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Modelling the bycatch reduction of a shrimp trawl with a combined Nordmøre grid and sieve panel configuration in the north east Atlantic deep-water shrimp (*Pandalus borealis*) fishery

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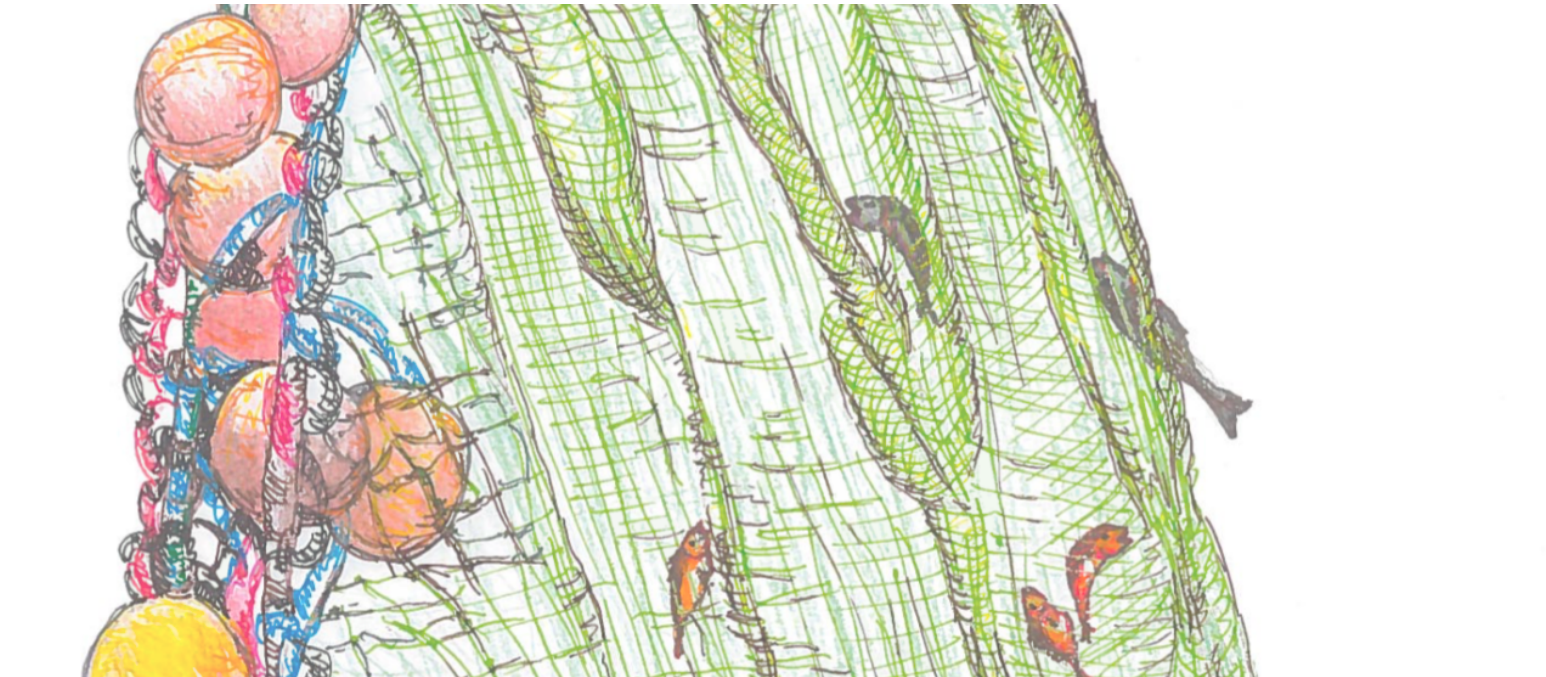

Illustration by Nadine Jacques

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Abstract

The aim of this study was to investigate whether a sieve panel could be an alternative to the Nordmøre grid or if a sieve panel could combine with the Nordmøre grid regarding bycatch reduction while simultaneously maintaining shrimp retention in the Northeast Atlantic deep-water shrimp (*Pandalus borealis*) fishery. These gears are the two most established bycatch reduction devices used today in shrimp fisheries internationally. Despite this, the incidental capture of non-target species, in particular the juvenile populations, continues to attract worldwide attention. This challenge was addressed by analyzing the selectivity of shrimp as well as three different bycatch species when the sieve panel replaced the Nordmøre grid. Alternatively, selectivity with a combination of the two was quantified using a special bootstrap technique. Passage was examined using four different sieve panel configurations (adjusting mesh size and sieving angle). When the sieve panel replaced the Nordmøre grid shrimp loss was higher when the small mesh size was used and unaffected with a large mesh size. Bycatch exclusion with a small mesh size was superior, with passage probability being almost consistently significantly higher through the sieve panel than the Nordmøre grid. When the selective devices were combined, small meshes again led to much more shrimp loss, while the large meshes added approximately just 3% shrimp loss.

Based on the results, this thesis demonstrated that a combination of a sieve panel, configured in the correct way, followed by a Nordmøre grid provides an opportunity to significantly reduce bycatch while simultaneously retaining shrimp. The results and the potential use of the methods in practice are discussed.

Keywords: Sieve panel, Nordmøre grid, shrimp fishery, bycatch

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1. Introduction

Shrimp trawl fisheries have been associated with the highest global incidental bycatch rates of any fisheries practice (Alverson, 1994; Broadhurst, 2000; Eayrs, 2007) and today represent the second most significant internationally traded fisheries commodity in terms of its value, particularly in tropical developing nations (Gillett & Food and Agriculture Organization of the United Nations., 2008). Since 2014, global shrimp catches have remained at 3.5 million tonnes, representing 15.1% of global fisheries value (Food & Agriculture Organization of the United Nations, 2016). But due to poor management practice throughout developing nations in particular (Silva Júnior et al., 2013), shrimp fisheries also account for the greatest economical loss as a result of bycatch and discards (Food & Agriculture Organization of the United Nations, 2016). Current annual shrimp landings in the north east Atlantic (NEA) deep-water shrimp fishery (*Pandalus borealis*) stand at 29,600 tonnes in subareas 1 and 2 (ICES, 2017a) with a low risk of over-fishing status as relative fishing mortality has remained well below the fMSY in annual ICES (International Council for the Exploration of the Sea) stock assessments.

Shrimp and prawn fisheries obtain the highest value among crustacean fisheries. Highest production rates of this crustacean come from Asia, producing 6 million tons annually and today is the second most important fishery commodity globally in respect to its value, giving rise to a widespread cultural and social dependence across many developing nations. But since 2014, when prices reached a recorded high, have experienced reduction due to supply and demand restrictions from primary exporters in Asia to buyers in the EU, United States of America and Japan (Food & Agriculture Organization of the United Nations, 2016). While some progress is being made across shrimp fisheries in respect to high incidental bycatch rates, tropical and subtropical nations remain at high risk of jeopardizing their long-term livelihoods if improved management approaches are not invested in, in particular the enforcement of these.

Deepwater habitats remain some of the most vulnerable yet least studied regions globally. However, the continual technological growth that fishing and marine exploration practices are undergoing, allowing deeper and more intensive exploitation of resources in these areas is becoming more and more common. Development of the deep-water shrimp fishery in Norway began in the late 1960s in the central regions of the Barents Sea (Larsen, pers. comm) with its primary catch coming from the Svalbard and Barents Sea regions. Catches can fluctuate greatly in these areas as, additional to fishing pressure, are greatly dependent on stock sizes of predator species, namely cod, hydrographic variations as a result of differing movements of water bodies and thus the location of the polar front (Guijarro Garcia et al., 2007).

Deep-water shrimp in Norway are targeted primarily using twin bottom trawls at depths between 150m – 700m, on average being fished at approximately 300m deep. The seabed in these fishing grounds is primarily soft, muddy bottoms in waters from 0-8°C. The use of towed-bottom gear gives rise to a high diversity of non-target species as incidental catch. Due to the nature of the shrimp fishing fleet as being often ill-equipped to process any of the incidental catch, the vast majority becomes discarded, having a very low survival rate thereafter. Furthermore the bycatch to shrimp catch ratio of 5:1 (Justice Foundation, 2003) represents a great loss of landings and thus income when shrimp fishery regions are closed as a result of these high bycatch levels which adds to the challenges already faced by fishermen and survival of these bycatch stocks (Sistiaga et al., 2015).

This fishery remains generally in good condition (Food & Agriculture Organization of the United Nations, 2016; ICES, 2017b). Annual scientific catch advice for the stocks is provided by ICES and management of the fishery is coordinated jointly by Norway and the EU. In the Svalbard Zone and the Barents Sea, Norway and Russia are the primary stakeholders to all fish resources with quotas also allocated to the EU as well as Iceland and Greenland. The Joint Norwegian Russian Fisheries Commission (JNRFC) uses the annual advice from ICES in negotiations and decision making for each following catch season for each managed species. The Institute of Marine Research (IMR) is the principle institute responsible for carrying out stock assessments of the deep-water shrimp and advising for sustainable annual catch rates. The main tool used for managing the fishery is the total allowable catch (TAC) system, which has been continually implemented since 1992. Furthermore, vessels must follow gear restrictions, namely a minimum mesh size of 35 mm, a grid with a maximum bar spacing of 19 mm as well as restrictions on by-catch that are landed as described below. These restrictions are controlled and enforced by the Norwegian coast guard at sea and control at the point of landing the catches is coordinated by the Directorate of Fisheries. Overall, the primary authority for fisheries management and policy in Norway is administered to the Norwegian Ministry of Trade, Industry and Fisheries.

If shrimp trawls are inadequate in selecting for catch during operations, the economic as well as the ecological viability for an array of bycatch species that act as important commercial species as well as place holders in complex trophic structures within shrimp fishery regions becomes threatened (Dayton et al., 1995; De Groot, 1984). Thus, the implementation of a sorting device in the NEA is mandatory and has maintained relative biomass and fishing mortality well within their respective reference points throughout the fishery's history (Gullestad et al., 2015; ICES, 2017a).

Metal sorting grids were first introduced in Norwegian shrimp fisheries in 1990 and became compulsory by 1993 in the Barents Sea and other international territories (Isaksen et al., 1992; Larsen et al., 2017). The NG is frequently used throughout global crustacean fisheries and was initially developed by Norwegian fishermen to reduce unwanted catch of jellyfish in the shrimp fishery (Isaksen et al., 1992). Since this time, it has proved to also function well in the exclusion of large fishes (Larsen et al., 2017). Despite the use of these devices along with the development of a bioeconomic model to improve maximum allowable catch estimations, bycatch levels have continued to threaten juvenile stock sizes (Food & Agriculture Organization of the United Nations, 2016; Guijarro Garcia et al., 2007; Gullestad et al., 2015). Additionally, the NG also has associated challenges with its implementation such as re-occurrences of clogging, oversaturation under high catch volume conditions and its different responses to high water flow through the trawl net (Grimaldo, 2006).

