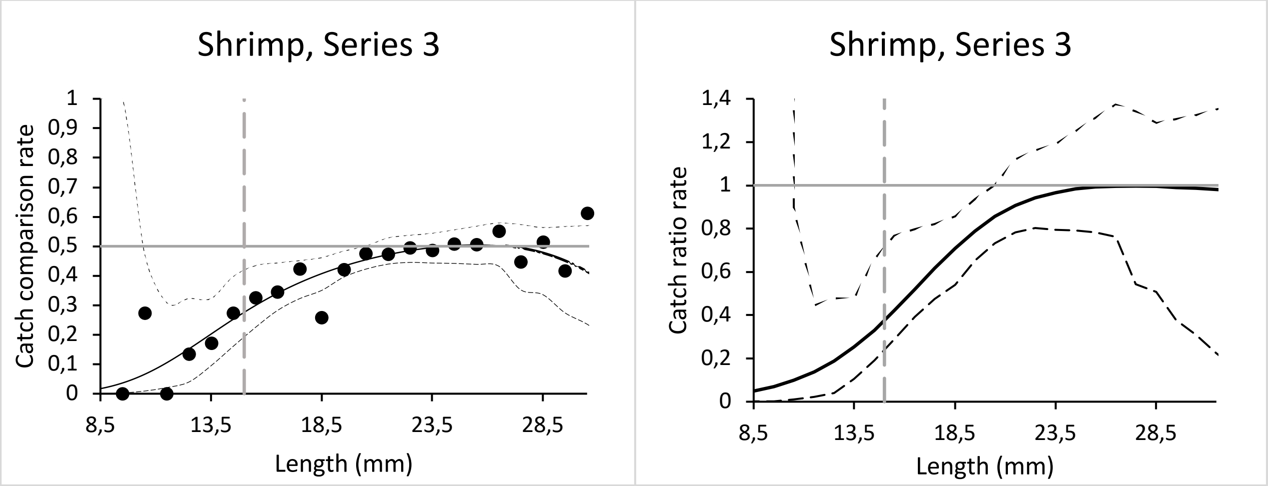

Figure 18: Catch comparison and catch ratio curve for shrimp in series 3 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends, while the grey dashed vertical line shows the MLS (Minimum landing size) of 15 mm.

Figure 18 shows the CC and CR curve for shrimps in series 3. This series tested the effect of increasing the panels from two to four in the codend as well as the mesh size from 35 mm to 40 mm while the lastridges were not tested. These two treatments demonstrate a significant effect on the catch efficiency between the codends. There is a reduction of shrimp caught in the test codend both under the MLS line and above which is shown by the upper confidence band moving under the 0.5 line. This significant reduction occurred for shrimp between 10.5-20.5 mm in carapace length. The CR curve supplement this and showing that the test-codend will retain approximately 50 % of what the baseline-codend will in length groups at 11.5 to 13.5 mm carapace length and about 80 % in length groups between 15 mm and 18.5 mm carapace length.

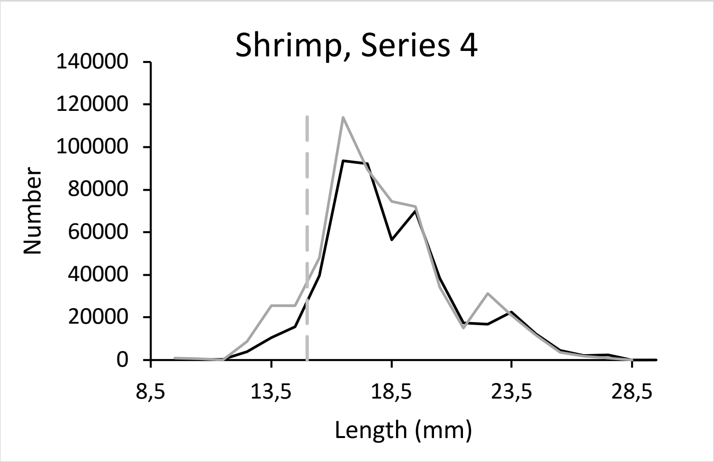

Figure 19: Catch frequency of shrimp series 4 for test codend(black) and Baseline codend(gray), grey striped line shows the MLS(minimum landing size) of 15 mm for shrimp.

Figure 19 shows the catch frequency of shrimp caught for series 4, which shows that we had a high catch frequency for this species around 18 mm carapace length, which is a bit smaller in size than the other three series. This could be because we changed area for this series where the shrimp got a bit smaller. Enough data gave us narrow confidence bands in the respected length groups, thus we can present the results with high accuracy.

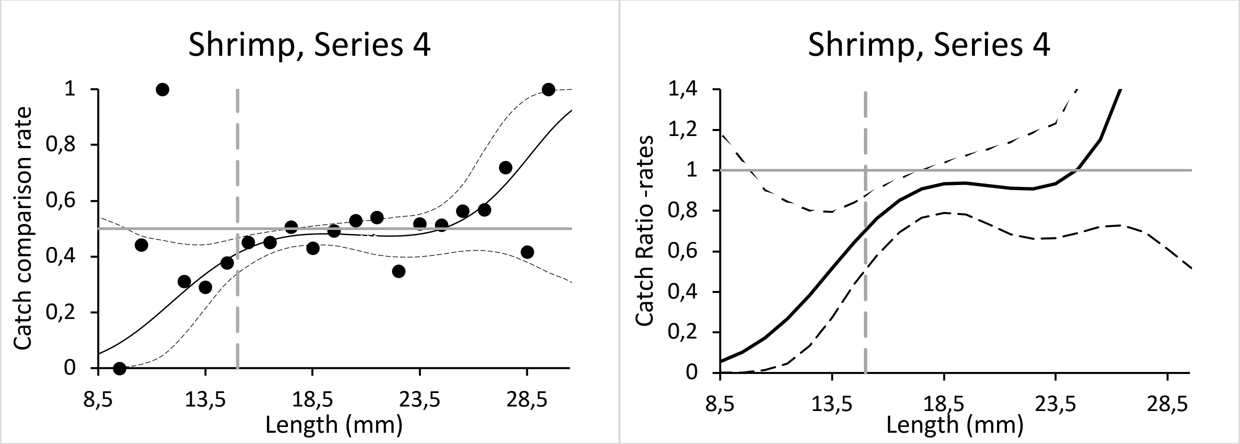

Figure 20: Catch comparison and catch ratio curve for shrimp in series 3 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends, while the grey dashed vertical line shows the MLS (Minimum landing size) of 15 mm.

Figure 20 shows the CC and CR curve for series 4. Here we tested the effect of shortening the lastridges by 30%. Different from the other series', the baseline codend and test codend were both configured with a four panel, 35 mm mesh sized codend. Figure 20 shows a significant reduction in catch efficiency of shrimp in the treatment codend within the size range of 10 to 17 mm. This is confirmed by the upper confidence band falling below the 0.5 line. Supplementing the CC, the CR shows that the test- codend will retain approximately 80 % of what the baseline- codend will in size groups from 12.5 mm to 13.5 mm and about 10 % at 15 mm carapace length.

3.2.2 Redfish

Redfish is a commercially important species and is of high concern due to the large numbers caught as bycatch in the NEA shrimp fishery. Since the low limit of 3 redfish per 10 kgs of shrimp was introduced, it has been a frequent contributor towards the reasoning for fishing areas being closed. Finding a selective technique to reduce the bycatch of this species may help in getting areas reopened and was therefore important to include in this study. Table 3 shows the fit statistics calculated from the catch comparison analysis.

Table 3: Fit statistics for the selected model. The CRaverage- is the percentage value of what the test codend will retain compared to the baseline codend. Values inside the parentheses is the 95 % confidence limits.

Length	**Series 1**	**Series 2**	**Series 3**	**Series 4**
3.5	-	2E-04 (3E-05 - 0.002)	-	-
4.5	-	0.001 (2E-04 - 0.003)	-	-
5.5	0.259 (0.098 - 0.522)	0.003 (0.001 - 0.008)	0.016 (0.009 - 0.032)	0.108 (0.023 - 0.463)
6.5	0.341 (0.224 - 0.475)	0.011 (0.006 - 0.021)	0.06 (0.038 - 0.093)	0.182 (0.055 - 0.501)
7.5	0.454 (0.389 - 0.555)	0.036 (0.02 - 0.055)	0.166 (0.106 - 0.221)	0.299 (0.13 - 0.57)
8.5	0.595 (0.444 - 0.802)	0.1 (0.061 - 0.136)	0.353 (0.232 - 0.43)	0.461 (0.267 - 0.651)
9.5	0.746 (0.47 - 1.146)	0.239 (0.145 - 0.3)	0.596 (0.419 - 0.703)	0.648 (0.467 - 0.747)
10.5	0.874 (0.457 - 1.561)	0.474 (0.31 - 0.567)	0.832 (0.634 - 0.971)	0.826 (0.671 - 0.9)
11.5	0.931 (0.431 - 2.067)	0.767 (0.573 - 0.913)	1.002 (0.768 - 1.173)	0.943 (0.781 - 1.041)
12.5	0.878 (0.373 - 2.776)	0.992 (0.781 - 1.357)	1.084 (0.76 - 1.328)	0.959 (0.792 - 1.095)
13.5	0.715 (0.292 - 3.67)	1.004 (0.711 - 1.899)	1.1 (0.592 - 1.567)	0.863 (0.667 - 1.084)
14.5	0.489 (0.17 - 4.871)	0.778 (0.427 - 2.406)	1.095 (0.357 - 1.956)	0.683 (0.448 - 1.095)
15.5	-	0.453 (0.172 - 2.75)	1.117 (0.164 - 2.672)	0.472 (0.234 - 1.132)
16.5	-	-	-	0.285 (0.103 - 1.147)
CRaverage-	51.34 (43.73 - 62.70)	16.20 (9.94 - 21.02)	38.63 (24.20 - 50.25)	80.60 (68.73 - 85.34)
P-value	<0.0001	<0.0001	<0.0097	<0.0917
Deviance	43.64	111.67	16.89	12.28
DOF	5	7	6	7

The p-values were expected to be low for the redfish, again due to the high sub sampling factors (table 1). However, visual inspection of the model fit to the data showed no inconsistencies between the catch data and the codend selection curves for the catch comparison and catch ratio. Therefore, the model was considered acceptable. The CRaverage-value for series 1 for example indicates that the test-codend would catch 51.35% of the total catch compared to the baseline-codend. The values in parentheses are the confidence limits, which are significant for all series for redfish, meaning we can say with a high degree of certainty that the test-codend leads to a reduction in catch efficiency for this species. In the following figures, the MLS line has been removed due to that redfish do not have a minimum landing size, ie; one redfish is one redfish, no matter the size.

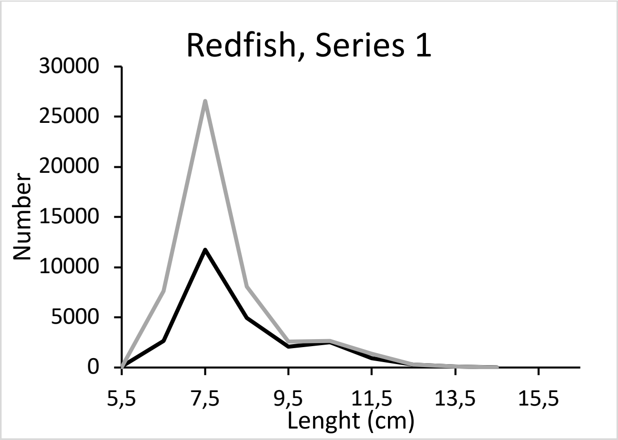

Figure 21: Catch frequency of redfish series 1 for test codend(black) and Baseline codend(gray).

Figure 21 shows the catch frequency of redfish caught for series 1. We see the concentration of redfish caught is highest around 7.5 cm. High catch frequency in the length groups between 5.5 cm and 9.5 cm give us sufficient narrow confidence bands, thus we are able to present the results with high accuracy. There is also a clear difference between catch frequency for the test and baseline codend visualized in the graph.

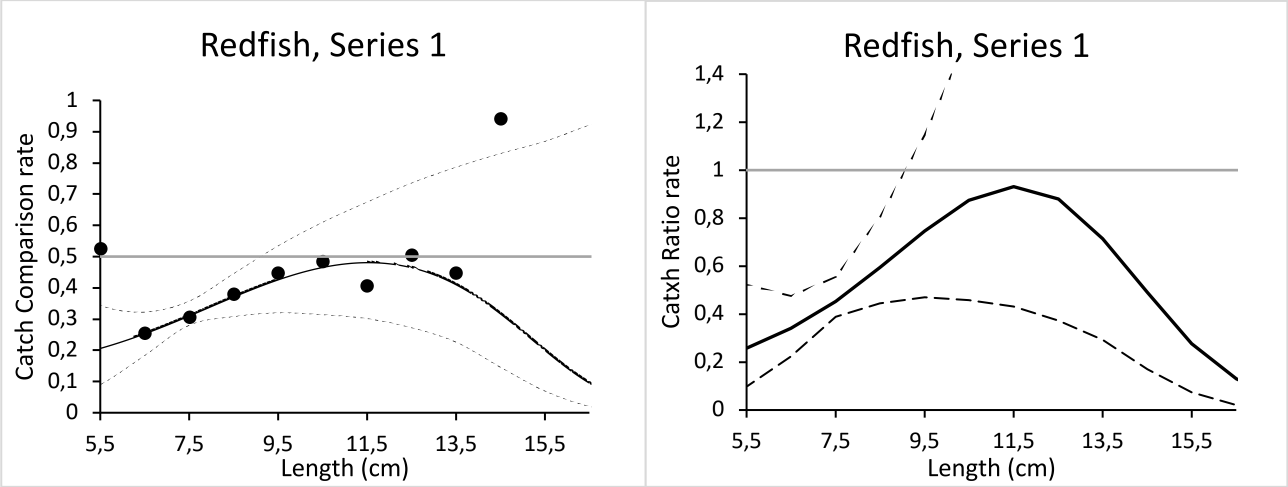

Figure 22: Catch comparison and catch ratio curve for redfish in series 1 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends

The CC and CR curve for the redfish in series 1, testing the effect of increasing the number of panels and the lastridge shortening, demonstrated a significant decrease in catch efficiency in the test codend compared to the baseline for sizes under 9 cm. This is supported by the upper confidence band moving below the 0.5 line. This means that these two treatments functioned to successfully exclude individuals of these length classes. The supplementing CR curve shows that the test codend retains approximately 50 % of what the baseline codend does in length groups below 7.5 cm for this species.