Where high numbers of fish and juvenile shrimp are caught in subareas 1 and 2 of the NEA, since 1984 management authorities have implemented respective Real Time Closures. Specifically, in the shrimp fisheries a fishing region can be subject to temporary closure if a proportion of the catch contains more than eight cod (*Gadus morhua*), twenty haddock (*Melanogrammus aeglefinus*), three Greenland halibut (*Reinhardtius hippoglossoides*) or three *Sebastes* spp (redfish). per 10kg of shrimp. Furthermore, a shrimp catch may contain no more than 10%, by weight, of undersized shrimp (i.e.; <15 mm carapace length) shrimp (Norwegian Directorate of Fisheries, 2018a, 2018b). Inefficiencies by the gear beyond these thresholds can lead to extended closures of the respective fishing ground, forcing fishers elsewhere until the catch composition changes. Furthermore, shrimp populations are widely regarded as not being dependent only on fishing pressure but also predation mostly by cod stocks as these are often found in the same areas (Berenboim et al., 2000; Guijarro Garcia et al., 2007). This outlines the interdependence between stocks in these regions and thus the need for effective fishing gears that do not jeopardize the balance between the two.

Efforts to rebuild cod stocks (the most commercial species in Norwegian commercial fisheries) in Norway to their peak size seen in 2008 (Food & Agriculture Organization of the United Nations, 2016) began in 1987 after extensive high-grading practices emerged when the stock had reached its lowest size. The NEA shrimp trawl fishery played a central role in removing juveniles of cod as well as other important juvenile stocks, encouraging implementation of permanent or part time closures in areas where bycatch limits were exceeded (Gullestad et al., 2015). Furthermore a discard ban was imposed by the Minister of Fisheries to make discarding of any dead or dying cod and haddock illegal from 1987 (Norwegian Directorate of Fisheries, 2018a). The Marine Living Resources Act (Ministry of Food and Fisheries, 2008) outlines the general principles necessary for the execution of fisheries inside Norwegian legislation. The discard ban and strict bycatch regulations are a result of the long-term policy for the northern fisheries as agreed between Norway and Russia through the annual meetings of the Joint Russian–Norwegian Fisheries Commission. This bilateral commission was established in 1976. This long-time relationship between Norway and Russia in the Barents Sea is considered to be a successful example of bilateral coastal state cooperation in the management of shared stocks (Gullestad et al., 2014).

While the Nordmøre grid (NG) is a well-established tool globally throughout shrimp fisheries, the potential for the sieve panel (SP) (otherwise known as a sieve net or a veil net) to contribute to reduced mature, as well as juvenile, bycatch while simultaneously minimizing the extent of shrimp loss has not been sufficiently researched throughout literature.

This study addressed this issue during sea trials in the Barents Sea. A NG and a square mesh SP were configured in the trawl net consecutively, followed by the codend in the rear (fig. 1). Passage efficiency of shrimp and three bycatch species (cod, redfish and polar cod

(*Boreogadus saida*)) was estimated for four different designs of the SP (table 1), constituted by two mesh sizes and two sieving angles while holding the configuration of the NG constant. Due to the lack of testing surrounding the SP as a BRD in this fishery, having the ability to quantify selectivity of the SP in four differing designs enables a substantial amount of insight into this gear's functionality. Manipulating the mesh size allowed for size dependence of different species to be observed while altering the sieving angle enabled exploration for a species' ability to detect the net and respond behaviorally, if possible. Furthermore, including the NG in this study's design broadens the investigations potential applicability within the industry.

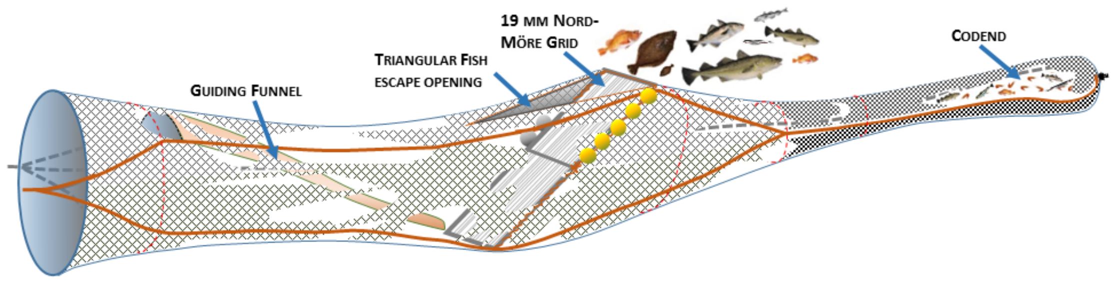

Figure 1. Trawl design (Roger B. Larsen).

Investigations into varying designs of soft excluder panels made from semi-flexible or flexible materials such as polyethylene, polyamide and fiber reinforced plastic have multiplied in recent years. The successful implementation of a SP in the North Sea brown shrimp fishery has been documented (Polet, 2002) and its installation is now mandatory under EU legislation for vessels. The favorability for SPs rather than grids has also grown with the fishermen due to their increased ease of handling during operation. SPs do not hold any rigid or heavy elements, have a straightforward design and construction and are low in cost (Boopendranath et al., 2010). Catches typically also contain less debris and benthic species, thus not becoming blocked as a result of their large sorting area (CEFAS, 2003) and reducing sorting time required on-board for catches (Polet et al., 2004). Trials made in the Belgium brown shrimp fishery using the traditional SP design with a nominal mesh size of 70 mm and the outlet codend with a mesh size of 80 mm (Polet et al., 2004) showed some potential to release juveniles, small fish species and invertebrates with bycatch exclusion rates of 29-50% in different seasons and less than 15% loss of shrimp. Despite this, difficulties still persisted in exclusion of many important commercial species that were below 10cm, with less than one quarter managing to reach the escape outlet. Studies by Karlsen and Larsen (1989) reported a summary of results with soft by-catch excluders in the Norwegian shrimp trawl fishery. During the period of 1983-1989 the implementation of a 60 mm square mesh panel was compulsory during parts of the year for the northern coastal (inshore) shrimp fleet. The panel studied was mounted at a ca. 40° angle in front of the codend with a bycatch escape opening in the top. The soft excluder panels became very disputed as experiments proved that the exclusion of shrimp could reach up to 15% by weight and that the retention of illegal and undersized fish was far too high at times to allow for its use in the fishery. However, the lessons from the working principle and the installation of the soft excluder panel was very useful for the development of the NG, which started at the Norwegian College of Fishery Science UiT in early 1989 (Larsen, pers. comm.). Many SP studies are expected to emerge in the near future (Herrmann pers. Comm) as the interest for this selection device grows. Thus, testing the SP using the following parameters was of high interest, particularly in addressing the following questions.

1.1 Research questions

The focus in this research is to analyse the size and species selectivity of a modified selective shrimp trawl. If a new design comprising a SP in front of a NG system works as intended, the problems of too large bycatches in the NEA shrimp fishery may be closer to reaching a solution.

Each SP design presented in this study was implemented to answer the following research questions:

1. Which SP design would be the most optimal stand-alone BRD for reducing bycatch and retaining shrimp?
2. Can a SP replace the NG for reducing bycatch and retaining shrimp?
3. How does the SP operate in reducing bycatch while retaining shrimp when paired with the NG compared to the current setting where a NG is implemented as a stand-alone BRD?

2 Materials and methods

2.1 Vessel, area and fishing gear

Trawls for data collection were carried out on board the research vessel (R/V) “Helmer Hanssen. This former commercial fishing trawler is 63.8m long with a 4,080 HP engine, owned and operated by the Arctic University of Norway. The research cruise took place during the 6 - 17th of November 2017 within the fishing grounds along the western side of Svalbard, i.e.; off the western coast of Isfjorden (N78^{o}18’ – E12^{o}25’). During this time of year, this northern latitude experiences the polar night from the 25th of October until the 16th of February thus the sun does not rise above the horizon and all fishing took place in darkness. Fishing trials were carried out with a commercial style gear and setup that is typically used for shrimp trawling in the NEA. This comprised of an Egersund Polar 2800# trawl and a pair of Injector Scorpion doors (8m^2, 3100 kg). The netting twine of the trawl was made of polyethylene (PE) in the wing sections and polyamide (PA) throughout the other sections. The trawl and doors were linked by 40m long double bridles and the door spread was 56-58 m at a towing speed of 3.0 – 3.2 knots. Attached to the fishing line was a 59m long ground-gear composed of five rockhopper-sections (30 m long in total) with Ø53 cm rubber discs and a 19 mm chain of 14.5 m length with five Ø53 cm steel bobbins (fig. 2). Scanmar distance sensors and Scanmar height sensors were adhered to the trawl to monitor its geometry throughout each trawl.

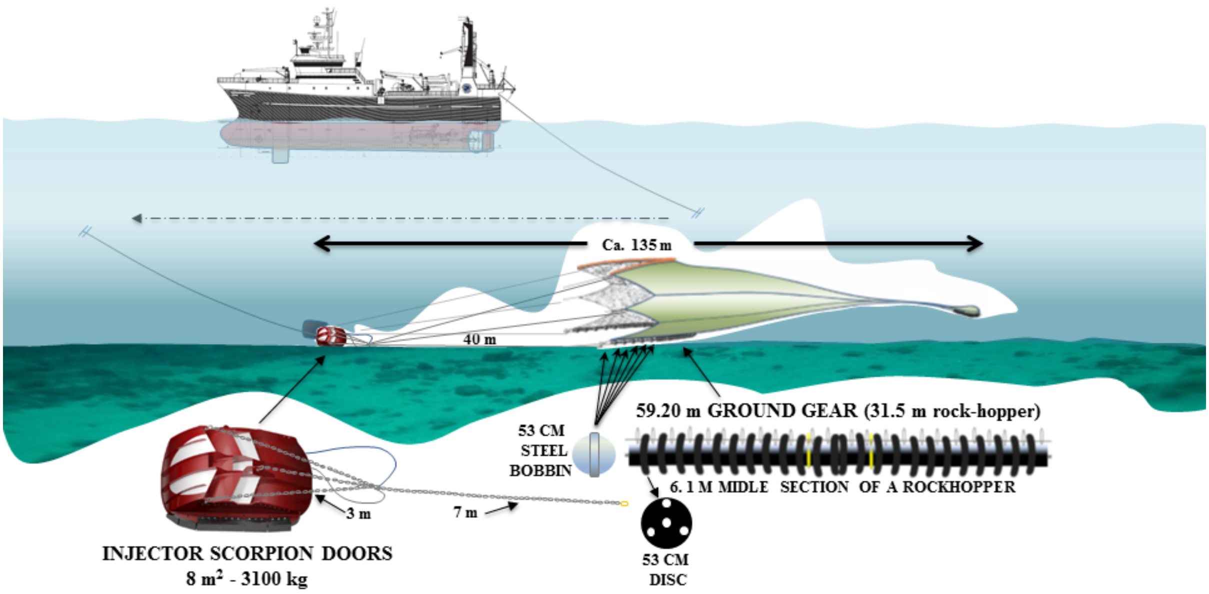

Figure 2. Setup of the 2800 mesh shrimp trawl used in our trials during the 6th-17th November 2017 (Roger B. Larsen).

The aft section of the trawl was replaced by a double belly configuration (fig. 3), allowing a setup consisting of two sections simultaneously. Each trawl belly was equipped with a four-panel NG section, where one side was equivalent in dimensions and construction to the two-panel standard NG section (Norwegian Directorate of Fisheries, 2018a) used by the Norwegian coastal fleet targeting shrimp. This was made from stainless steel (1.5 m high and 0.75 m wide) and was mounted to maintain an angle of 45° ± 2.5° during fishing. The second trawl belly was configured with a similar grid installation (2.1 m high and 0.75 m wide), mounted to maintain an angle of 30°. The bar spacing of the NG was measured using a caliper following the guidelines in Wileman et al. (1996) as 18.8 mm ± 0.4 mm (mean ± standard deviation) for the standard grid and to 18.9 ±1.2 mm (mean ± standard deviation) for the long grid.

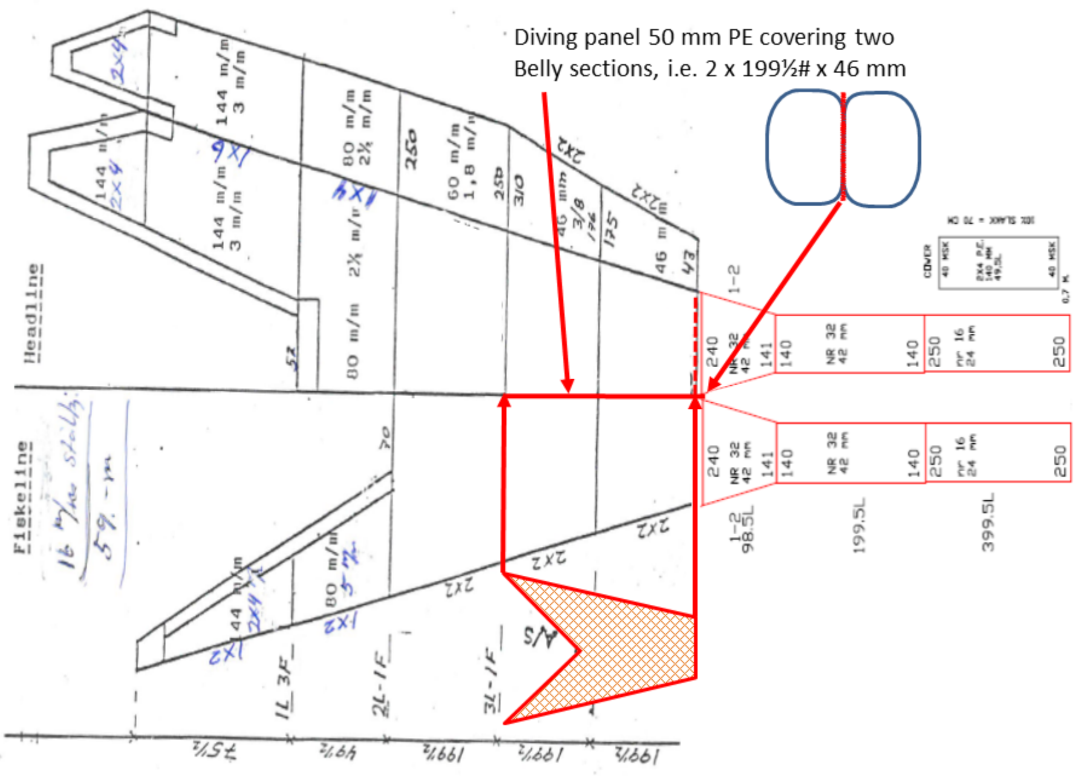

Figure 3. A construction drawing of the 2800 mesh Egersund Polar shrimp trawl containing a twin-belly system (Roger B. Larsen)

The two grid sections were each coupled with the same sized triangular escape outlet in the panel of mesh above the grid. This measured 35 meshes long and 70 meshes wide, forming a triangle shape approximately 1.6 m long and 0.75 m wide. The SP was attached in front of the grid section (fig. 1) which had either a 200 mm or a 300 mm nominal mesh size (fig. 4). The SP was mounted in a 6.5 m long funnel in front of the grid section (fig. 5). Prior to testing it was believed that there are two primary variables that affect the efficiency of a SP. These are the mesh size and the angle at which the SP is installed inside the trawl. Therefore, to get an overview of optimal SP design two different mesh sizes and two different inclination angles were chosen for testing. This allowed for the ability to test these two factors and to what extent they effect the sieving efficiency. Thus, the SP was installed at four different configurations to be tested, each with a change in mesh size and/or inclination angle (table 1). The two SP designs with a 300 mm mesh size were tested at an angle of 10° during haul numbers 1648-1659 and at 20° during haul numbers 1660-1670 (fig. 6).

Table 1: The four SP configurations tested.

Design ID	Mesh size (mm)	Inclination angle (degrees)
SD1	200	10
SD2	300	10
SD3	200	20
SD4	300	20

For the NG, a triangular escape outlet was added above the SP with dimensions as for the NG. Each of these escape outlets (over the NG and the SP) were fitted with small meshed covers (mesh size 18.9 ± 1.2 mm) in order to collect all sizes of fish and shrimp species that escaped (fig. 6) (Wileman et al., 1996).

Small individuals that were able to pass through the SP and consecutively the NG were collected in the codend. This was fitted with a small meshed inner net (mesh size 18.5 ± 0.9 mm) at a low hanging ratio (i.e. small opening in the transverse direction) to prevent fish and shrimp from escaping. To ensure that the SP and the NG outlets did not become blocked during trawling by the covers, five detachable Ø200 mm plastic floats supported each cover (each with a 2.7 kg lifting capacity) (fig. 7).

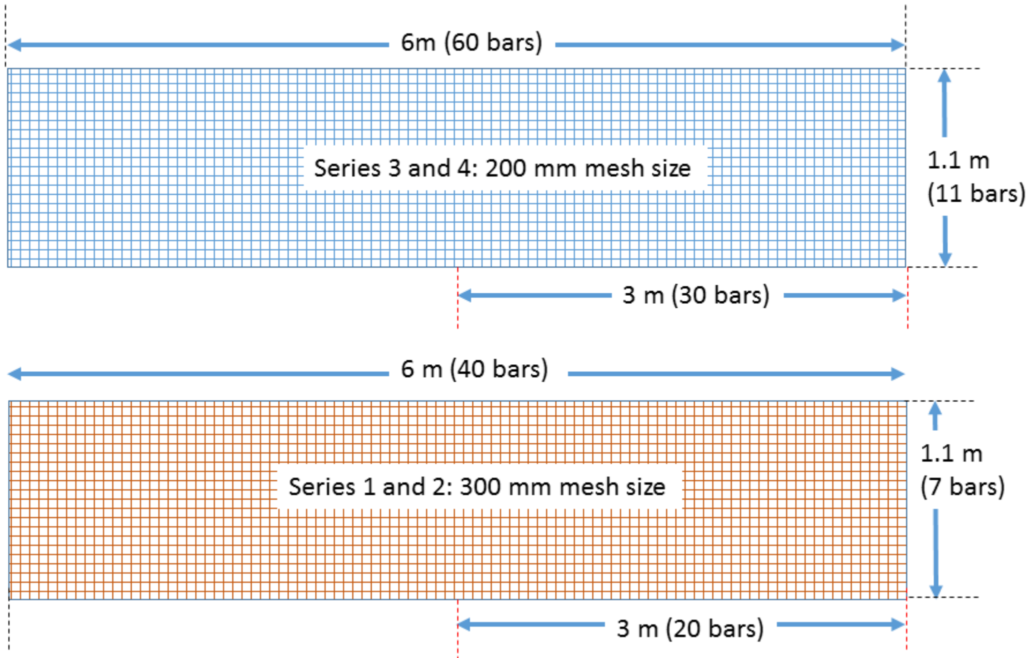

Figure 4. Structure of the 6 m and 3 m long 300 mm and 200 mm square mesh sieve panel (Roger B. Larsen).

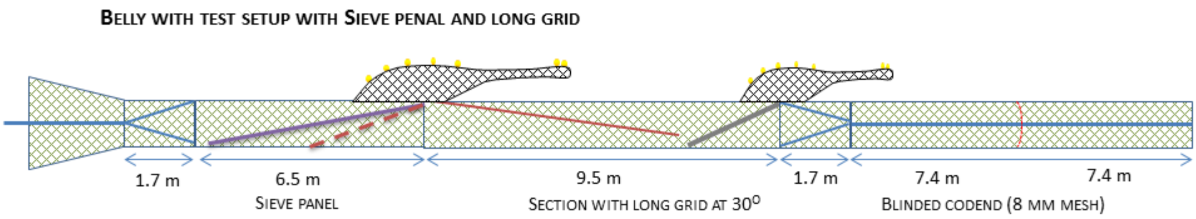

Figure 5. The test setup with a SP section, a NG section and a blinded codend as used during the trials (Roger B. Larsen).

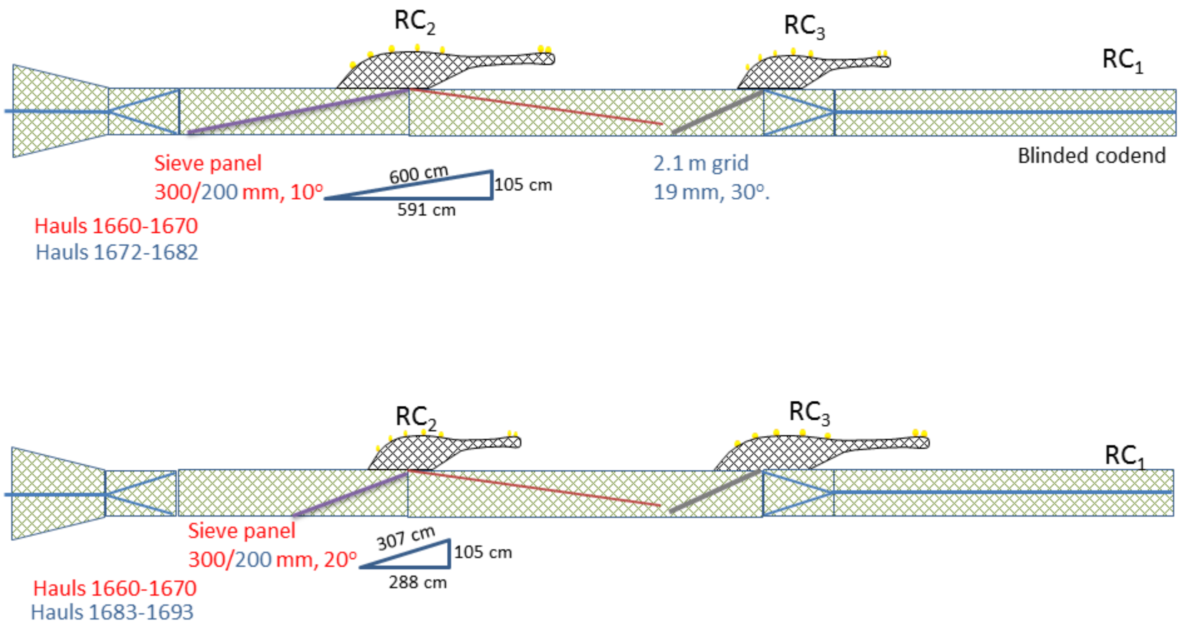

Figure 6. The test setup to retain escaping fish (RC) with a SP section and cover RC2, a NG section with cover RC3 and a blinded codend RC1 (Roger B. Larsen).