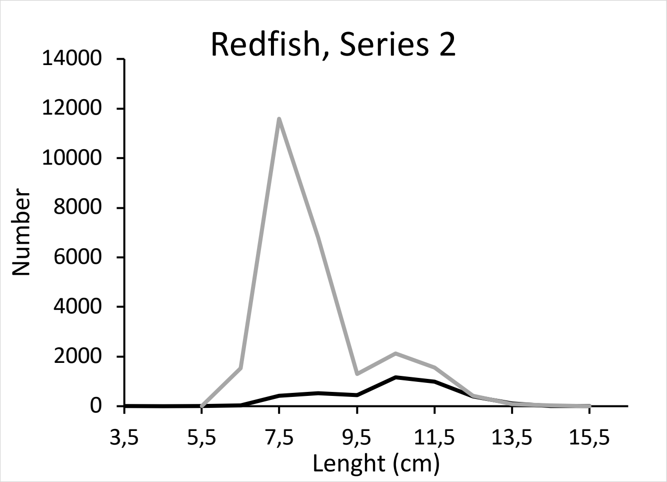

Figure 23: Catch frequency of redfish series 2 for test codend(black) and Baseline codend(gray).

Figure 23 shows the catch frequency of redfish caught for series 2. We see the concentration of redfish caught is highest around 7.5 cm for the baseline codend, while the highest concentration in the test codend is around 10 cm. There is also a clear difference between catch frequency for the test and baseline codend visualized in the graph, with the test codend having a much lower catch frequency in length groups from 5.5 cm to 9.5 cm.

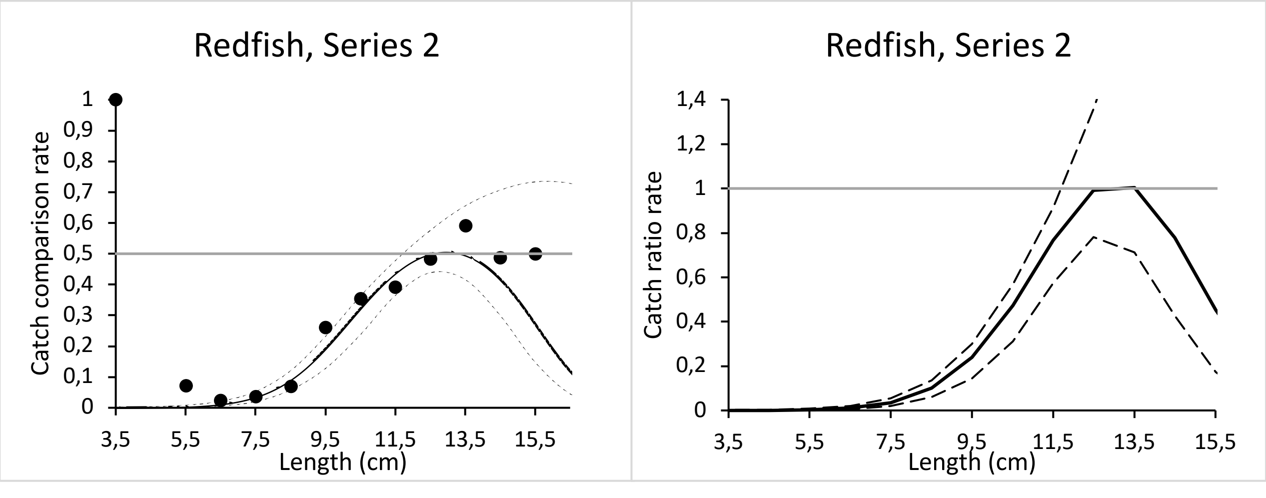

Figure 24: Catch comparison and catch ratio curve for redfish in series 2 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends

Figure 24 portrays the CC and CR curve in series 2 for the redfish. This series investigates the effect of changing all three treatments in the test codend. This produced a significant decrease in redfish below 11.5 cm due to the location of the upper confidence band below the 0.5 line. Thus, we can say with confidence that implementing these treatments on the codend significantly excludes bycatch of redfish below 11.5 cm. The supplementing CR curve shows that the test codend retains approximately 10 % of what the baseline codend will in length sizes of 7.5 cm, which will say that we achieved with these treatments about 90 % reduction in that length group.

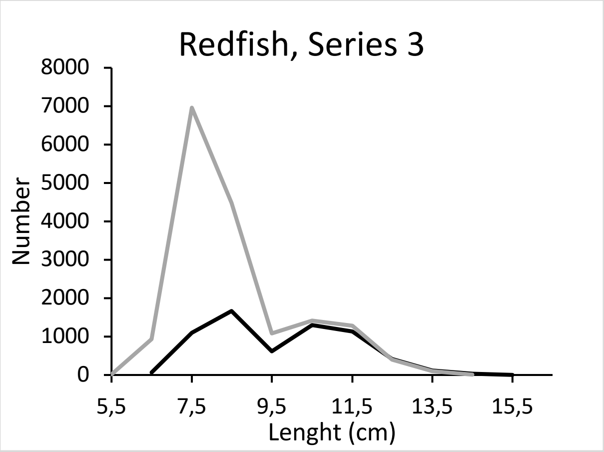

Figure 25: Catch frequency of redfish series 3 for test codend(black) and Baseline codend(gray).

The catch frequency of redfish caught for series 3. We see the concentration of redfish caught is highest around 7.5 cm for the baseline codend, while the highest concentration in the test codend is around 8 cm. There is also a clear difference between catch frequency for the test and baseline codend visualized in the graph, with the test codend having a much lower catch frequency in length groups from 5.5 cm to 8 cm.

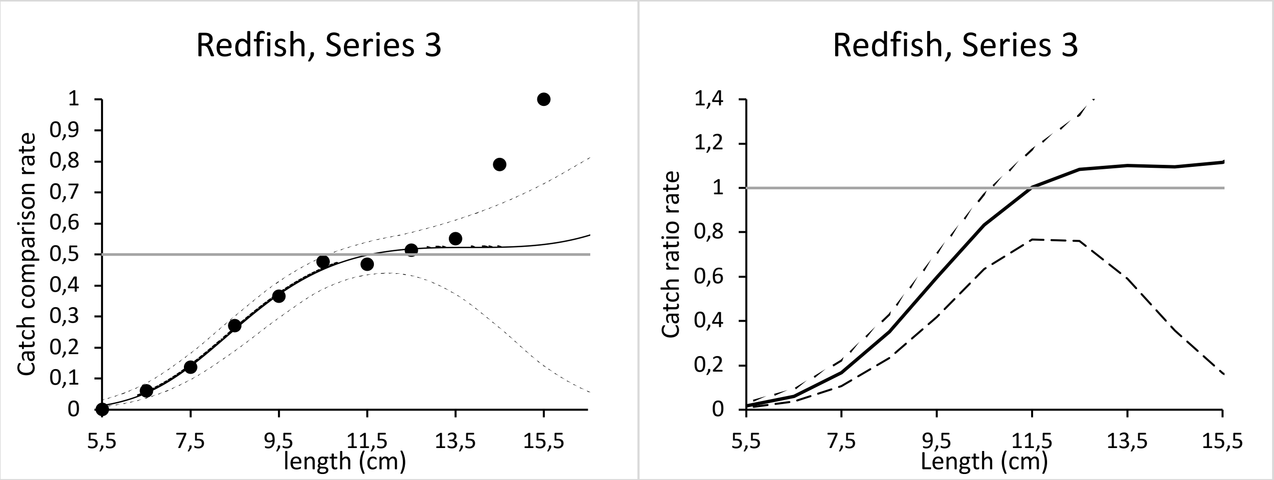

Figure 26: Catch comparison and catch ratio curve for redfish in series 3 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends.

Figure 26 presents the CC and CR curve for redfish in series 3. Here the test codend identifies the difference in catch when the mesh size and the number of panels are increased. As we can see from figure 26 there is a significant decrease in catch efficiency for redfish by applying these treatments. The significant decrease was observed for individuals below 10.5 cm. We could not prove that individuals above this point were affected significantly more or less by the treatments tested. The supplementing CR curve show that the test codend retain approximately 20 % than what the baseline codend will at 7.5 cm length group, meaning we will have around 80 % reduction for this species with the treatments applied.

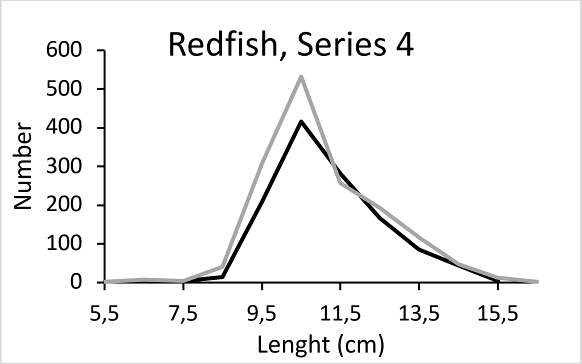

Figure 27: Catch frequency of redfish series 4 for test codend(black) and baseline codend(gray).

The catch frequency of redfish caught for series 4. We see the concentration of redfish caught is higher in size than the other series, at about 10.5 cm. This may be because we changed area for this series, thus fishing on a different school of redfish which was larger in size. It can also be that since this series had a four panel construction in the baseline codend, that we actually manage to reduce the smaller redfish's simply by changing the construction by going from a two to a four panel codend.

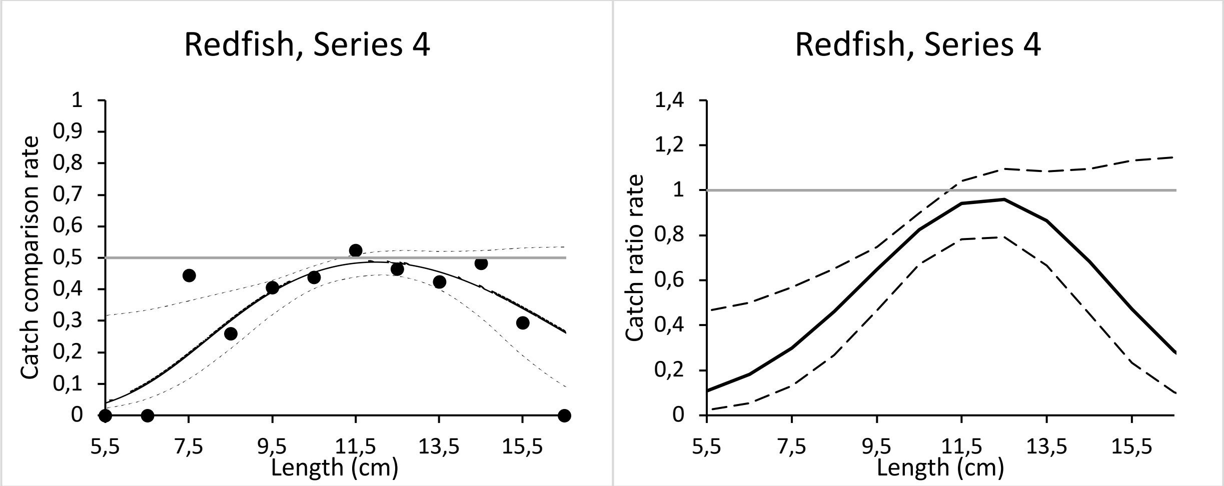

Figure 28: Catch comparison and catch ratio curve for redfish in series 4 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends.

Figure 28 shows the CC and CR curve for the redfish in series 4. This series tested the impact of altering the lastridge ropes only while both codends fished using a four panel configuration and had an identical mesh size. Figure 28, displays the significant decrease in redfish below 10.5 cm in size, which is supported by the upper confidence band falling under the 0.5 line. The supplemented CR curve show that the test codend retains approximately 60 % of what the baseline codend will in length group at 7.5 cm. meaning we will have a reduction at about 40 % with applying the treatment in this length group.

3.2.3 Greenland halibut

Like the Redfish, the Greenland halibut has a low catch limit of 3 per 10 kgs of shrimp caught. This also poses a high risk of areas being closed when the bycatch of the species gets too high. Greenland halibut were only caught in the area that series 1-3 were conducted in. Therefore, no results will be presented for Greenland halibut in series 4. Table 4 shows the fit statistics calculated in the catch comparison analysis for Greenland halibut from the catch data gathered during the trials.

Table 4: Fit statistics for the selected model. The CRaverage- is the percentage value of what the test codend will retain compared to the baseline codend. Values inside the parentheses is the 95 % confidence limits.

Length	Series 1	Series 2	Series 3
7.5	-	-	0.399 (0.065 - 1.027)
8.5	-	-	0.451 (0.114 - 1.034)
9.5	1.172 (0.242 - 2.643)	0.331 (0.053 - 0.945)	0.51 (0.196 - 1.026)
10.5	1.199 (0.353 - 2.521)	0.409 (0.118 - 0.969)	0.577 (0.31 - 1.045)
11.5	1.225 (0.456 - 2.472)	0.501 (0.237 - 0.968)	0.65 (0.443 - 1.046)
12.5	1.25 (0.556 - 2.323)	0.604 (0.371 - 0.996)	0.729 (0.55 - 1.061)
13.5	1.275 (0.68 - 2.195)	0.715 (0.533 - 1.026)	0.813 (0.648 - 1.083)
14.5	1.297 (0.813 - 2.108)	0.827 (0.68 - 1.068)	0.901 (0.739 - 1.123)
15.5	1.318 (0.941 - 2.011)	0.935 (0.811 - 1.141)	0.99 (0.84 - 1.2)
16.5	1.336 (1.055 - 1.935)	1.03 (0.923 - 1.206)	1.08 (0.925 - 1.29)
17.5	1.351 (1.154 - 1.784)	1.107 (0.981 - 1.273)	1.168 (1 - 1.383)
18.5	1.363 (1.188 - 1.674)	1.158 (0.99 - 1.381)	1.25 (1.046 - 1.489)
19.5	1.371 (1.135 - 1.645)	1.179 (0.94 - 1.494)	1.324 (1.073 - 1.596)
20.5	1.374 (1.021 - 1.765)	1.168 (0.853 - 1.574)	1.387 (1.058 - 1.712)
21.5	1.373 (0.867 - 1.908)	1.125 (0.76 - 1.649)	1.434 (1.003 - 1.874)
22.5	1.365 (0.664 - 2.102)	1.055 (0.606 - 1.712)	1.462 (0.918 - 2.062)
23.5	1.352 (0.476 - 2.485)	0.964 (0.448 - 1.782)	1.469 (0.782 - 2.368)
24.5	1.331 (0.306 - 2.953)	0.857 (0.284 - 2.141)	1.453 (0.623 - 2.899)
25.5	1.304 (0.187 - 3.74)	0.743 (0.166 - 2.612)	1.412 (0.462 - 3.803)
26.5	1.27 (0.104 - 4.658)	0.631 (0.079 - 3.899)	1.346 (0.321 - 5.059)
27.5	1.228 (0.056 - 6.843)	0.527 (0.036 - 6.604)	1.258 (0.195 - 8.181)
28.5	1.18 (0.03 - 9.253)	-	1.15 (0.106 - 13.361)
29.5	1.126 (0.018 - 12.047)	-	-
CR$_{average}$-	133.74 (112.31 - 159.85)	99.90 (89.26 - 110.90)	114.59 (96.00 - 135.10)
P-value	<0.5132	<0.5011	<0.1397
Deviance	12.18	13.33	22.11
DOF	13	14	16

As opposed to the shrimp and redfish, no subsampling was carried out for the Greenland halibut. From the fit statistics we see that the distance between the deviance and DOF is low. Thus, the model selected can be considered to be acceptable.