Thus, the catch was collected in three compartments: SP cover, NG cover and blinded codend. Directly after each tow, the catch from each compartment was sorted by species, and all by-catch species were measured to the nearest centimeter below. No subsampling was carried out for any of the fish species but, due to the immense catches of shrimp from many tows, measuring the full shrimp catch was often not possible and hence a subsample was measured. In these instances, a random portion of approximately 1 kg of the shrimp catch from each compartment was taken. A 1 kg subsample size was considered adequate to provide a size distribution that was representative for the shrimp of its respective compartment. The carapace length was then measured for each shrimp of the subsample using calipers measuring to the nearest millimeter below.

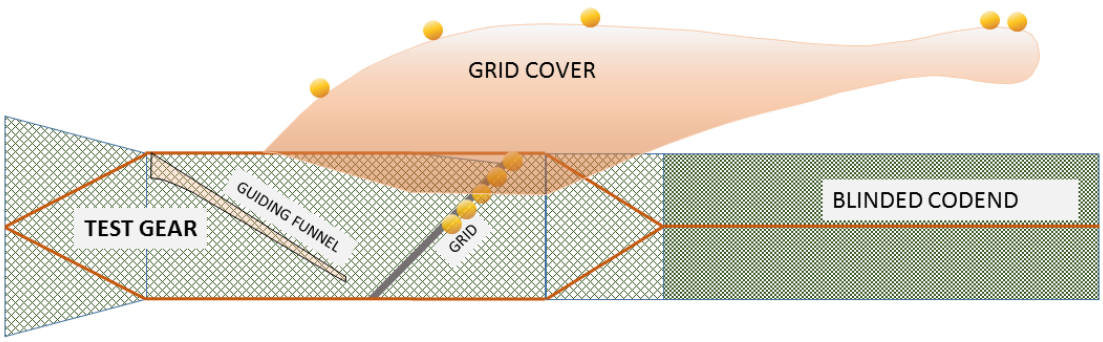

Figure 7. Closer details of the aft sections of the experimental setup for the NG section with a small meshed cover installed over the escape outlet in the upper panel and an inner net ("blinder") in the codend. The small circles represent Ø200 mm plastic floats (Roger B. Larsen).

2.2 Modeling and estimation of selection processes in the sorting system

The probability that a fish or shrimp will be retained in the inner net of the codend ($p_{combined}(l)$: overall retention probability of the selection system) upon entering the experimental gear section depends on the probability that it passes through the SP ($p_{panel}(l)$: passage probability through the sieve panel) toward and subsequently through the NG, into the codend ($p_{grid}(l)$: passage probability through the NG with conditioned passage through the sieve panel). The combined size selection process in the sorting section with both SP and NG installed can be described by the following dual sequential model:

$$p_{combined}(l, \boldsymbol{v}_{panel}, \boldsymbol{v}_{grid}) = p_{panel}(l, \boldsymbol{v}_{panel}) \times p_{grid}(l, \boldsymbol{v}_{grid}) \quad (1)$$

Where l is the total length of the fish or the carapace length of the shrimp. The vector is a vector of parameters for the parametric model used to describe the SP passage probability. The vector is a vector of parameters for the parametric model used to describe the NG passage probability (conditioned to entering the zone of the grid).

As different species have different morphologies and behaviors, models (1) needs to be applied separately for the deep-water shrimp and the three bycatch species. Since it was of interested to investigate the SP and NG performance on average, the analysis was made for data summed across all hauls. Thus, expressions (2) and (3) were minimized, which is equivalent to maximizing the likelihood for the observed data in the form of the length dependent number of individuals measured as retained in the codend (nc_l) versus collected in the SP cover (np_l) and in the NG cover (ng_l).

$$-\sum_l \sum_{i=1}^{ms} \left\{ \frac{np_{il}}{qp_i} \times ln\left(1.0 - p_{panel}\left(l, \boldsymbol{v}_{panel}\right)\right) + \left(\frac{ng_{il}}{qg_i} + \frac{nc_{il}}{qc_i}\right) \times ln\left(p_{panel}\left(l, \boldsymbol{v}_{panel}\right)\right)\right\} \quad (2)$$

Where qc_j, qp_j and qg_j represent the sampling factors for the fraction of individuals measured in the blinded codend, SP cover and NG cover for each haul j respectively. The sampling factors can take a value from 0.0 to 1.0 (1.0 if all individuals are length measured). The inner summation in (2) is over the hauls conducted with the specific SP configuration investigated and the outer summation over length classes in the data.

$$-\sum_l \sum_{i=1}^{m} \left\{ \frac{ng_{il}}{qg_i} \times ln\left(1.0 - p_{grid}\left(l, \boldsymbol{v}_{grid}\right)\right) + \frac{nc_{il}}{qc_i} \times ln\left(p_{grid}\left(l, \boldsymbol{v}_{grid}\right)\right)\right\} \quad (3)$$

The inner summation in (3) is over all hauls conducted since the SP passage data is not present in (3) and the NG configuration was identical for all hauls conducted. Expressions (2) and (3) are applied independently of each other to estimate the passage probability respective to the SP and the NG.

Before (2) can be applied with (1) to estimate $p_{panel}\left(l, \boldsymbol{v}_{panel}\right)$ and $p_{grid}\left(l, \boldsymbol{v}_{grid}\right)$, the parametric models needed for these two processes had to be selected.

The starting point for this modelling is the standard *logit* size selection model $logit(l, L50, SR)$,often used to describe the length dependent retention probability for trawl netting and sorting grids (Wileman et al., 1996; Grimaldo and Larsen, 2005):

$$logit(l, L50, SR) = \frac{\exp\left(\frac{ln(9)}{SR}\times(l-L50)\right)}{1-\exp\left(\frac{ln(9)}{SR}\times(l-L50)\right)} \qquad (4)$$

L50 and *SR* are the two parameters that characterize this model (4). L50 quantifies the length of fish or carapace length of shrimp with 50% probability of been retained. SR quantifies the steepness of the curve by the difference in *L75* and L25 (see Wileman et al., (1996) for details). $logit(l, L50, SR)$ provides an s-shaped curve with a monotonous increase in retention probability with size in terms of length. In this study the length dependent net or grid passage probability was modelled therefore the probability of being released had to be expressed in the selection model. This is 1 – the probability of being retained. Based on the $logit(l, L50, SR)$ model, the following model was used as a starting point for modelling the length dependent SP or NG passage probability:

$$p(l, \boldsymbol{v}) = rlogit(l, L50_1, SR_1) = 1 - logit(l, L50_1, SR_1) = \frac{1}{1-\exp\left(\frac{ln(9)}{SR_1}\times(l-L50_1)\right)}$$
$$where \quad \boldsymbol{v} = \begin{pmatrix} L50_1 \\ SR_1 \end{pmatrix} \qquad (5)$$

While considering the use of equation (5) to model the SP and NG passage probability, three additional models (6)-(8) were considered that account for not all fish or shrimp making contact with the SP or NG to provide a size dependent probability of passing through. The simplest of these models is the $rclogit$ model which includes one contact parameter C_1 with a value in the range of 0.0 to 1.0. An estimated C_1 value of 1.0 for a species means that every individual of that species contacts the SP or NG in a way that provides them a length dependent chance of passing through the device. In the case of an individual fish or shrimp not contacting the SP or NG, or being poorly oriented when making contact, the result will be reflected in the C_1 value.

$$p(l,\boldsymbol{v}) = rclogit(l, C_1, L50_1, SR_1) = C_1 \times rlogit(l, L50_1, SR_1) = \frac{C_1}{1-\exp\left(\frac{ln(9)}{SR_1}\times(l-L50_1)\right)}$$
$$where \quad \boldsymbol{v} = \begin{pmatrix} C_1 \\ L50_1 \\ SR_1 \end{pmatrix} \tag{6}$$

The last two models considered for sieve net and grid passage probability were:

$$p(l,\boldsymbol{v}) = rclogitS2(l, C_1,\ L50_1, SR_1,\ L50_2, SR_2) = C_1 \times rlogit(l, L50_1, SR_1) + (1 - C_1) \times rlogit(l, L50_2, SR_2)$$
$$= \frac{C_1}{1-\exp\left(\frac{ln(9)}{SR_1}\times(l-L50_1)\right)} + \frac{1-C_1}{1-\exp\left(\frac{ln(9)}{SR_2}\times(l-L50_2)\right)}$$
$$where \quad \boldsymbol{v} = \begin{pmatrix} C_1 \\ L50_1 \\ SR_1 \\ L50_2 \\ SR_2 \end{pmatrix} \tag{7}$$

And

$$p(l,\boldsymbol{v}) = rclogitS3(l, C_1,\ C_2, L50_1, SR_1,\ L50_2, SR_2,\ L50_3, SR_3) = C_1 \times rlogit(l, L50_1, SR_1) + C_2 \times rlogit(l, L50_2, SR_2) + (1 - C_1 - C_2) \times rlogit(l, L50_3, SR_3)$$
$$= \frac{C_1}{1-\exp\left(\frac{ln(9)}{SR_1}\times(l-L50_1)\right)} + \frac{C_2}{1-\exp\left(\frac{ln(9)}{SR_2}\times(l-L50_2)\right)} + \frac{1-C_1-C_2}{1-\exp\left(\frac{ln(9)}{SR_3}\times(l-L50_3)\right)}$$
$$where \quad \boldsymbol{v} = \begin{pmatrix} C_1 \\ C_2 \\ L50_1 \\ SR_1 \\ L50_2 \\ SR_2 \\ L50_3 \\ SR_3 \end{pmatrix}$$

(8)

The rationale behind also considering the two much more complex models (7)-(8) to calculate passage probability is that they can account for not all fish or shrimp individuals having the same contact mode with the SP or NG. Frandsen, Herrmann, & Madsen (2010) describe first implementing this modelling technique in a selectivity study of Nephrops whereby modelling contact with the codend mesh with the *rclogitS3* model allowed for the wider range of contact modes that Nephrops typically enter the net in to be accounted for. In this study, different orientations and size ranges of the species would be able to pass through, thus demanding a model more resilient to this variation. To do this each contact model has its own set of selection parameters *L50* and *SR*. In the case of (7) and (8), two and three contact modes are accounted for respectively. In (7) with two contact modes, the fraction of individuals that is sorted with these modes are respectively C and $1-\mathrm{C}$. In (8) with three contact modes, the fraction of individuals that get sorted by with these are respectively C_1, C_2 and $1-C_1-C_2$. The sum of these fractions always sums up to 1.

The above considerations mean that in total four different models for $p(l,\boldsymbol{v})$ would be included for consideration for the different SPs individually and for the NG. The combined process (a SP followed by the NG) will then be estimated based on the models independently selected for the SP and the NG and used in (1). The estimations for the SPs were conducted testing each of the models (5)-(8) minimizing expression (2) and then selecting the model that resulted in the lowest AIC value (Akaike, 1974). Similarly, the estimation for the NG was conducted testing each of the models (5)-(8) minimizing expression (3) and then selecting the model resulting in the lowest AIC value.

The ability of the selected models to describe the experimental data sufficiently well was based on calculating the corresponding p-value. In case of poor fit statistics (p-value < 0.05), the residuals were inspected to determine whether the poor result was due to structural problems when modelling the experimental data or if it was due to over-dispersion in the data (Wileman et al., 1996).

Once the models had been selected for the different species for the four SPs and the NG and the corresponding model parameters have been estimated, $p_{panel}(l, \boldsymbol{v}_{panel})$ and $p_{grid}(l, \boldsymbol{v}_{grid})$ respectively can be used to quantify the combined size selection and standalone size selection. This is in terms of the length dependent probability for entering the codend for a system with each of these three configurations.

Efron 95 percentile confidence bands (Efron, 1982) for the SP passage probability, the NG passage probability, the combined codend entry probability as well as the parameters describing the processes, were obtained with a double bootstrap method using the software tool SELNET (Herrmann et al., 2012). For each species analyzed, 1000 bootstrap repetitions were conducted to estimate the confidence intervals applying the techniques established by Efron (1982). This method accounts for the natural variation arising as a result of within-haul variation and between haul variation (Sistiaga et al., 2010) rather than more traditional pooling methods of the data across the hauls where there is a potential for underestimation of the confidence intervals of the model parameters (Fryer, 1991). The double bootstrapping methodology accounts for uncertainty by means of nested re-sampling. This employs an outer loop to address the between-haul-variation and an inner loop to address within-haul-variation (Eigaard et al., 2012).

For the SP and the NG operating stand-alone, the process of producing confidence intervals was straight forward as outlined above. However, in order to infer the effect of changing from one sieve panel design *a* to *b*, the difference in the length-dependent sieve panel passage probability $\Delta p_{panel}(l)$ was estimated:

$$\Delta p_{panel}(l) = p_{panel\_b}(l) - p_{panel\_a}(l) \qquad (9)$$

The 95 % confidence intervals for $\Delta p_{panel}(l)$ were obtained based on the two bootstrap population results (1000 bootstrap repetitions in each) for $p_{panel\_a}(l)$ and $p_{panel\_b}(l)$ respectively. As they are obtained independently of each other, a new bootstrap population of results for $\Delta p_{panel}(l)$ was created using:

$$\Delta p_{panel}(l)_i = p_{panel\_b}(l)_i - p_{panel\_a}(l)_i \;\; i \in [1 \ldots 1000] \qquad (10)$$

Based on the bootstrap population, Efron 95% percentile confidence limits were obtained for $\Delta p_{panel}(l)$ as described above.

In order to calculate the combined process (SP followed by the NG), as modelled in equation (1), a different procedure was required. This was based on taking the product of the SP and the NG curve calculations with their respective confidence bands from the individual processes as described below. The 95 % confidence intervals for $p_{combined}(l)$ according to (1) were obtained based on the two bootstrap population results (1000 bootstrap repetitions in each) for $p_{panel}(l)$ and $p_{grid}(l)$ respectively. As they are obtained independently from each other, a new bootstrap population of results for $p_{combined}(l)$ was created using:

$$p_{combined}(l)_i = p_{panel}(l)_i \times p_{grid}(l)_i \;\; i \in [1 \ldots 1000] \qquad (11)$$

where *i* denotes the bootstrap repetition index. As resampling was random and independent for both groups of results it is valid to generate the bootstrap population of results for the product based on (11) using two independently generated bootstrap files (Larsen et al., 2018; Moore et al., 2003). Based on the bootstrap population, Efron 95% percentile confidence limits were obtained for $p_{combined}(l)$ as described above.

3 Results

3.1 Catch data

A total of 36 hauls were made during the experimental period. Of all the relevant bycatch species in the NEA deep-water shrimp fishery, cod (*Gadus morhua*), polar cod (*Boreogadus saida*), and Redfish (*Sebastes* spp.) were captured sufficiently often to be included in this study (table 2). A total of 13,604 shrimp, 13,302 cod, 1226 redfish and 4166 polar cod were length measured. Subsampling was only necessary for the deep-water shrimp. A sampling error was only made during the 13th haul, whereby the shrimp data could not be recorded for the analysis. But due to the analysis methodology in that data was to be analyzed species – wise, length measures collected for other species within this haul did not need to be discarded and thus, a balanced sample is not demanded (table 2). This does however negatively affect the uncertainties calculated for the shrimp curves from SD2 slightly, but as long as this is taken into account, the benefit of having a larger sample for the bycatch species outweighs this consideration.

Of the 4 models tested for each SP design, the model with the lowest AIC value was selected to model the SP passage probability and thus compute the bootstrap intervals. The AIC estimator punishes for added complexity of a model (twice that of the number of parameters), but accounts for the ability of the model to describe the data. Shrimp catches in this study were, for the first time in this kind of selectivity study found to be best described by the most complex of the 4 models tested (*rclogitS3*) in all four SP designs tested as well as for the NG. For cod, the *rclogitS2* model described the data for cod passing through the NG best, seen by the lowest AIC out of the four potential models (table 3). This was also found to be the best fitting model for SD2 passage of cod, whereas the remaining three SP designs were best described by the *rclogitS3* model, thus this combination was used in the following bootstrap analysis. For redfish, passage through the NG and SD3 was best described by the simplest, *rlogit* model, while SD1, SD2 and SD4 required the added parameters of the *rclogitS2* model to obtain sufficient fitting. As seen for redfish, passage through the NG of polar cod also required just the *rlogit* model. SD1 and SD3 passage data were best described by the *rclogitS2* model, while the lowest AIC was computed when the *rclogit* model described polar cod passage through SD2 and SD4 SP designs.

The parameter values and fit statistics, as displayed in table 4 – 7, outline how the models selected through information theorem fit with the selectivity data. The fit statistics calculated were strong for all species with the exception of shrimp. Due to the amount of sub-sampling necessary during data collection the low p – values seen for shrimp can be attributed to over-dispersion of the data (Alzorriz et al., 2016), particularly as large shrimp length classes had relatively low frequencies (R B Larsen et al., 2017b). This can be safely assumed because there is no clear indication of inconsistencies between the catch data and the fitted grid passage probability curves for shrimp. Thus, the calculated model can be regarded as legitimate in displaying the length-dependent passage probability (Larsen et al., 2018). The p-values estimated with each selected model can be used to determine if the deviation observed between each estimated length dependent curve and the catch can be considered a coincidence. For all bycatch species analyzed (excepting for cod caught with SD2) a p-value >0.05 confirmed this. Further indication of a well-fitted curve can be found from inspection of the deviance versus the degrees of freedom. As an individual's fate at each BRD is binomial, based on the maximum likelihood estimate, if the randomness during this process satisfies this binomial assumption, then it can be expected that the deviance and DOF are similar. If the margin between these two statistics is too great, it is reflected in the low p-value and it is more likely that the passage probability through the device(s) cannot be as a result of coincidence.

Table 2: Summary on number of individuals that were length measured in catch data in individual hauls. np denotes the number of individuals measured from the sieve panel cover. ng denotes the number of individuals measured from the grid cover. nc denotes the number of individuals measured in the blinded codend. Values in () are subsampling ratio's in percentages (weight ratio) which are provided only if subsampling did take place. '*' denotes counts that were not attainable.

Haul ID	SD	Trawl ID	Deep-water shrimp			Cod			Redfish			Polar cod		
			np	ng	nc	np	ng	nc	np	ng	nc	np	ng	nc
1	1	1672	894 (10.6)	5407 (36.29)	238 (1.4)	186	63	130	61	9	4	23	30	147
2	1	1673	1410 (16.39)	2764 (25.13)	186 (1.43)	218	67	109	55	7	3	24	10	72
3	1	1674	1492 (11.3)	2976 (20.96)	209 (1.14)	160	61	105	52	5	4	31	16	67
4	1	1675	863 (7.31)	4923 (38.16)	171 (1.01)	245	36	91	40	8	2	21	12	58
5	1	1676	815 (8.49)	4647 (45.56)	323 (1.7)	269	22	71	26	12	3	19	4	57
6	1	1677	1058 (8.67)	3865 (29.73)	257 (1.24)	303	71	112	58	8	6	40	12	72
7	1	1678	1124 (10.04)	6153 (49.26)	182 (1.19)	354	94	122	31	8	1	43	19	83
8	1	1679	1630 (14.17)	3113 (30.22)	173 (1.33)	459	175	182	23	1	3	25	24	100
9	1	1680	1071 (10.5)	2365 (16.31)	158 (0.98)	334	148	114	24	4	0	31	33	91
10	1	1681	614 (5.39)	20.29 (17.49)	173 (0.96)	336	85	142	29	5	4	19	15	88
11	1	1682	2343 (18.16)	2373 (29.3)	208 (1.68)	444	88	90	38	9	5	32	14	77
12	2	1648	7276 (94.49)	11231(89.85)	684 (5.03)	46	27	58	17	10	2	2	5	23
13	2	1649	*	*	*	52	134	253	17	21	9	19	25	111
14	2	1650	5300 (35.57)	4830 (30.38)	142 (0.95)	97	160	148	9	19	5	30	76	107
15	2	1651	5961 (43.51)	3457 (26.19)	252 (1.68)	68	101	84	23	9	4	17	24	48
16	2	1652	3207 (30.54)	4416 (37.11)	222 (1.66)	74	96	84	8	11	2	14	22	80
17	2	1653	3308 (24.69)	2452 (19.16)	249 (1.37)	36	92	74	6	20	2	30	20	59
18	2	1654	1892 (14.33)	3730 (28.69)	161 (1.05)	43	79	150	17	16	7	4	22	96
19	2	1655	2594 (20.75)	17282 (89.8)	222 (1.52)	110	42	105	12	6	3	25	9	71
20	2	1656	6021 (44.6)	3660 (27.52)	342 (2.18)	154	142	75	15	12	1	12	29	56
21	2	1658	8664 (91.2)	3406 (28.38)	310 (1.87)	61	65	92	5	11	1	6	16	90
22	3	1684	2820 (24.74)	7049 (81.02)	177 (1.36)	363	43	22	20	2	2	28	5	30
23	3	1685	5617 (49.71)	6200 (100)	536 (2.82)	223	29	49	13	2	3	0	6	64
24	3	1686	4898 (45.78)	5500 (100)	411 (2.27)	196	37	62	11	1	0	12	7	63
25	3	1687	4345 (49.38)	2415 (17.63)	292 (1.79)	227	106	48	14	7	0	7	12	28
26	3	1688	1668 (12.54)	7700 (100)	969 (6.17)	439	73	65	18	1	2	15	8	29
27	4	1660	8768 (88.57)	4877 (82.66)	246 (1.86)	89	32	59	15	10	0	21	4	38
28	4	1661	2584 (19.14)	2639 (23.15)	118 (0.82)	139	91	162	11	7	1	36	10	91
29	4	1662	5430 (40.52)	4101 (31.79)	255 (1.45)	96	100	134	11	12	3	18	14	108
30	4	1663	8262 (64.05)	3831 (42.1)	297 (1.98)	179	96	80	10	8	0	31	12	116
31	4	1664	4593 (41.75)	3531 (34.62)	180 (1.33)	145	65	131	37	13	2	18	11	73
32	4	1665	10938 (88.21)	2989 (24.7)	203 (1.31)	83	97	72	15	21	6	30	19	110
33	4	1666	12374 (86.53)	3335 (30.32)	189 (1.18)	66	49	76	11	5	0	24	12	78
34	4	1667	5081 (51.85)	3398 (31.76)	147 (1.1)	169	74	80	12	10	4	12	8	84
35	4	1668	7477 (80.4)	1937 (14.79)	201 (1.21)	177	54	78	14	12	1	27	15	160
36	4	1670	4069 (34.19)	7046 (59.71)	245 (1.71)	212	77	70	23	7	1	6	6	103

Table 3. AIC values for model fits. Values given in bold indicate the lowest AIC value, thus, the model used to calculate the bootstrap intervals.