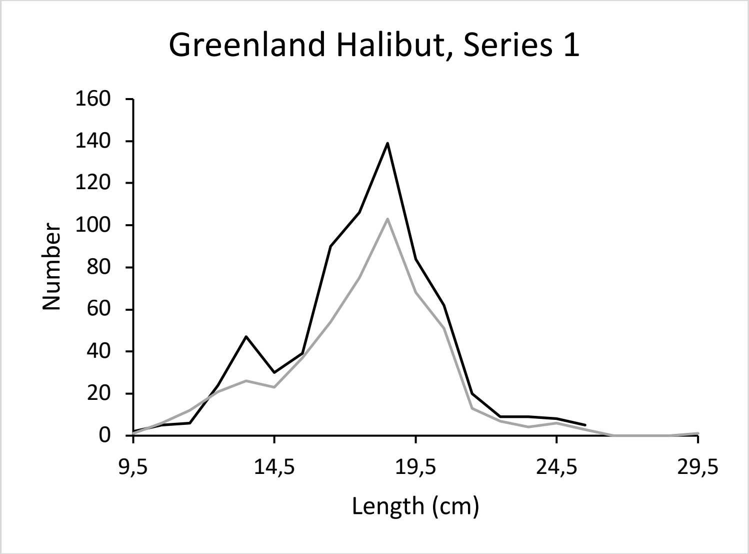

Figure 29: Catch frequency of Greenland halibut series 1 for test codend(black) and Baseline codend(gray).

Figure 29 shows the catch frequency of Greenland halibut caught in series 1. We see the concentration of halibut caught is highest at 19.5 cm for both test and baseline codend. There is also a difference between catch frequency for the test and baseline codend visualized in the graph, with the test codend having a higher catch frequency over 11.5 cm through the serie.

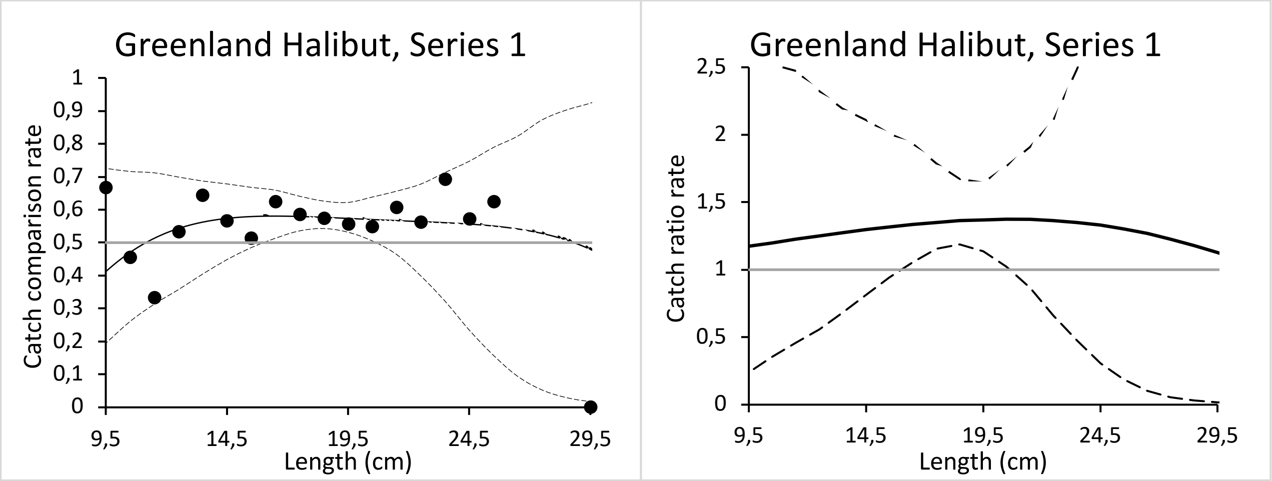

Figure 30: Catch comparison and catch ratio curve for Greenland halibut in series 1 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends.

Figure 30 displays the CC and CR curve for the Greenland halibut in series 1. Here we can see that for the length classes between 16 and 20.5 cm the test codend has a significantly higher catch efficiency than the baseline trawl. Therefore, shortening the lastridges and configuring the codend with four panels rather than two will lead to an increase in catches of Greenland halibut in this size range. This is also supported with the catch ratio curve that the treatments make the test-codend retain approximately 10 % more than the baseline codend in length group of 18.5 cm.

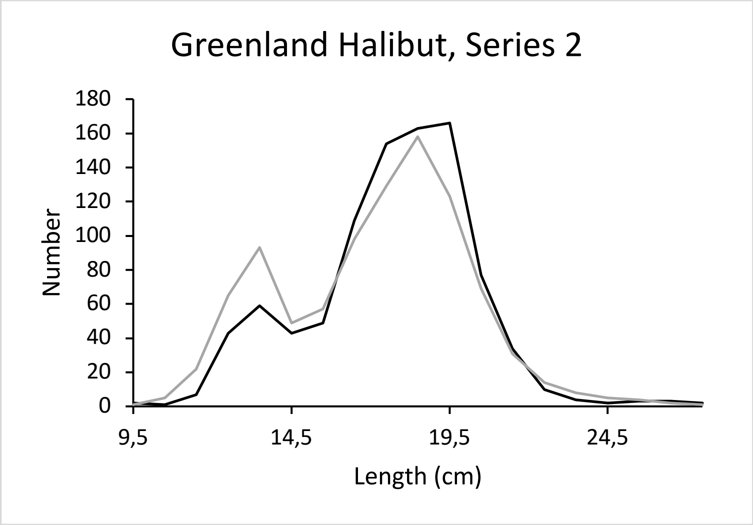

Figure 31: Catch frequency of Greenland halibut series 2 for test codend(black) and Baseline codend(gray).

The catch frequency of Greenland halibut caught in series 2, showing the highest concentration of halibut caught is at 19 cm for the baseline codend and 19.5 cm for the test codend. There is also a difference between catch frequency for the test and baseline codend visualized in the graph with the baseline codend having a higher catch frequency to 15.5 cm and from 22.5 cm to 25.5 cm and the test codend being higher in size ranges between 16 cm to 22.5 cm.

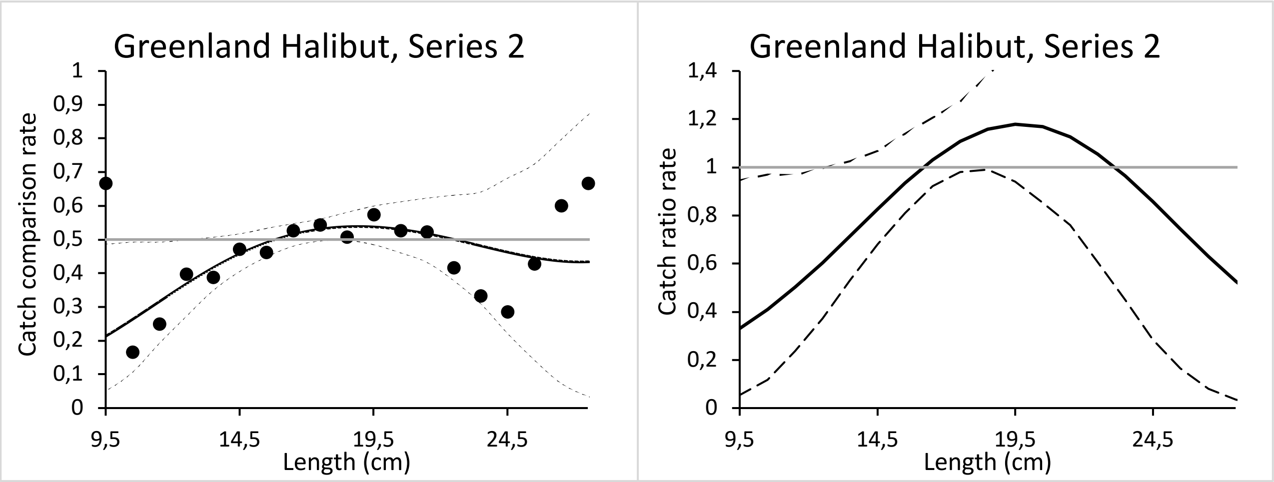

Figure 32: Catch comparison and catch ratio curve for Greenland halibut in series 2 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends.

Figure 32 shows the CC and CR curve for Greenland halibut in series 2. From the figure we can see that there is a significant reduction in catch efficiency for individuals smaller than 11.5 cm in the test codend. This is confirmed by the upper confidence band moving slightly below the 0.5 line. There is also an indication for an increase in catch efficiency in the test codend for individuals between 16 cm and 19 cm. This effect is not significant however based on the lower confidence band not moving over the 0.5 line. In this setup the test codend tested all three treatments combined; increased mesh size, a four panel codend and 30% shortened lastridges against the baseline codend. The supplemented CR curve shows that the test codend have approximately 5 % reduction in individuals below 11.5 cm.

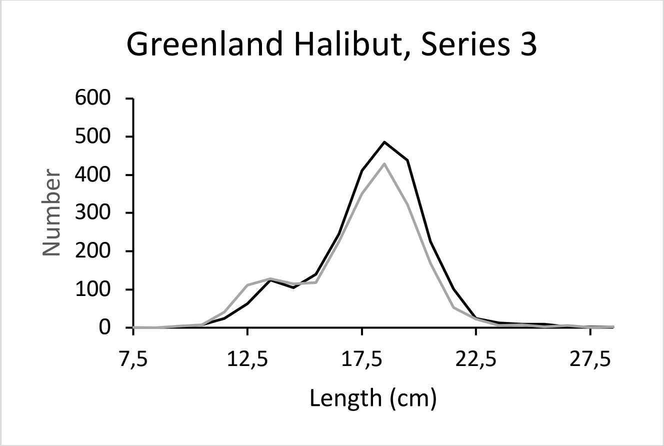

Figure 33: Catch frequency of Greenland halibut series 3 for test codend(black) and Baseline codend(gray).

The catch frequency of Greenland halibut caught in series 3, with highest catch frequency for both codends at 18.5 cm length.

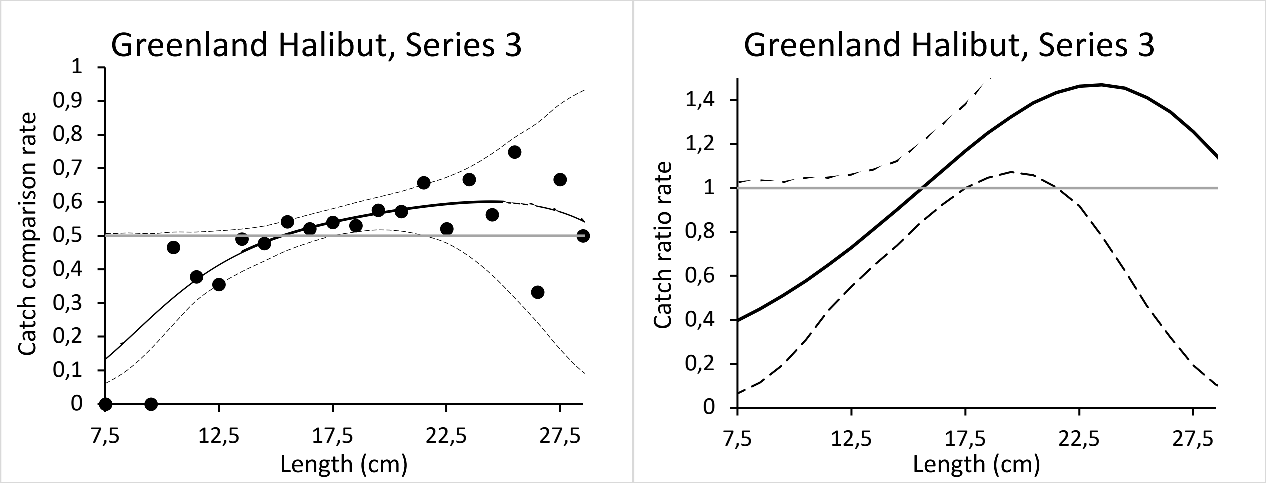

Figure 34: Catch comparison and catch ratio curve for Greenland halibut in series 3 with 95 % confidence bands (black dashed lines). The horizontal grey line shows where the catch is equal between the two codends.

From figure 34 a significant increase in catch efficiency can be observed in the test codend. This occurred for individuals between the length classes of 18 cm to 21 cm, supported by the lower confidence band crossing over the 0.5 line for this length interval. Thus, increasing the mesh size and adding two additional panels does not successfully release more individuals of this species. Instead it contributes to increased retention of some larger year classes. With the test codend retaining approximately 8 %more than the baseline codend in length group of 19.5 cm.

3.3 Bycatch criteria's species wise

To gain a better impression on how the codends compared to each other as well as the bycatch criteria allowed for each species in each haul across the series, bar charts for each species was made to outline this. Even though the treatments can work in reducing the bycatch it remains important to quantify this against the permitted limit in the NEA-shrimp fishery. Keeping in mind that the results represented below are based on the populations fished during this particular cruise,and should not be extrapolated to other areas. We were also fishing in an area that was otherwise closed due to high bycatch rates, therefore higher bycatch rates there are to be expected.

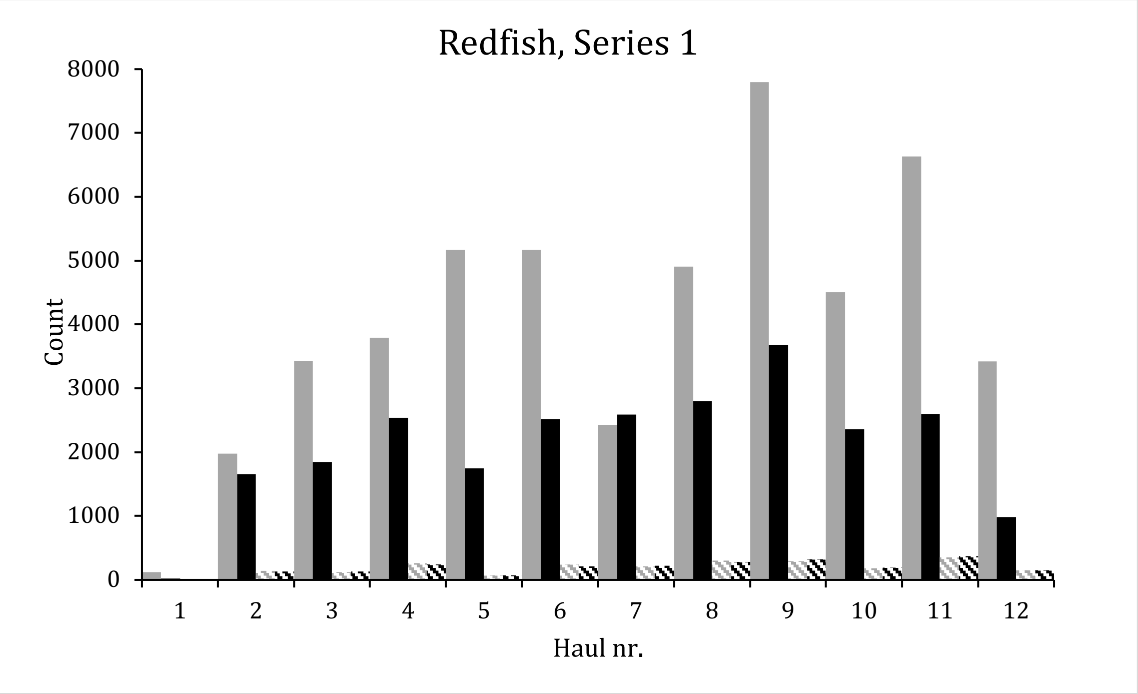

Figure 35: Catch of redfish in series 1 across all hauls for the test (black bar) and the baseline (gray bar) codend. The striped line bars show the criteria limit allowed for the test (black bar) and the baseline (grey bar) codend.

From figure 35, except for haul 7, we clearly see the reduction of redfish when the test codend was fishing. While the treatments of shortening the lastridges and going from two to four panels works in reduction of redfish in this series, we are still not close to reduce the catch efficiency enough to reach the limits allowed in this fishery. Thus, this area will remain closed.

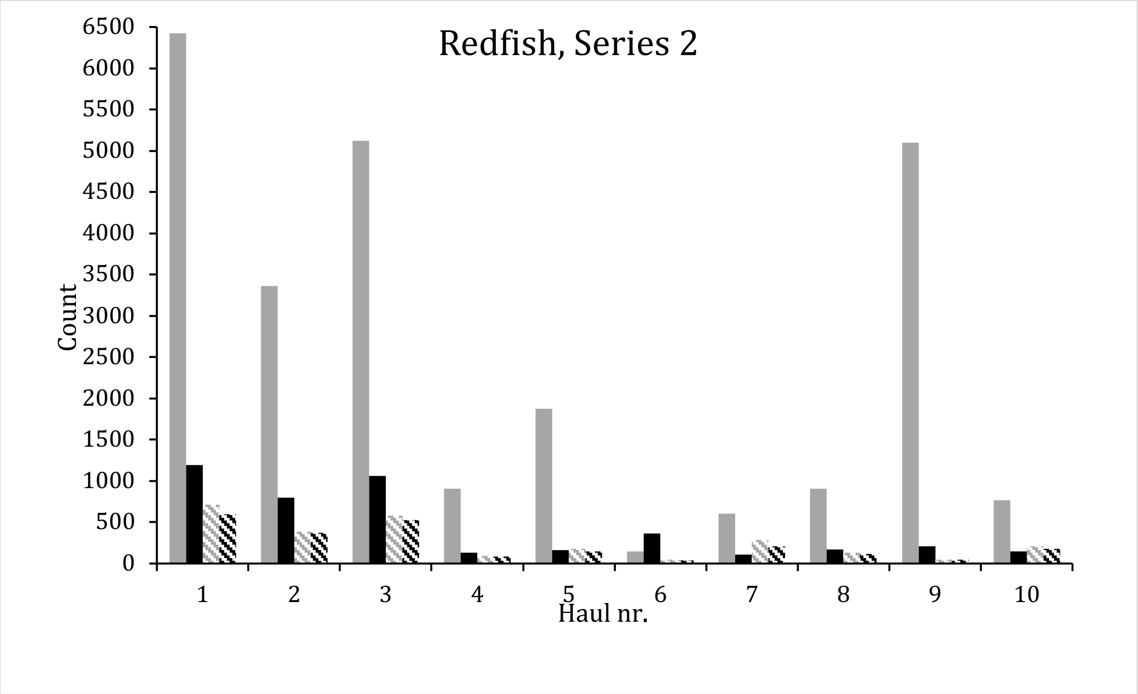

Figure 36: Catch of redfish in series 2 across all hauls for the test (black bar) and the baseline (grey bar) codend. The striped line bars show the criteria limit allowed for the test (black bar) and the baseline (grey bar) codend.

From figure 36 in series 2 we can see a clear reduction in redfish between the test and baseline codend. But again, in this series, most of the hauls did not have enough reduction to fall below the limit. Haul 7 and 10 however did catch a legal amount of redfish in the test codend. Thus, the combined testing of the three treatments has the potential to enable the level of redfish catch tolerated for this fishery.

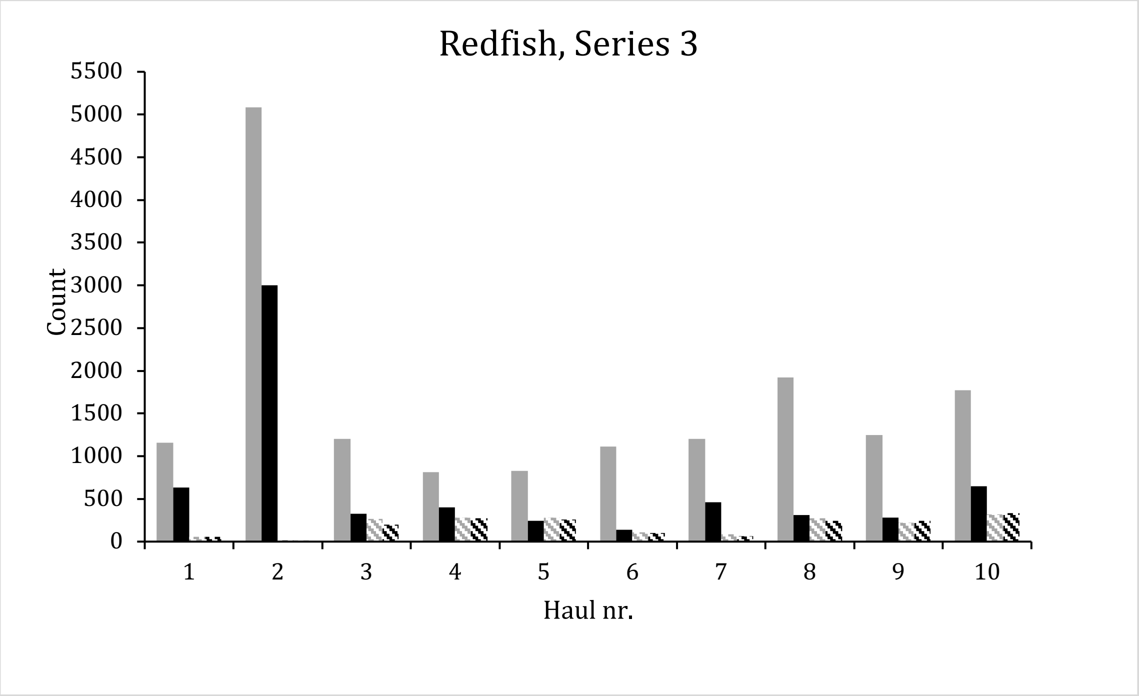

Figure 37: Catch of redfish in series 3 across all hauls for the test (black bar) and the baseline (gray bar) codend. The striped line bars show the criteria limit allowed for the test (black bar) and the baseline (grey bar) codend.

Catches of redfish in series 3 clearly reduced for all hauls when the treatment was tested. The treatments tested here were increasing the number of panels and the mesh size in the codend. While some hauls had a catch approaching the limit it still remained to be too high, thus the area would have been kept closed with these treatments enforced in the fishery.

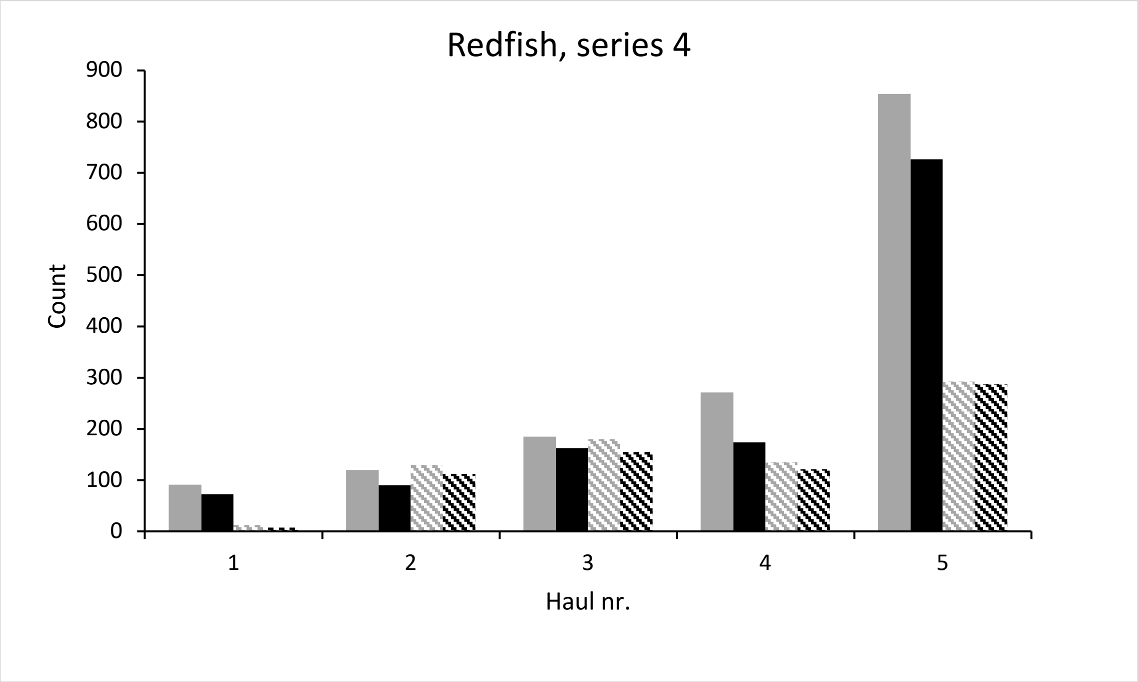

Figure 38: Catch of redfish in series 4 across all hauls for the test (black bar) and the baseline (grey bar) codend. The striped line bars show the criteria limit allowed for the test (black bar) and the baseline (grey bar) codend..

Figure 38 is showing redfish catch and criteria limits for series 4. Lower catches may be as a result of four panels being used in both codends. While just five hauls could be completed, the effect of more opened meshes as a result of shortening the lastridges in the test codend is noticeable. However, catch levels could not be reduced to acceptable levels except for haul nr. two, where both the baseline- and test codend fell below their respective limits.

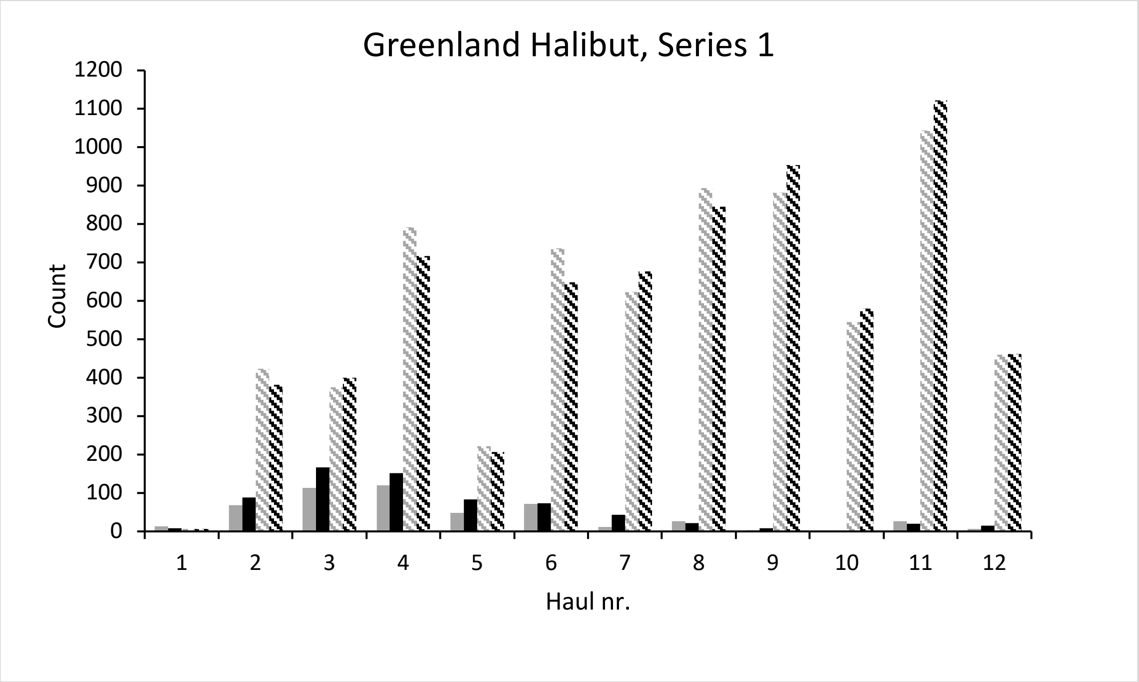

Figure 39: Catch of Greenland halibut in series 1 across all hauls for the test (black bar) and the baseline (grey bar) codend. The striped line bars show the criteria limit allowed for the test (black bar) and the baseline (grey bar) codend.

For the Greenland halibut the catches in relation to their legal limits are rather different compared to the redfish. Throughout all hauls in series 1 except for the first, the catch fell below the allowable limits. We also see that the test codend retains slightly more than the baseline codend for this species using these treatments.