Species	Model	NG	S D1	S D2	S D3	S D4
Deep water shrimp	*rlogit*	114461.39	82747.46	30319.61	15461.03	24393.61
	rclogit	114439.36	82336.63	30126.61	15314.14	24386.95
	rclogitS2	114253.50	82228.26	30126.58	15310.05	24390.95
	rclogitS3	**114238.11**	**82116.00**	**30074.54**	**15296.24**	**24365.55**
Redfish	*rlogit*	**171.94**	455.41	387.39	**83.07**	375.81
	rclogit	173.94	457.41	375.66	85.07	377.81
	rclogitS2	174.47	**453.89**	**371.65**	89.02	**375.61**
	rclogitS3	176.05	454.90	376.25	92.78	376.14
Cod	*rlogit*	5603.51	4529.49	2456.77	1714.86	3779.84
	rclogit	5605.51	4412.52	2288.14	1623.80	3660.14
	rclogitS2	**5577.65**	4357.51	**2275 .72**	1612.78	3646.83
	rclogitS3	5579.92	**4350.18**	2276.82	**1611.99**	**3641.30**
Polar cod	*rlogit*	2453.78	882.16	816.26	260.35	1053.44
	rclogit	2455.78	877.20	**786.14**	257.76	**1045.77**
	rclogitS2	**2446.96**	**873.27**	790.14	**257.16**	1049.28
	rclogitS3	2448.12	877.61	794.21	260.35	1049.45

Some caution should be carried out regarding the low number of hauls available when the SD3 was tested. As the remaining SP designs have at least 10 hauls-worth of data each and the SD3 design has just 5, there may be some unrecognized error existing in the passage probability results in this case. But this uncertainty is portrayed in the selectivity parameters and confidence bands calculated for each curve. Since the selectivity parameters remain within the appropriate bounds and the confidence bands each contain the selection curve and are sufficiently narrow, inferences drawn from these can be regarded as trustworthy. Moreover, as described by Herrmann et al. (2016), the covered codend method applied in this study allows much more flexibility for analysis as it allows sufficient uncertainty levels to be attained using less available data.

Table 4. Parameter values and fit statistics for selected models for shrimp. Values in () are 95% confidence limits. Note that L50 and SR are provided in mm.

	Nordmøre Grid	Sieve panel 1	Sieve panel 2	Sieve panel 3	Sieve panel 4
Model	*rclogitS3*	*rclogitS3*	*rclogitS3*	*rclogitS3*	*rclogitS3*
C_1 (%)	98.0 (54.5, 98.0)	86.3 (43.0, 92.9)	94.9 (0.2, 96.4)	0.9 (0.8, 0.9)	1.0 (0.9, 1.0)
C_2(%)	1.1 (1.0, 43.3)	3.4 (2.7, 47.9)	2.0 (1.1, 94.0)	0.0 (0.0, 0.2)	0.0 (0.0, 0.1)
$L50_1$ (mm)	34.24 (28.07,	29.46 (28.19,	200 .00 (34.56,	42.96 (29.01,	81.49 (28.09,
SR_1 (mm)	6.82 (0.10, 11.68)	1.67 (0.10, 15.05)	65.73 (0.10, 86.22)	12.86 (0.10, 49.92)	3.77 (0.10, 37.88)
$L50_2$ (mm)	17.48 (17.41,	23.03 (18.93,	20.90 (17.95,	22.02 (19.42,	23.56 (20.36,
SR_2 (mm)	0.12 (0.10, 4.83)	0.10 (0.10, 3.31)	0.10 (0.10, 5.17)	0.10 (5.15, 50.10)	0.10 (0.10, 3.84)
$L50_3$ (mm)	15.06 (14.04,	18.73 (14.02,	16.98 (0.10, 19.68)	19.50 (14.98,	18.37(14.99, 20.12)
SR_3 (mm)	1.78 (0.10, 4.85)	2.94 (0.10, 4.05)	2.09 (0.10, 6.58)	0.10 (0.10, 3.54)	5.10 (0.10, 5.89)
P-value	0.3361	0.0001	<0.0001	0.0068	0.0177
Deviance	16.72	43.51	56.59	27.40	24.44
DOF	15	14	15	12	12

Table 5. Parameter values and fit statistics for selected models for cod. Values in () are 95% confidence limits. Note that L50 and SR are provided in cm and '*' defines values that do not attribute to the respective model.

	Nordmøre Grid	Sieve panel 1	Sieve panel 2	Sieve panel 3	Sieve panel 4
Model	*rclogitS2*	*rclogitS3*	*rclogitS2*	*rclogitS3*	*rclogitS3*
C_1 (%)	62.4 (31.6, 88.1)	3.7 (2.9, 37.9)	52.5 (37.0, 66.9)	21.9 (3.9, 39.8)	34.7 (26.1, 54.8)
C_2(%)	*	29.3 (7.9, 74.3)	*	51.7 (8.0, 72.2)	14.2 (8.2, 50.8)
$L50_1$	17.15 (15.18, 19.33)	72.53 (33.21, 75.99)	78.52 (59.71, 200.00)	55.21 (27.46, 85.05)	92.03 (79.31, 186.66
SR_1	2.86 (0.10, 4.49)	0.10 (0.10, 30.05)	56.81 (6.88, 159.65)	44.95 (0.10, 87.53)	2.71 (0.10, 115.36)
$L50_2$	10.67 (8.50, 13.33)	32.52 (17.00, 49.01)	15.14 (13.87, 18.75)	19.90 (14.13, 62.97)	32.57 (13.51, 57.02)
SR_2	3.60 (0.10, 5.95)	19.05 (0.10, 17.56)	2.83 (0.58, 8.37)	8.39 (0.10, 73.87)	0.10 (0.10, 16.36)

L50₃	*	15.16 (10.45, 17.92)	*	12.07 (4.18, 18.07)	12.29 (9.63, 13.17)
SR₃	*	6.79 (0.10, 11.21)	*	1.84 (0.10, 122.91)	4.11 (0.10, 6.11)
P-value	>0.9999	0.5517	0.0317	0.8507	0.3060
Deviance	30.23	85.63	106.19	70.63	86.93
DOF	80	88	81	84	81

Table 6. Parameter values and fit statistics for selected models for redfish. Values in () are 95% confidence limits. Note that L50 and SR are provided in cm and '*' defines values that do not attribute to the respective model.

	Nordmøre Grid	Sieve panel 1	Sieve panel 2	Sieve panel 3	Sieve panel 4
Model	*rlogit*	*rclogitS2*	*rclogitS2*	*rlogit*	*rclogitS2*
C_1 (%)	*	13.0 (8.3, 65.0)	51.1 (36.3, 65.8)	*	39.4 (17.9, 66.8)
C_2(%)	*	*	*	*	*
$L50_1$	*	32.23 (21.07, 32.99)	33.84 (32.00, 35.21)	*	35.00 (29.21, 70.91)
SR_1	*	0.68 (0.10, 10.80)	1.38 (0.10, 12.63)	*	0.1 (0.10, 100.00)
$L50_2$	*	13.39 (0.10, 19.20)	12.70 (11.83, 19.67)	*	12.45 (0.10, 18.54)
SR_2	*	7.52 (0.10, 19.20)	1.84 (0.10, 10.63)	*	8.96 (0.10, 100.00)
$L50_3$	*	*	*	*	*
SR_3	*	*	*	*	*
P-value	0.9778	0.6505	0.9989	0.8712	0.1542
Deviance	13.61	23.63	7.65	11.52	27.52
DOF	26	27	23	18	21

Table 7. Parameter values and fit statistics for selected models for polar cod. Values in () are 95% confidence limits. Note that L50 and SR are provided in cm and '*' defines values that do not attribute to the respective model.

	Nordmøre Grid	Sieve panel 1	Sieve panel 2	Sieve panel 3	Sieve panel 4
Model	*rclogitS2*	*rclogitS2*	*rclogit*	*rclogitS2*	*rclogit*
C_1 (%)	37.1 (27.2, 95.3)	36.4 (19.8, 82.2)	25.1 (16.5, 38.9)	65.9 (44.8, 92.6)	39.7 (27.6, 70.3)

C_2(%)	*	*	*	*	*
$L50_1$	18.55 (16.32, 19.00)	19.1 (15.63, 21.01)	9.53 (8.43, 12.89)	19.30 (17.87, 200.00)	10.79 (8.15, 15.89)
SR_1	0.10 (0.10, 6.25)	1.58 (0.10, 5.17)	1.81 (0.10, 4.84)	0.84 (0.10, 177.24)	4.82 (1.70, 8.63)
$L50_2$	13.70 (6.91, 14.99)	12.93 (9.56, 14.28)	*	10.99 (8.07, 15.40)	*
SR_2	5.81 (0.10, 6.59)	2.95 (0.10, 3.65)	*	2.54 (0.10, 4.40)	*
$L50_3$	*	*	*	*	*
SR_3	*	*	*	*	*
P-value	0.1908	0.5873	0.8333	0.7151	0.1572
Deviance	18.36	12.24	9.78	7.98	20.4
DOF	14	14	15	11	15

3.2 Species-wise comparisons

3.2.1 Shrimp

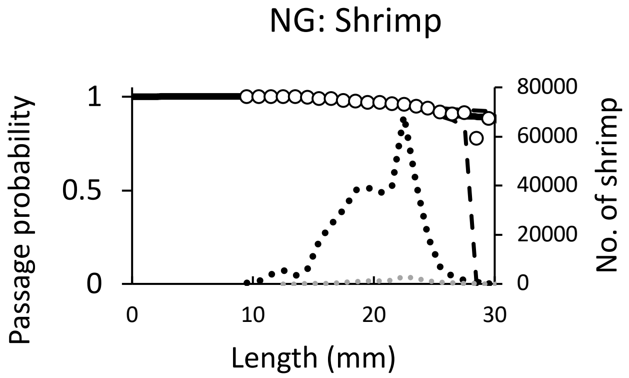

Figure 8. Shrimp passage through the NG (black line) with 95% confidence bands (dashed lines) with shrimp counts in compartment one (black dotted line) and compartment two (grey dotted line).