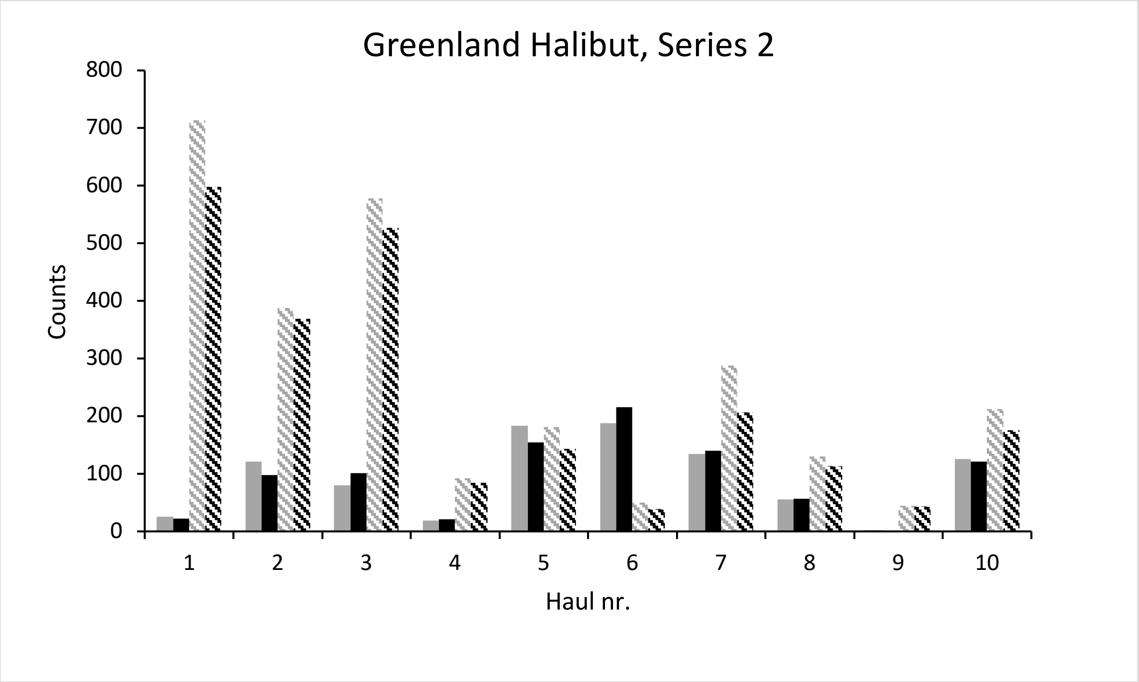

Figure 40: Catch of Greenland halibut in series 2 across all hauls for the test (black bar) and the baseline (grey bar) codend. The striped line bars show the criteria limit allowed for the test (black bar) and the baseline (grey bar) codend.

In series 2, in which all treatments were applied to the test codend we can see from figure 40 that all hauls except haul nr. 5 and 6 caught below the limit. There were also some hauls where the test codend retained more than the baseline, showing that the treatments applied could lead to a higher catch efficiency for this species.

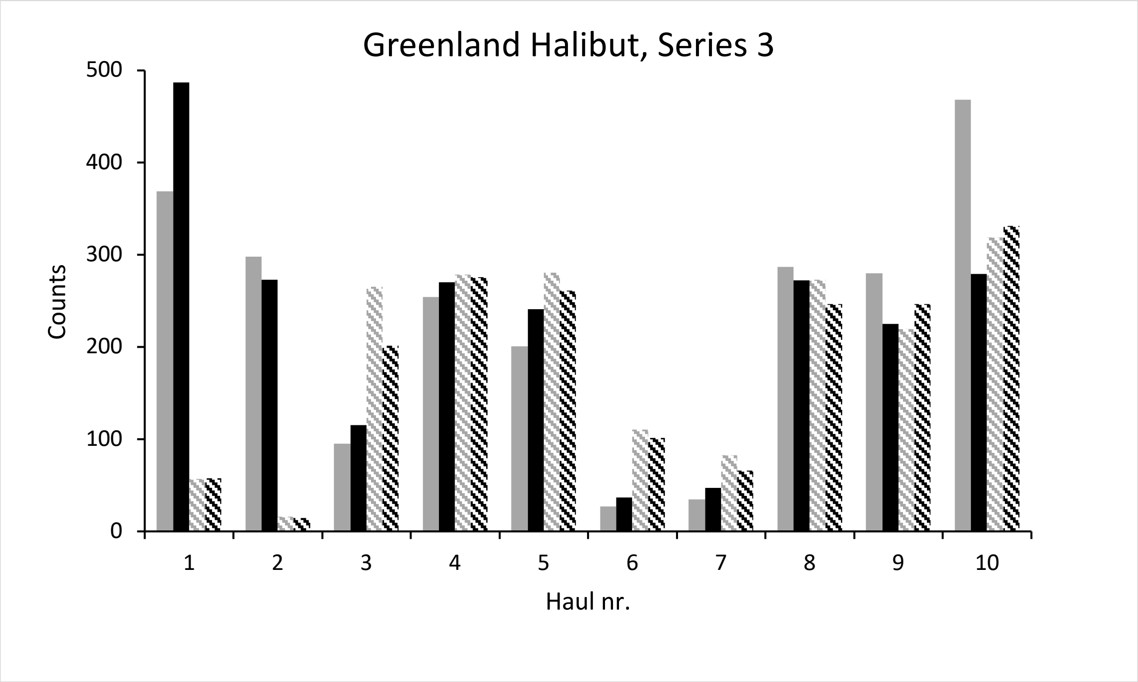

Figure 41: Catch of Greenland halibut in series 3 across all hauls for the test (black bar) and the baseline (grey bar) codend. The striped line bars show the criteria limit allowed for the test (black bar) and the baseline (grey bar) codend.

In series 3, which tested the treatments of an increased mesh size and a four panel codend, the results varied. As shown in figure 41, the baseline codend in haul nr. 1, 2, 8, 9 and 10 caught above the limit as opposed to the test codend which caught over the limits in haul nr. 1, 2 and 8.

3.4 Treatment Tree

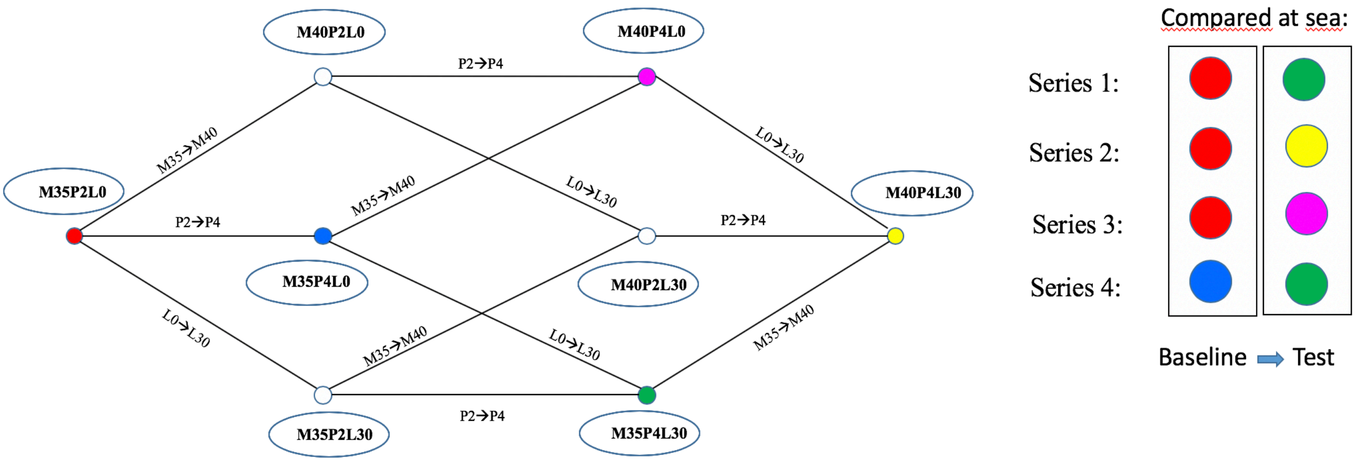

Figure 42: Treatment tree with series 1-4 of the test-and baseline gears compared at sea. With the colour red being the baseline codend of M35P2L0 for series 1,2 and 3. The corresponding colors for each series show the test codend. The blue colour in series 4 shows the baseline codend of M35P4L0 with the corresponding green as the test codend.

This trial gave us the chance to investigate the effect of three different treatments, mesh size, panels and shortened lastridges. For each of these treatments we had two options. We had mesh size (M) at 35 mm or 40 mm, panels (P) at either two or four and the lastridge shortening (L) at either 0 (no shortening of the lastridges) or (L) of 30, (a 30% shorter set of lastridges). From this we were able to construct a formal framework which we called the "Treatment tree", as shown in figure 42. This tree shows the pathways each series takes, and from using equation 5, by connecting catch ratio with the absolute selectivity R (the ratio of the absolute selectivity of the test codend vs the baseline codend) the effect of treatments that were not tested at sea could be calculated. This saves a large degree of time and resources in testing additional variations of these treatments at sea.

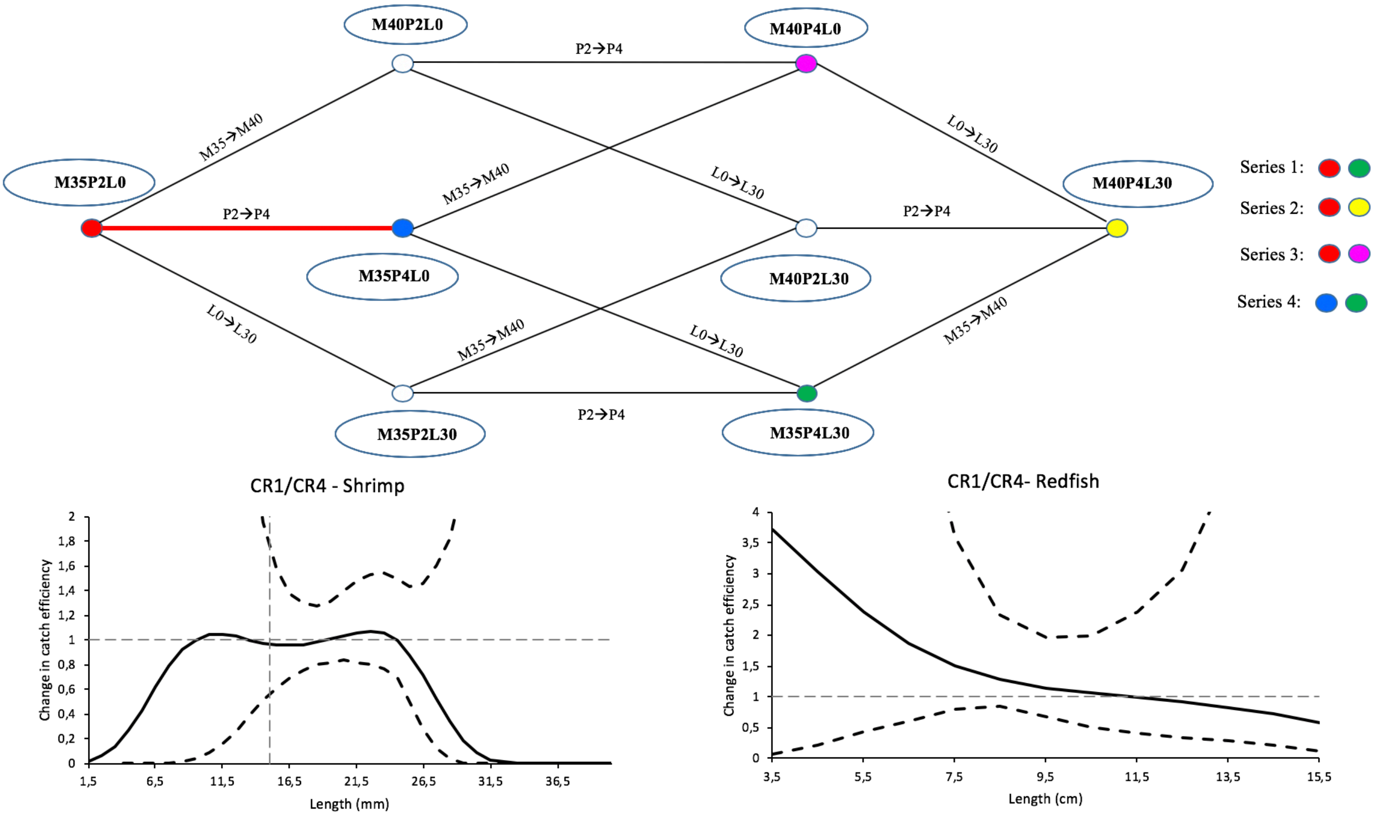

Figure 43: Treatment tree showing the change in catch efficiency for shrimp and redfish granted we take the path highlighted (red).

Figure 43 indicates the effect of going from a two panel to a four panel codend (beginning at the red dot) while the mesh size is held at 35 mm and the lastridges ropes remain at full length (M35P2L0 to M35P4L0). We are able to isolate this effect and show the change in catch efficiency by dividing the catch ratio (CR) for series 1 by the catch ratio (CR) for series 4 for both the shrimp and the redfish. In other words we are able to calculate the catch efficiency for an experiment that was not tested at sea. We now gain the insight that there will in fact be no change to the catch efficiency for the shrimp or the redfish when mesh size alone is changed, and this is confirmed by the confidence bands not going above or under the 1.0 line. Greenland halibut is missing because it was not caught in series 4.

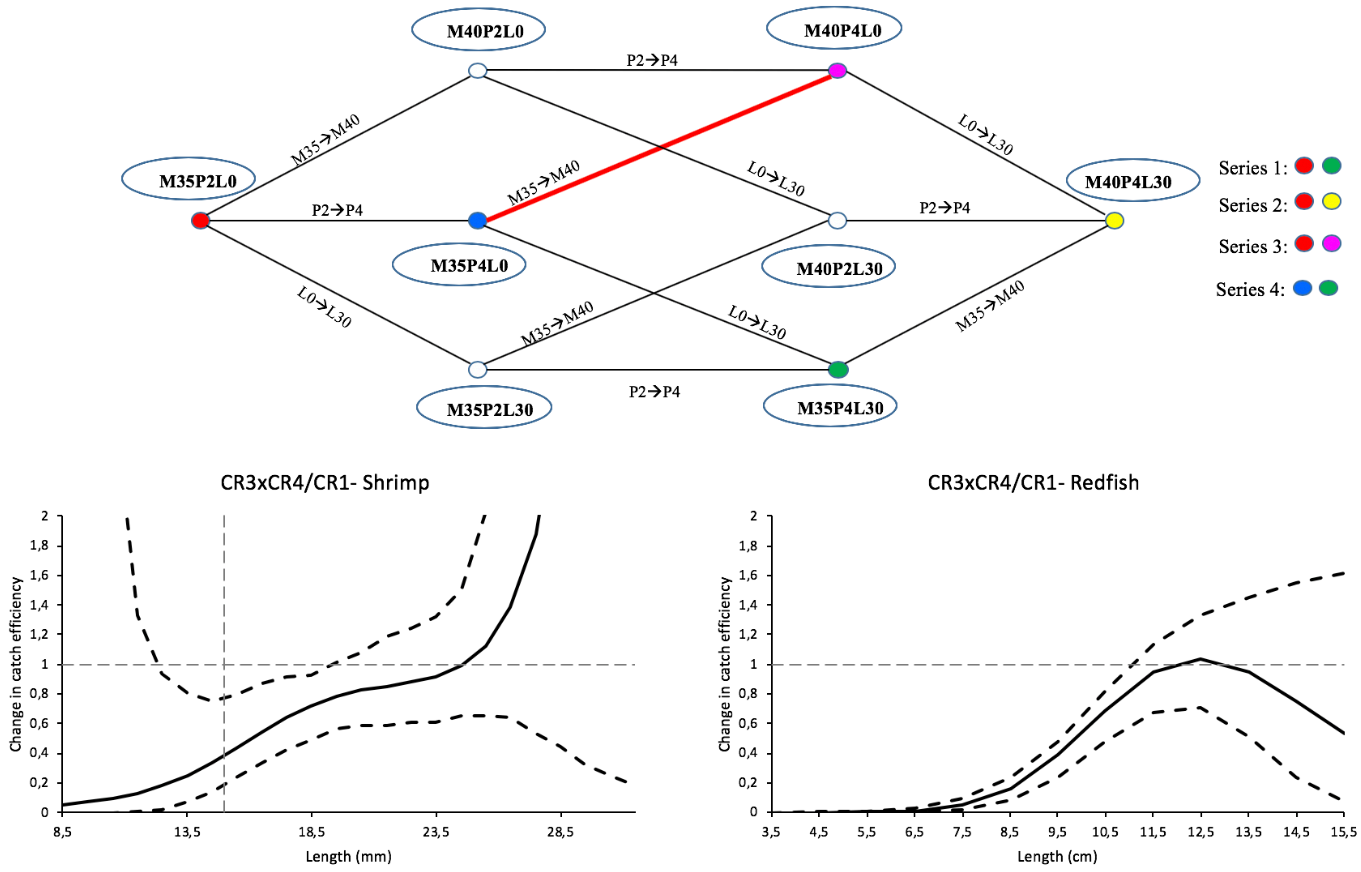

Figure 44: Treatment tree showing the change in catch efficiency for shrimp and redfish granted we take the path highlighted (red).

In figure 44 we see the change in catch efficiency for shrimp and redfish by increasing the mesh size from 35 mm to 40 mm on the condition that we start from the configuration; M35P4L0 (blue dot), thus moving to M40P4L0. We can isolate this effect by multiplying the CR of series 3 by the CR of series 4 and divided the result by the CR of series 1. The result reveals that increasing the mesh size alone leads to a reduction in catch efficiency for the shrimp and for the redfish for individuals below 11 cm. For the shrimp, the effect will lead to reduced catch by 20 % at 15 mm carapace length and for the redfish we get a reduction of approximately 90 % at 7.5 cm length and 20 percent at 10 cm in length. Greenland halibut again is not analyzed here as results from series 4 were not available.

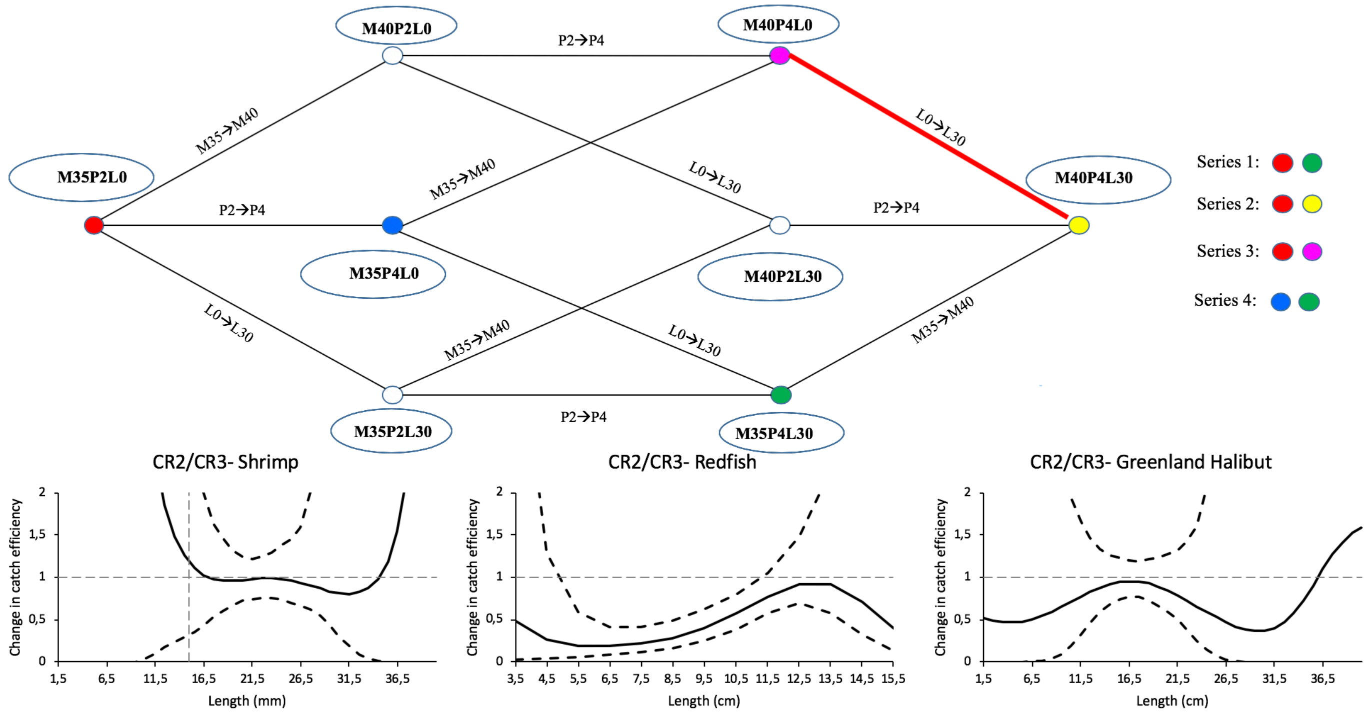

Figure 45: The treatment tree showing the change in catch efficiency for shrimp, redfish and Greenland halibut granted we take the path highlighted red.

Figure 45 presents the change in catch efficiency for the shrimp, redfish and Greenland halibut when the lastridges are shortened on the condition that we start with M40P4L0 (pink dot), while the two remaining treatments are held constant. Here we can see that shortening the lastridges leads to no change in the catch efficiency for shrimp and Greenland halibut. Redfish however showed a reduction in catch for the size classes between 5 cm and 11 cm, with nearly 60 % reduction in size group 7.5 cm.

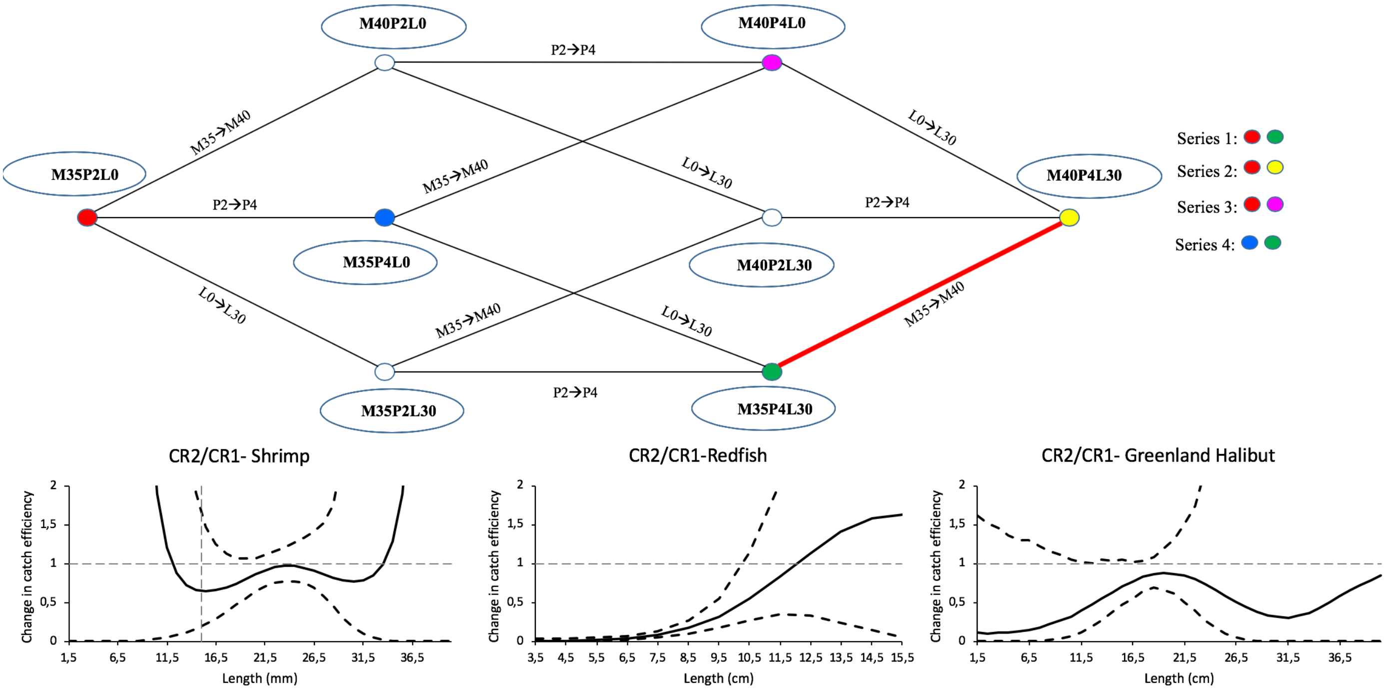

Figure 46: Treatment tree showing the change in catch efficiency for shrimp, redfish and Greenland halibut granted we take the path highlighted red.

Figure 46 shows the change in catch efficiency for shrimp, redfish and Greenland halibut if only the meshes are increased from 35 mm to 40 mm, while all other conditions remain unchanged. This requires in the treatment tree that calculations are made starting from the green dot (M35P4L30). Through this process it can be expected that the catch efficiency for shrimp and Greenland halibut remains the same while there will be a reduction in redfish below 10 cm in length and a reduction of approximately 90 % in length group of 7.5 cm.

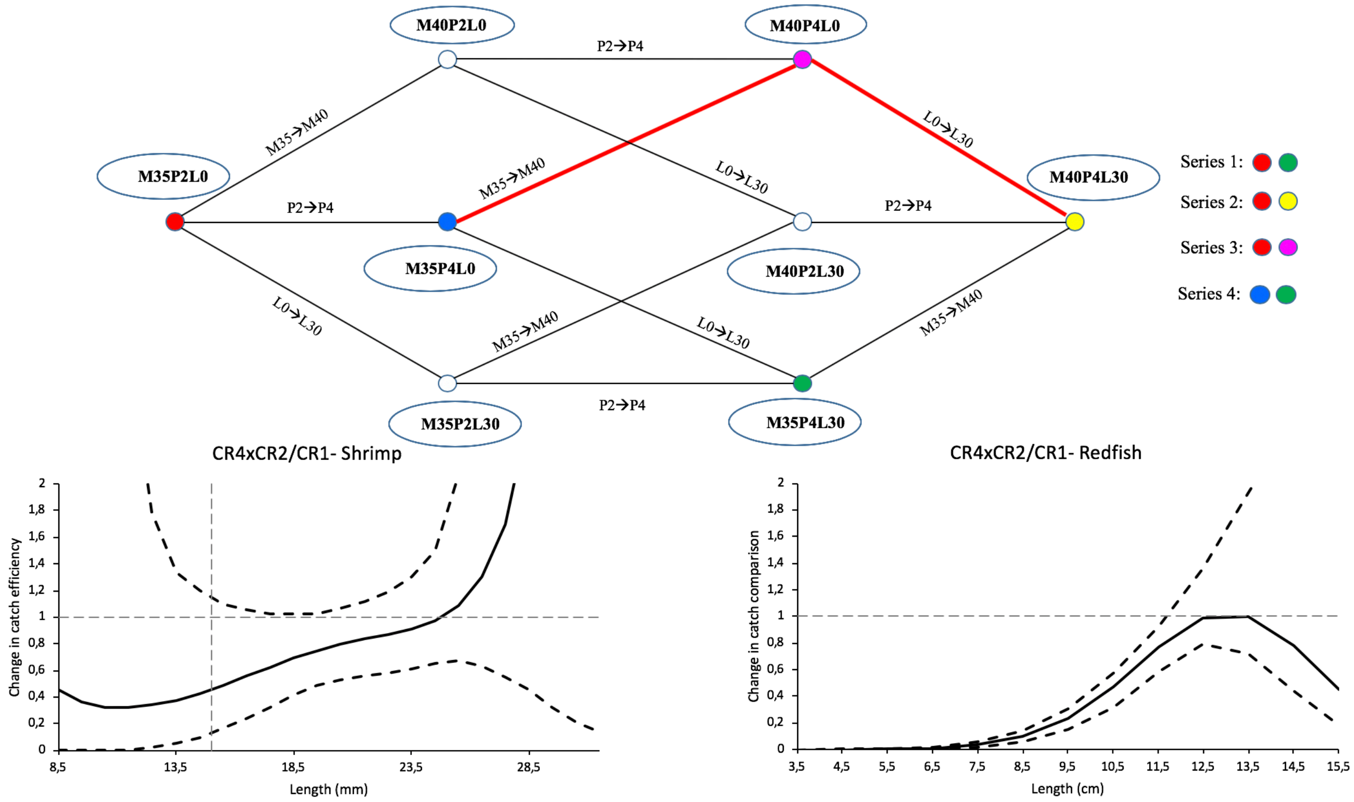

Figure 47: The treatment tree showing the change in catch efficiency for shrimp and redfish granted we take the path highlighted red.

Figure 47 shows the change in catch efficiency for shrimp and redfish if meshes are increased while the lastridges are shortened by 30 % thus using the blue dot as the starting point (M35P4L0). From the figure we can see that applying these treatments will lead to no significant change in catch efficiency for the shrimp and a significant reduction in catch efficiency for the redfish under 11.5 cm and a reduction of approximately 90 % in size group of 7.5 cm. Greenland halibut is not part of this analysis since there was no catch of this species in series 4.