Shrimp, being the target fishery in question, was included to ensure that its catch was not implicated as a result of the change in selectivity device. First exploration of the data began through analyzing the efficiency of each device's design as a standalone apparatus. The NG (fig. 8) allowed shrimp to pass through with higher confidence for the larger size ranges, but exceeding approximately 27 mm, wider confidence intervals restrict any robust conclusions to be made regarding retention in the codend and this outcome is also translated to the remaining shrimp curves as a result of the reduced data available in these size classes. For the SP designs, a smaller mesh size showed some indication of determining reduced retention in the codend as the SD1 and SD3 curves displayed shrimp loss beginning from approximately 16 mm and 19 mm respectively. Larger mesh sizes of the SD2 and SD4 designs were able to retain shrimp up to 26 mm with high confidence (fig. 9), closely emulating the capabilities of the NG.

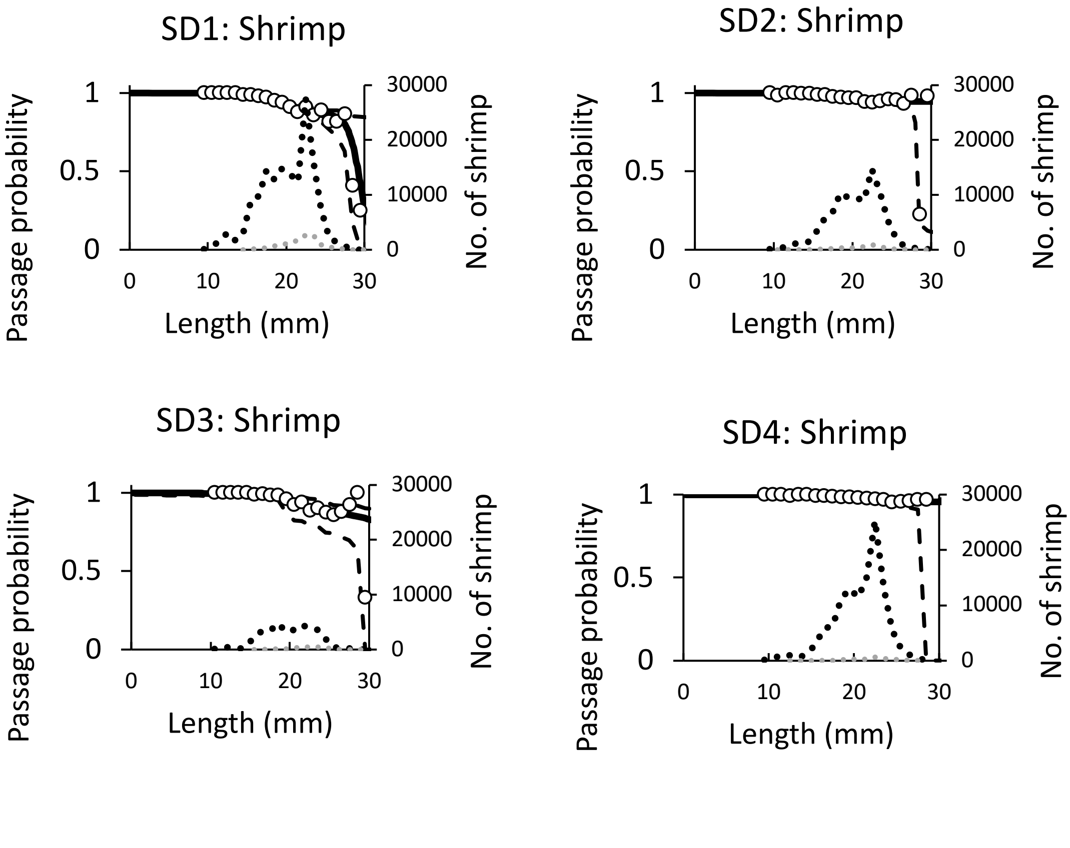

Figure 9. Shrimp passage through the SP designs (black line) with 95% confidence bands (dashed lines) with shrimp counts in compartment one (black dotted line) and compartment two (grey dotted line).

The comparisons between the SP designs and the NG are displayed in figure 10 (note: narrower y axes to allow clearer inferences of results). Subtracting the passage through the NG from the relative SP indicated a significant difference only when SD1 and SD4 were in question. As the curve moves slightly into the lower half of the figure when a smaller mesh size is used it is indicated that the NG performs significantly better for the 19 mm – 27 mm length class range. Surprisingly, the SP is able to improve retention of shrimp from that observed by the NG. When configured with a 300 mm mesh size for shrimp measured between 15 mm and 27 mm (a very large size interval), more individuals are able to pass into the codend

Differences calculated between the four designs (fig. 11) to draw comparisons in performance showed a marginal difference in passage probability in all instances where a change in mesh size was compared. The differences were most pronounced in the case of SD4 - SD1 where the minimum difference between the designs reached up to 5% in the 17 mm – 29 mm size range. Above this length though, confidence in estimates quickly decreases and the different variables in mesh size and angle no longer determine shrimp passage. Similarly, below these lengths, changes in mesh size and angle did not affect shrimp passage, thus the designs function similarly. Changing mesh size alone indicated to be more effective than angle (SD2-SD1 and SD4-SD1), but the combined effect of these two variables is most evident.

As observed above, three out of four of the SP designs gave rise to increased shrimp exclusion, thus the possibility of improving the selectivity device's setup through analyzing their *combined* effect was explored. As expected, the addition of another BRD in the setup (figure 12) introduced a further potential obstacle between shrimp and the codend, thus, shrimp loss became more pronounced, particularly when meshes were smaller. This was indicated in SD1 and SD3 trend lines in figure 12 by the more negative slope gradients on the right-hand side of the curves. These combined SP and NG designs again gave rise to a significant difference when compared to the baseline configuration used in today's deep – water shrimp fishery (fig. 13). Some of the larger year classes suffer a minimum of 10% added exclusion from the net in the combined designs with a small mesh size. But a satisfying result was observed for the larger mesh size configurations. A 300 mm mesh size SP added to the gear generated just an added 3% loss of the catch for shrimp falling in the upper half of the size spectrum.

To summarize, shrimp passage through the SP designs did not show any clear dependency on the angles of the panel. But the influence of mesh size was observed. A higher loss of shrimp

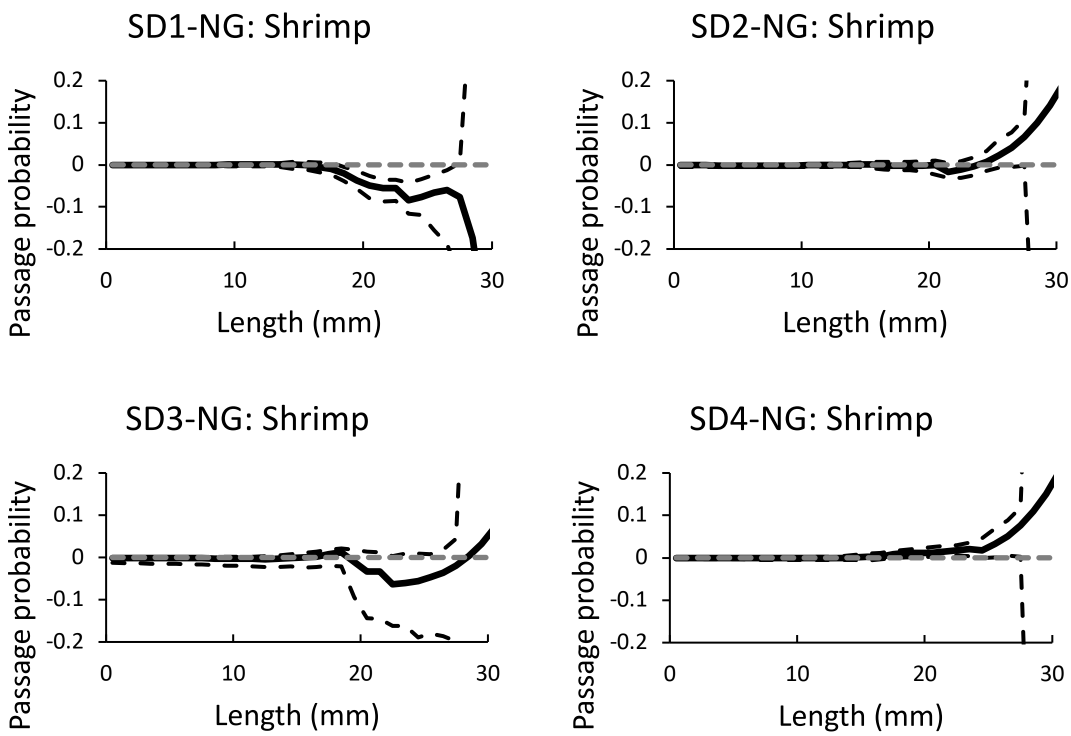

Figure 10. Shrimp passage differences between the SP and the NG (black line) with 95% confidence bands (dashed black line).

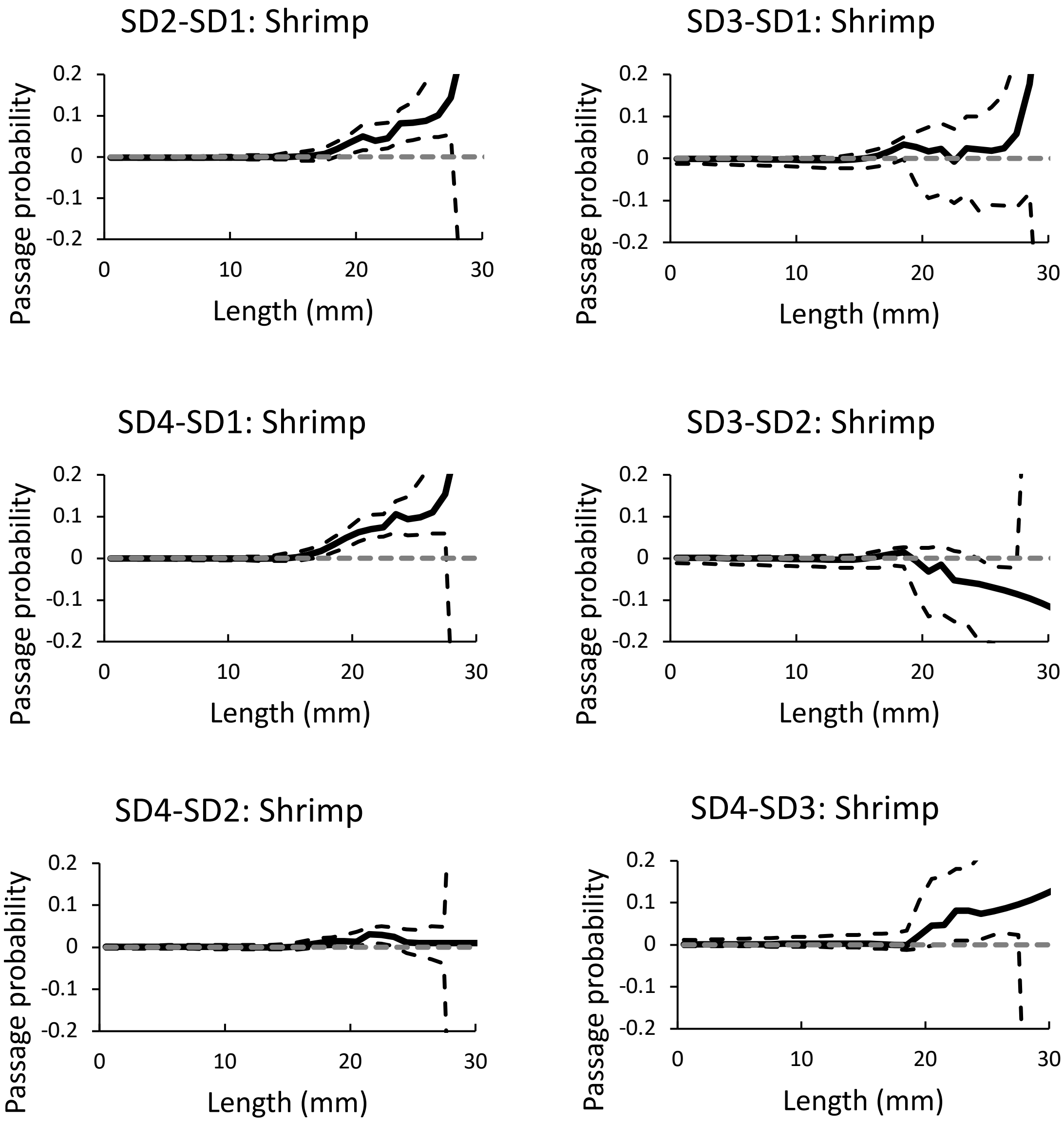

Figure 11. Shrimp passage differences between SP designs (black solid line) with 95% confidence bands (dashed black line).