4 DISCUSSION

A challenge with introducing selectivity devices which select against bycatch in the shrimp fishery is that often there is a high loss in shrimp catches (Polet, 2002; Gorman and Dixon, 2015; Dag Mollan pers. comm). Results from this study again demonstrate this; we observe a loss in shrimp below a certain size when treatments to release bycatch are applied. This loss of shrimp catch would most likely not be acceptable for the fishermen, while a small drop in the smallest shrimp can be. This was the case with the findings of Isaksen et al. (1992) where agreeable losses of shrimp by using the Nordmøre grid were tolerated by the industry given its ability to exclude large bycatch. Another important factor contributing to the Nordmøre grid’s success was how easy it was to handle and install for the fishermen. Furthermore the low cost of the grid itself helped propel the grid into the fishery. This is important to keep in mind when testing and implementing new gear changes. The best improvements one can make provides the maximum benefit at the lowest cost to the fishery. Experiments with certain sorting devices, such as sieve panels and double-grid systems, may help reduce bycatch, but are in some cases too intricate and difficult to handle thus may become more of a nuisance for the fishermen. When sorting devices are not effective in avoiding the bycatch of juvenile fish species, there is a risk of high discard rates and overfishing. Norway has over the years established a set of regulations and management measures to promote sustainable exploitation in fisheries, where undersized fish below the legal size is spared and unwanted bycatch is minimized (Gullestad et al., 2015). This problem is addressed in the NEA- where closures of areas are implemented when the bycatch becomes too high. This however costs the fishermen time and effort in searching for other areas to fish. This study does not test intricate systems but rather showcases easy treatments to the codend that are easily adaptable and of low cost. Therefore, the aim of this study was to address this issue and investigate if there are changes that can be made to the codend in combination with the Nordmøre grid that help improve selectivity in the NEA-shrimp fishery.

4.1 Sources of error

During this study we investigated our designs in an area that was closed to the shrimp fishery due to the high bycatch rates (The Directorate of Fisheries, 2019). We were hoping this area would give us enough bycatch from commercially important species such as Redfish, Cod, Haddock and Greenland halibut in order to conduct a catch comparison analysis. Unfortunately catch of cod and haddock was too low, but catches of redfish and Greenland halibut were sufficient. Therefore, it is important to understand that these analyses and respective results for the redfish and Greenland halibut may not be extrapolated to the bycatch of cod and haddock, i.e. a reduction in redfish or Greenland halibut with these treatments may not lead to the same reduction in cod and haddock. Further, we fished at a time of year which was not optimal for shrimp fishing, and our catch data from this area and the results presented are in regard to the biomass in that area at that time and thus may represent additional causes of error if trialed in other areas at different times where catch compositions may differ. It is also worth mentioning that this study was conducted onboard a commercial trawler and does not have the same processing facilities that a research vessel has as well as a crew that is experienced in conducting scientific data collection. However, strict measures were taken before the trials started and the crew members was taught the correct approaches on how to handle and collect data of high standards. With that said, the results presented for the species above should give a clear view on how these treatments work for these particular species.

4.2 Results

Below, the results from series 1-4 will be discussed as well as the treatment tree findings. All treatments and results discussed for each codend in the series was in combination with the Nordmøre grid.

4.2.1 Series 1

This series tested the effect of two treatments (P and L) against the regular baseline codend used in the fishery today. Lastridges was actually common to use at the end of the 1960 when fishing for cod, saithe and haddock, but when both scientist and fishermen understood the factors effecting the selectivety of the codend, the fishermen cut them away (Isaksen and Valdermarsen, 1990). The experiments done by Isaksen and Valdermarsen (1990) showed that this simple change done to the codend could greatly affect the selectivity of a standard codend. Based on the results of this study, it is apparent that shortening the lastridges is indeed something to consider implementing in the shrimp fishery. For series 1, we could see that this was the only series where we had no significant change in catch efficiency for the shrimp, suggesting that these treatments of shortening the lastridges 30 % and going from a two to four panel design will not lead to any losses of shrimp catches, supported by figure 14. Since this series also tested the effect of a four panel construction, the effect of only the lastridges could be difficult to extrapolate. However, we calculated the effect of going from a four panel construction to a two panel construction (figure 43) using the treatment tree. From that figure we can see that only changing panels will not lead to any reduction for both shrimp or redfish, meaning the significant reduction in redfish for individuals below 9 cm is the results of shortened lastridges. For the fleet this means that fishermen will be able to implement these treatments to their trawls without worrying about any shrimp losses and having the opportunity to be able to reduce redfish bycatch. However, while we were able to reduce the catch of redfish, the Greenland halibut under these treatments underwent an increase in catch efficiency, i.e. the test codend caught more Greenland halibut than the baseline codend did. This is not a desired effect we wanted to see. The Greenland halibut has the same bycatch criteria as the redfish with only 3 per 10 kg of shrimp. Interestingly though, redfish bycatch was above the bycatch limit in all hauls, while for the Greenland halibut it fell below the maximum allowed level for all hauls except the first. This however may change if the catch composition for the Greenland halibut increases in areas, i.e. if there are more Greenland halibut in an area, these treatments will lead to an increased catch of this bycatch species. Therefore, these treatments may not be the solution to implement if we want to open in areas where redfish and Greenland halibut biomass is high.

4.2.2 Series 2

Series 2 tested the effect of changing all three treatments (M, P and L) against the regular baseline codend. Increasing mesh size has a significant effect on selection (Thomassen and Ulltang, 1975) and problem facing fisheries using small mesh size in the codend is high discard rates because the meshes are far too small to provide effective protection to the juvenile bycatch species that occur during fishing (Suuronen and Sarda, 2007). However, increasing mesh size in a fishery like this, could lead to less bycatch of juvenile bycatch species, as well as a long term gain in bigger sizes of shrimp. The downside is the short term losses the fleet will struggle with by not being able to fish the smaller sizes of shrimp. Therefore, by increasing mesh size to the treatments in this study we wanted to see if we were able to reduce the bycatch without having a reducing effect on the shrimp catches. The results for this series showed that we would have a significant reduction in shrimp above the MLS between 15-19 mm carapace length, with approximately 7 % reduction at length groups between 16 mm to 18 mm carapace length. From the perspective of the shrimp fishers this may not be acceptable as they will lose some of the high-quality shrimps for which they can get a fairly good price. However, in this series we see a significant reduction in catch for both redfish under 11.5 cm and Greenland halibut under 11.5 cm. From figure 36 we can see that haul 7 and 10 caught below the allowed catch limit for redfish in series 2, but there were also several hauls where the test codend caught close to this limit compared to the baseline codend. In figure 40 we see that the Greenland halibut catch remained under this maximum allowable limit in all hauls except for haul 5 and 6. But conversely, there were also hauls where the test codend caught slightly more Greenland halibut than the baseline. This may be due to the creation of more squared meshes accomplished by the shortening of the lastridges against the diamond meshes in the baseline codend, as the morphology of a flatfish, like the Greenland halibut is less likely to escape through square meshes (Sistiaga et al., 2019). The results from this series may not be acceptable for the fishers as we have a significant reduction in shrimp catches, but this combination of treatments may have the greatest potential out of the treatments in this study for seeing areas reopened if the criteria limits remain the same.

4.2.3 Series 3

This series tested the effect of two treatments (M and P) on the regular baseline codend. Here a significant reduction was observed both above and below the MLS line for the shrimp in size classes between 10.5 mm and 20.5 mm. For the redfish there was a significant reduction in length classes under 10.5 cm while we saw an increased catch efficiency for the Greenland halibut in length classes between 18 cm to 20 cm. Interestingly, this series compered to series 2, did not have the shortened lastridges and therefore was hypothesized it would lead to less reduction of shrimp than series 2, but it actually had a higher reduction of shrimp with approximately 50 % in length group of 11.5mm and almost 10 % in length group of 18.5 mm. Leading us to believe that increasing the mesh size while also shorten the lastridges (in this case by 30 %) will lead to less reduction in shrimp catches. Due to the significant loss of catch efficiency for the shrimp under these treatments, it seems unlikely that the shrimp fleet will implement these. Important insights from this series however are that we are able to reduce the catch efficiency of redfish without shortening the lastridges, and that the Greenland halibut catches may not increase as a result of the shape of the meshes, but because of an increased halibut biomass in the area as the trial went on.

4.2.4 Series 4

This series is special from the others due to the baseline trawl consisting of a four panel codend instead of two. This series give us insight into the effect of shortening lastridges by 30%, on the condition that a four panel codend is already implemented in the fishery. We know from our treatment tree that only changing panels will have no significant effect in catch efficiency on both shrimp and redfish. Previous research by Isaksen and Valdermarsen, (1990), showcased this effect, only they tested it with a codfish trawl, but the principle remains the same. This series is also interesting on the basis it gives insight on what will happen by only shortening the lastridges. The results here indicate that if this treatment should be used, the fleet must acknowledge that they will have shrimp loss between the size classes 10 mm and 17 mm. The highest loss however is under the MLS length with approximately 20 % reduction at 13 mm carapace length and about 10 % reduction at MLS-length. This series would see the fishermen loose some of the acceptable size range shrimp between 15 mm and 17.5 mm carapace length, but if this shrimp loss is acceptable, this treatment will lead to reduced catches of redfish and may lead to closed areas being opened. The series also showcase the effect lastridges have in selection, and it should be investigated further with lower reduction percentage, as 30 % may be a little too high, making the meshes more squared and therefore may be too effective in selectivity of shrimp. Which research into square meshes (Reeves et al,. 1992; Thorsteinsson, 1992) showcase as a very effective tool to improve selection.

4.2.5 Treatment tree

With the treatment tree (figure 42) we are able to calculate branches of different treatment combinations which were not tested at sea. This provides insight into what will happen if some of the treatments this study tested are implemented in the fishery, and then what will happen if different variations of these treatments are applied. The first branch that was calculated changed from a two panel codend to a four panel codend with the condition that we started out with the configuration M35P2L0 (figure 43). The absence of any impact on shrimp or redfish catch seen means that implementation of a four panel codend from this setup may be an acceptable option for the fleet. This is because research shows that a four panel codend can lead to a better quality of the catch as it gives more room for the fish to move around inside the trawl (Dag Mollan, pers. comm.) Furthermore, the added water flow provided through the codend with a four panel design may assist in sorting out sand, clay and various unwanted fauna from the netting (Dag Mollan, pers. comm.). Implementing a four panel construction should be consider for the fleet, and then further testing with various treatments with the four panel constructions, specifically shorter reduction of lastridges, as series 1, 2 and 4 showed promising results. The second branch we calculated increased the mesh size from 35 mm to 40 mm with the starting configuration of M35P4L0 (figure 44). The catch efficiency of this treatment lead to a reduction of shrimp between 12.5 and 19 mm and of redfish below 11 cm. Despite the loss of redfish, the loss of shrimp may lead the fleet to be reluctant to implement an increased mesh size if the starting point is M35P4L0 due to the loss of shrimps that could follow.

The third branch calculated with the treatment tree tested the effect of shortening the lastridges alone (L0-L30) on the condition that the starting point was M40P4L0 (figure 45). Here we can see no change in the catch efficiency for the shrimp or the Greenland halibut but for the redfish there was a significant reduction in catch for size classes between 5 and 11 cm. Thus if this treatment codend was already implemented in the fleet, we would have a significantly lower catch efficiency of juvenile redfish. However, since series 3 showed unsatisfying results, this will perhaps not be treatments most popular to continue investigating, but it is interesting that from the starting point we get no reduced effect of shortening the lastridges for both shrimp and Greenland halibut. Showcasing that reduction of the lastridges is an effective tool to reduce redfish while having no significant effect on shrimp or Greenland halibut.

For the fourth branch we calculated the effect of increasing the mesh size from 35 to 40 mm with the condition that the starting point was the configuration M35P4L30 (figure 46). For this treatment, again no change in catch efficiency for both the shrimp and Greenland halibut was observed, but a significant change in catch efficiency for juvenile redfish was seen. If the starting point for the fleet was a codend of M35P4L30 there should be no problem in increasing the mesh size to 40 mm. This result is very interesting since series 1 had the best results showing no significant reduction in shrimp catch. Therefore, this treatment should be further investigated since series 1 is probably the best option to implement for the fleet. The only downside to series 1 is the increased catch efficiency for the Greenland halibut, but by increasing the meshes from 35 mm to 40 mm could prove to alleviate some of this problem since we can see a slight indication of this happening in figure 49 even though it is not a significant reduction.

For the fifth branch we calculated the effect of both increasing the mesh size from 35 mm to 40 mm and shortening the lastridge ropes by 30% (L0-L30) while keeping the panels constant (M35P4L0) (Figure 47). These treatments lead to no significant change in catch efficiency for the shrimp but a significant reduction in catch efficiency was seen for juvenile redfish. Implementing these treatments could result in good outcomes for this fishery in relation to their ability of releasing redfish while simultaneously retaining shrimp. Like the results from the fourth branch results, this is also something that should be investigated further, especially in areas with Greenland halibut to see if we can get a reduced effect for this species.

4.3 Management

As part of this study I spoke to several of the main institutions in the Norwegian management system in order to gain insight into how and why the bycatch criteria has not changed since 2005, and what their thoughts are in regards to new gear designs and the possible implementation of new technical regulations in the future.

The Norwegian directorate of fisheries - *Development section*

The headquarters of the Norwegian Fishery Directorate is located in Bergen. Here I was able to speak to the head of the development section; Anne Kjos Veim, and senior advisor; Dagfinn Lilleng. In this department they work on management plans regarding Norwegian marine areas, competing use of the sea, area and protection plans, the development of more efficient and environmentally friendly fishing gear as well as leading research cruises and cleanup projects of lost fishing gear. They are also involved in the project “optimization of a shrimp trawl fishery”. It became clear from their point of view that it would be sensible to produce revised bycatch limits or to find improved gear technologies which exclude enough bycatch to keep areas open. The Russian fisheries sector and management partner requires a large amount of documentation in order to enable changes to the policies, and as it stands today the JNRFC has not modified the rules since 2005. They did stress however that all stakeholders strive for the same goal, good cooperation and long-term profit in the fishery.

Their strategy going forward is to establish a common rule in collaboration with Russian management, based on a bio-economic approach which contains a clause whereby calculations are updated on a regular basis as the relative price between shrimp, cod, haddock and Greenland halibut changes. Their suggestion is to look at the bycatch under one unit instead of species wise and then calculate the juvenile equivalents. Based on their calculations done in 2016, this will lead to a closing criteria of 24 juvenile cod (or equivalent) for every 10 kg of shrimp, where 1 juvenile cod is equivalent to = 1.7 haddock, 1 Greenland halibut and 7.8 redfish, which is much higher than the limit exercised today. However, after consulting with the marine research institute (HI), they expressed that allowing a removal of 5% of the redfish stock would risk leading it to a condition that in the long term would see it becoming redlisted. Therefore, it was decided to suggest a model which would not involve this level of damage for redfish. This would mean a bycatch limit at that time of 24 juvenile cod or equivalent, where the value of 1 cod-juvenile would be equivalent to 1.7 haddock, 1 Greenland halibut and 1 redfish. This is higher than today’s catch limit and could lead to certain areas being opened again or keep certain areas from getting closed. Since this proposal was submitted in the commission (JNRFC) in 2016, they have not come to any agreement and the catch limits remain unchanged. Both Anne Kjos Veim and Dagfinn Lilleng acknowledged that this is a complex issue with many moving parts, including traditional, political and economic views to consider. As the rules have not changed since 2005 it is not given that the Russians wants them to change, since they have been the side that has been holding back on setting higher bycatch criteria.

There is no quick fix, and a new suggestion is set to be presented this Autumn (2020) under the 50th session of the JNRFC. The suggestion will likely be a continuation of the rules mentioned above in combination with technical regulations to the gear where results have shown reduction in bycatch species, such as those presented in this paper. This fishery is also

MSC- certified[6], which from the fishery's perspective is positive, but can introduce difficulties regarding relaxation of current regulatory systems. Nevertheless, the shrimp stock is deemed to be in good condition (ICES, 2019), thus an outtake of redfish below 5% with the 24 juvenile cod equivalents should not introduce any problems as long as new management measures are calculated using a precautionary approach and are audited at least every five years in order to account for changes to the price coupled with the regular stock assessments for all species that have economic and ecological importance.

In my talks I also presented the idea voiced by some fishermen regarding a dynamic rule for different areas where allowing them to fish if they use specific bycatch reduction treatments on their trawls in order to receive access. Here both Anne Kjos Veim and Dagfinn Lilleng stressed that this would be very difficult for authorities to control and would most likely not work until a system is in place which would allow monitoring of the entire catch process remotely i.e. using video cameras etc. The technology still demands a lot of development as well as the bureaucracy required in order for it to be appropriately established with industry members.

Marine Research Institute (HI)

At the Marine Research Institute (HI) I spoke with Bjarte Bogstad, a scientist stationed at their headquarters which are situated across the street from the Fisheries directorate in Bergen. His primary work revolves around stock assessment, stock advising and stock interactions for fish stocks in the Barents Sea. It became clear that this is a complex issue both biologically and politically. All species in this fishery interact and rely on each other, thus predictions are difficult to make with any certainty, and with more actors joining the fishery, in particular Russian vessels, more factors and potential sources of error must be taken in to account when presenting new assessments and suggesting new limits and regulations. Challenges also lies within the redfish species, since it is very difficult telling them apart, especially the juveniles, knowing which species that is most commonly discarded as bycatch can be difficult to assess. Since advice from ICES differs between the species, with *Sebastes mentella* considered to be in good shape and a no fish policy or zero catch advice for the *Sebastes norvegicus*, negotiations can prove to be difficult. He does believe in the need for

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[6] Certified In 2012 – for Norwegian NEA cold-water shrimp
Certified In 2013 – for Faroese and Estonia NEA cold-water shrimp

some change in the coming years, but indicated that it depends on the Norwegian fisheries directorate and the Russian counter partner to find common grounds. As the political landscape, particularly surrounding the Svalbard zone, is turbulent at the moment it may prove challenging. There has also been less pressure from the industry recently and given the administration requirements by Russian management bodies to change the policies the outcome of the upcoming Autumn (2020) commission meeting will be difficult to predict.

What I personally found most interesting however is that latest years of data from their annual cruises indicated a gradual movement east of both shrimp and redfish, suggesting that the fleet will most likely follow as well. This was observed by the increased activity in the Russian zone as well as more Russian vessels joining the fishery in the last couple of years. With expected increases in the shrimp fishery and with closures in the Norwegian zone (figure 50), I wanted to understand the activity surrounding area closures in the Russian zone, so I reached out to the head of the Control Section Rolf Harald Jensen.

The Norwegian Directorate of Fisheries - *Control Section (Sjøtjenesten)*

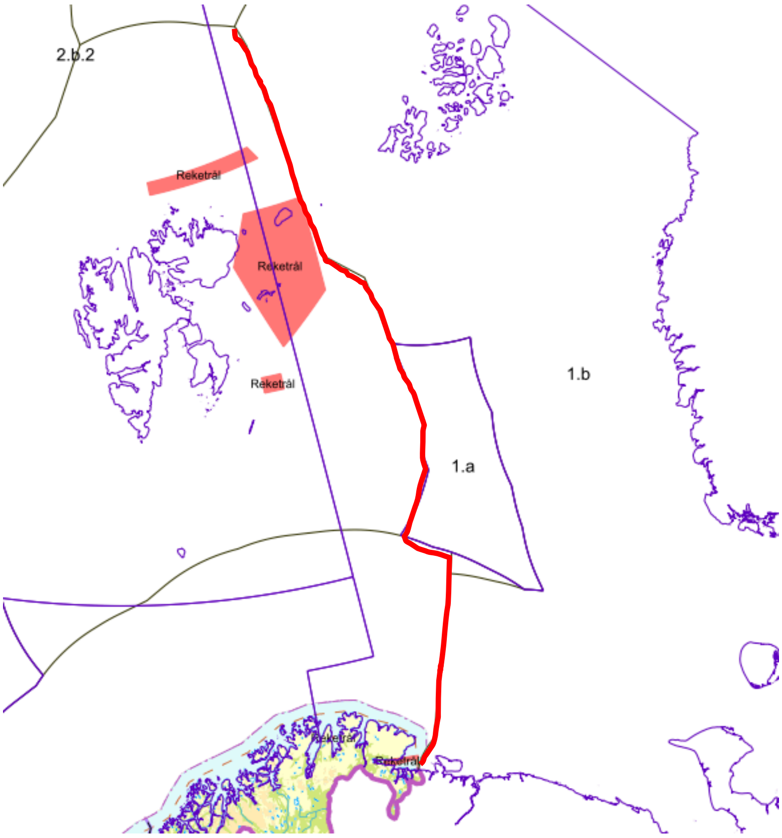

Figure 48: ICES sub areas 2.c, 1.a and 1.b showing the closed areas for shrimp trawling. The red line shows the divide between the Norwegian and Russian Zone.

Rolf Harald confirmed the increase in activity in the Russian zone and as far as he knew there were yet to be further areas closed on their side due to the high bycatch rates. This may be as a result of most of the activity historically occurring in the Norwegian zone, but with the increase in Russian vessels as well as the movement seen of shrimp stocks moving east, it is likely that Russian fisheries managers may grow more open to the idea for change when it comes to the strict bycatch criteria in the fishery. It could be predicted that if this fishery becomes more popular for the Russian sector, it may be difficult to keep areas open while keeping the bycatch rules as they are today. Thus, Russian management may become more inclined to negotiate new regulations. From a Norwegian standpoint however, as the shrimp moves east, it may become important to consider that Russian proposals will be given more weight in negotiations concerning TACs with Norway.

Interestingly, when questioning Rolf Harald regarding dynamic area rules, he was more positive compared to the outlooks from the Directorate of Fisheries. If the rules have clear guidelines and are not made too complicated, this should not be a problem for control purposes to implement. He mentioned the Norwegian king crab fishery as an example, where there is a regulatory divide approximately close to Nordkapp (Cape North at 71 °01N - 25°47E), with a quota regulated area east of longitude 26°E and free fishing west of 26°E. This sort of system could be translated to the shrimp fishery, and perhaps more feasible in the Norwegian inshore shrimp fishery where the northern areas of Norway (i.e. Varangerfjorden, bordering the Russian sector of the North-East Atlantic) differs considerably to the southern counterpart (i.e. Skagerrak) in shrimp sizes compared again to the Barents Sea. However, based on the talks with Anne Kjos Veim and Dagfinn Lilleng, this sort of fragmentation is not being considered going forward.

From these conversations with management institutions it remained apparent that this is a complex issue and one that will be difficult to navigate in the future. Historically the JNRFC has held a good reputation in making decisions and arrangements, even throughout difficult political climates. The issue regarding bycatch in the deep-sea shrimp fishery has yet to be fully resolved, as the redfish remain to be a central component that Russian authorities do not want to address. Applying a bio-economic model as a management tool should facilitate the handling of such a complex issue, but with the fishery having earned MSC-certification in 2012 and 2013 there is considerable risk involved regarding the fishery's perception in the public eye as well as increasing its value. However, the certification may not be lost if the bycatch limit is increased, as long as the shrimp stock remains in a healthy condition. Of high interest will be the results of this year's commission meeting; if we will continue down the same path or if some changes will be administered, either as increased bycatch limitations or as the implementation of new selectivity devices. Or perhaps a combination of the two.

4.4 Industry

To contrast my talks with the management institutions I also reached out to several shrimp fishermen. Some of these fishermen are also involved in the project" optimization of the shrimp trawl fisheries" and both fishermen and management were involved in the treatments tested in this study. These fishermen are very passionate about their jobs and often pave the way for new experiments to be trialed as they are often the ones who have tried it out first. One such fisherman is Dag Mollan, skipper of M/tr Katla, a coastal shrimp trawler who mostly operates in the north of Norway. He stressed that there are differences in shrimp sizes throughout Norwegian waters, with bigger individuals being more often found in the north of Norway than in the south (Helgeland/Skagerak). It would for instance be counterproductive to administer the same treatments in all areas, such as shortening of the lastridges by a full 30%. This would likely be too much, particularly in the south. The M/tr Katla is currently fishing in Varangerfjorden using a double trawl setup with a 2 panel codend and 20% shortened lastridges. Instead of having a four panel codend, he uses four lastridges in the codend, which mimic a four panel codend. He says it works as they intended, less bycatch with a small drop in the smallest shrimp sizes (a few kilograms less). He did stress however that the shrimp, in particular in Varangerfjorden are of bigger size. Using this configuration in the south would most likely be too costly for the fishermen. However, it is worth mentioning that by not fishing on the smallest populations of shrimp one ensures it for their catch later as it grows and in turn returns a higher price. Fishermen in southern Norway agree with Dag Mollan, where shortening of lastridges does not work favorably in those areas. In particular a 30% shortening has become a trend in discussion, and report that shortened to this extent would be detrimental to the industry and that more studies should be done trialing reductions of 20, 15 or 10% for example.

Speaking with these fishermen revealed their willingness to change and adapt. These are truly resilient and adaptable people, exceptionally interesting and talented in trying new things. This applies to not only the skippers and the shipowners, but the crew onboard the vessels as well. I personally, for example, tried to test an experiment onboard the Arctic Viking with the skipper Bjarni Petersen in the fall of 2019 in Isfjorden (78°10N - 14°00E), Svalbard. There we cut a 2 meter triangular hole directly behind the grid section of the trawl. The results from explorative review were very satisfying in the exclusion of bycatch. Unfortunately, it worked in the same fashion for shrimp, but I was surprised by their incredible eagerness and willingness to solve this problem. They were a crew who were always thinking of new ideas to test on their gears in the search for an easy, cost effective way to enable them to exclude bycatch enough to allow resumed fishing in closed areas.

4.5 Future solutions

This study identifies the outcome when 30 % shortened lastridges, increased mesh size and a four panel codend are applied to a standard two-panel, 35 mm codend in the deep sea shrimp trawl fishery. A significant reduction effect was observed for redfish in all series'. We also saw that there was a simultaneous loss of shrimp in all series except for series 1. This suggests that this treatment works most optimally in sorting out redfish while retaining the shrimps, however, in this series we also noted an increase in Greenland halibut catches. This could prove to be an obstacle if the treatments of shortened lastridges and a four paneled codend were to be introduced in areas where populations of Greenland halibut is high. While the other series also had a reduction in redfish, the loss of shrimp in these instances was too great. Thus, I believe that applying these treatments will not be an acceptable alternative for the fishermen. This is due to the concerns already voiced by them regarding the 30% shortened lastridges, where adding more treatments would be a difficult selling point. Series 2 was the only series where less Greenland halibut was retained in the test codend than in the baseline. But as this was such a small difference, it would not yield enough of an effect for it to be considered for implementation in this fishery, however, this series though it had some reduction in shrimp catches above the MLS-length, the reduction was quite low (around 7 % between 16 mm to 18 mm carapace length). Therefore, I would suggest continued trials using these treatments, but with lower percent shortened lastridges, as this may also lead to more reduction of Greenland halibut as the meshes becomes more diamond shape as shortened percentages lastridges are applied (figure 5).

Based on this study, series 1 testing the 30% shortened lastridges and a four panel codend also requires further investigation. Exploring the effect of a lower percentage shortening may be beneficial for this series as well since it led to no significant changes in shrimp catches and produced a high reduction in redfish catches. The reason for the higher retention rate of Greenland halibut however may be due to the shape of the meshes being more square with the 30% shortened lastridges (figure 5) compared to the diamond meshes which fit the profile of a greenland halibut to allow more escape (Sistaga et al., 2019). Most importantly any new technical regulations to the gear will require thorough testing and investigation before becoming commercially applied in the fishery. It should also be worth mentioning that investigations in survival rate of shrimp and bycatch species after released from the codend should be conducted. Study from an Australian prawn fishery showed that fish escaping through a 38 mm square mesh codend incurred more severe damage than those escaping from a 45 mm diamond mesh codend (Farmer et al., 1998). In comparison, fish such as Cod and haddock has a high chance of survival especially through the Nordmøre grid (Soldal and Engås, 1997). With the use of smaller meshes, investigations considering survival rate escaping through these treatments codends should be conducted. If the majority of shrimp and bycatch species do not survive the interactions trough the trawl and selection gear, compulsory selection reduction devices will have few conservational benefits.

Investigations and research into bycatch problems in the shrimp fishery all over the world shows how much time and effort has been invested in order to solve this issue, in particular those related to shrimp trawling, where the highest bycatch and discard rates occur (Hermann et al., 2019; Larsen et al., 2018abcd; Grimaldo and Larsen 2005; Silva et al,. 2012; Lomeli et al 2018ab:2019). There are opposing views on how to handle this problem, some claiming it would be best to have different criteria relating to different areas, as bycatch rates of different species can greatly vary in respect to the fishing region. An example is that the shrimp is bigger in the Northern Norway than it is in the south of Norway, and therefore it would be easier to have dynamic rules that depend on where the fishing takes place. Others outline how this would be too difficult to control and enforce (pers. comm Anne Kjos Veim and Dagfinn Lilleng). These opposing views occur not only between the fishermen and management, but within the management institutions as well. Nevertheless, co-operation between industry and management to solve this issue is key, and with these groups working together solutions can be found. With working models, new technology and a precautionary ecosystem approach to this, some of the difficulties surrounding the fishery has already be alleviated. While some question shrimp fisheries both in terms of their environmental and ecological impact, stakeholders have exhibited an increasing eagerness to solve the industries downfalls instead of pushing them aside (Hall et al., 2000). This is something I myself noticed both during this study with the captain Bjarni Petersen and his crew as well as throughout the talks conducted with the shrimp fishermen. It will be interesting to see what will happen at this year’s commission meeting. If catch limits and technical regulations remain unchanged, both fishermen and management will continue to test new ideas and come up with solutions to better not just the fisheries, but the seas in which they take place.

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