catches when a mesh size of 200 mm was installed was evident. In comparison to the 200 mm mesh larger 300 mm mesh size, shrimp catches are only minimally lost in the size range of approximately 17 mm to 27 mm where a minimum of approximately 5% more are seen to be excluded. Thus, introducing a 300 mm mesh size SP in the trawl net coupled with a NG at either 10° or 20°, can be a viable option when aiming to conserve catch in this fishery.

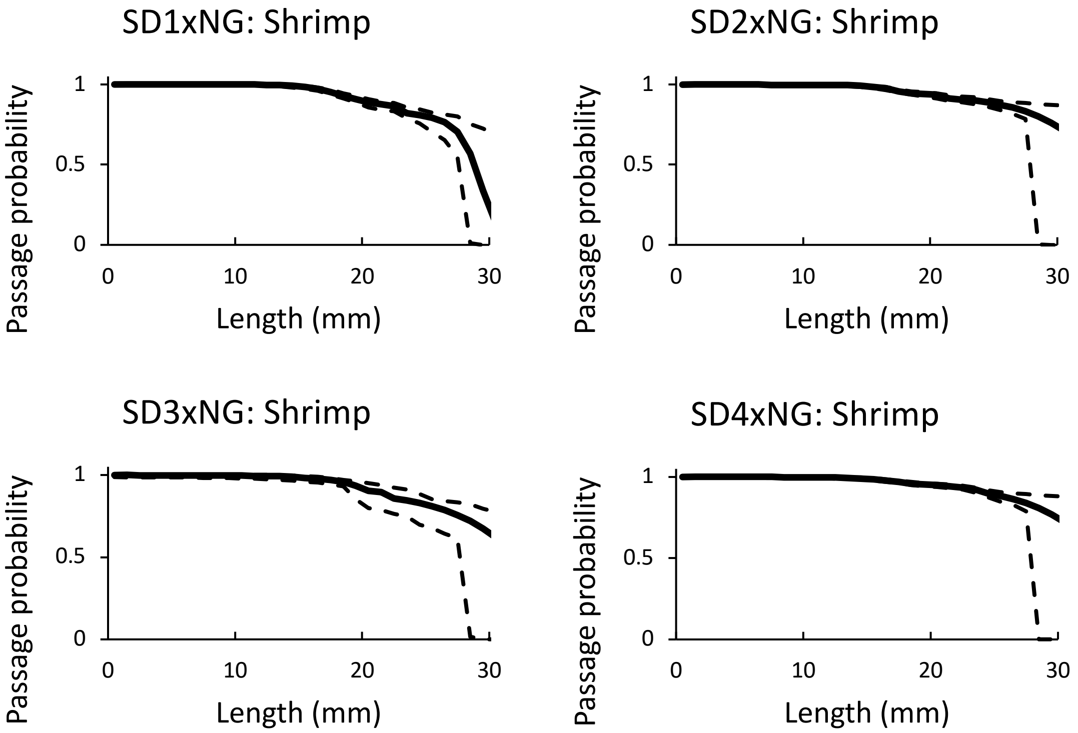

Figure 12. Shrimp passage (solid line) through a combined BRD setup with 95% confidence bands (dashed lines).

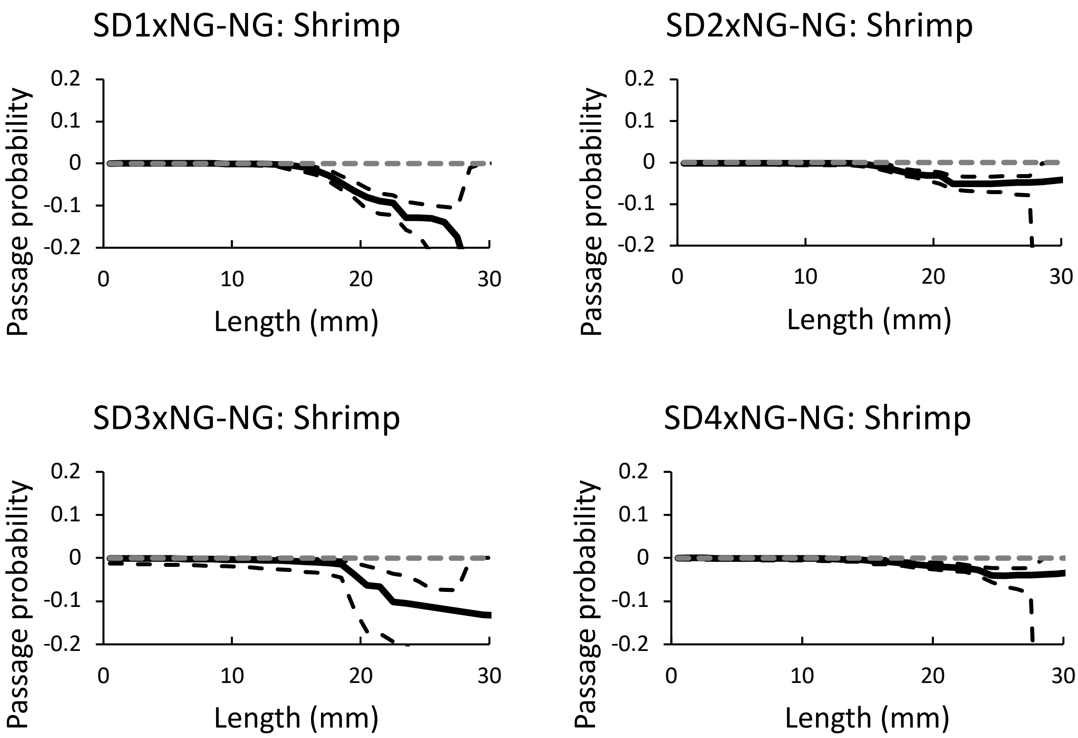

Figure 13. Shrimp passage differences between the combined BRD setup and the NG stand- alone (solid black line) with 95% confidence bands (dashed black line).

3.2.2 Cod

The cod, an important bycatch species required for consideration in selectivity experiments, due to its high commercial and cultural importance in Norway, is at risk of growth overfishing by the shrimp fishery if juveniles are not able to be excluded from the codend.

During shrimp trawl operations, the NG begins to reduce cod bycatch once year classes reach approximately 10 cm (fig. 14). This steep selection curve ends at the age where the risk for retention in the trawl net with the shrimp catch is directly size dependent. This is at the point of approximately 20 cm.

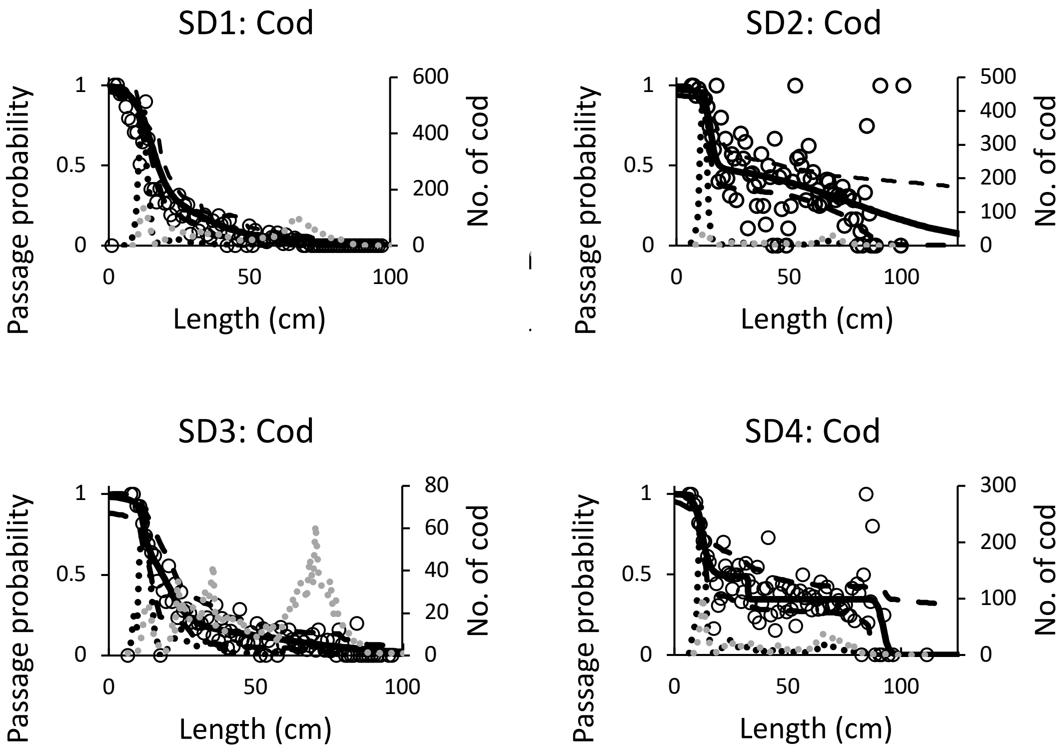

Figure 15. Cod passage through the SP designs (black line) with 95% confidence bands (dashed lines) with shrimp counts in compartment one (black dotted line) and compartment two (grey dotted line).

When a SP is installed in the trawl it is unable to match the low size range and minimum length for passage through, allowing a much wider interval of individuals to pass through comparatively for all designs particularly after this 20 cm threshold exhibited by the NG alone (fig.15, 16). The larger mesh size demonstrates a clear increase in bycatch passing through the SP, while none of the designs were able to exclude (the opposite to passage through) more cod below 20 cm. This is of course undesirable and thus, the SP is inadequate in replacing the NG for this gadoid species.

Comparisons drawn between the SP designs (fig. 17) revealed the significant effect that increasing mesh size has on passage of individuals within approximately 20 cm and 90 cm. The lack of effect of angle again is also observed because the confidence bands include the

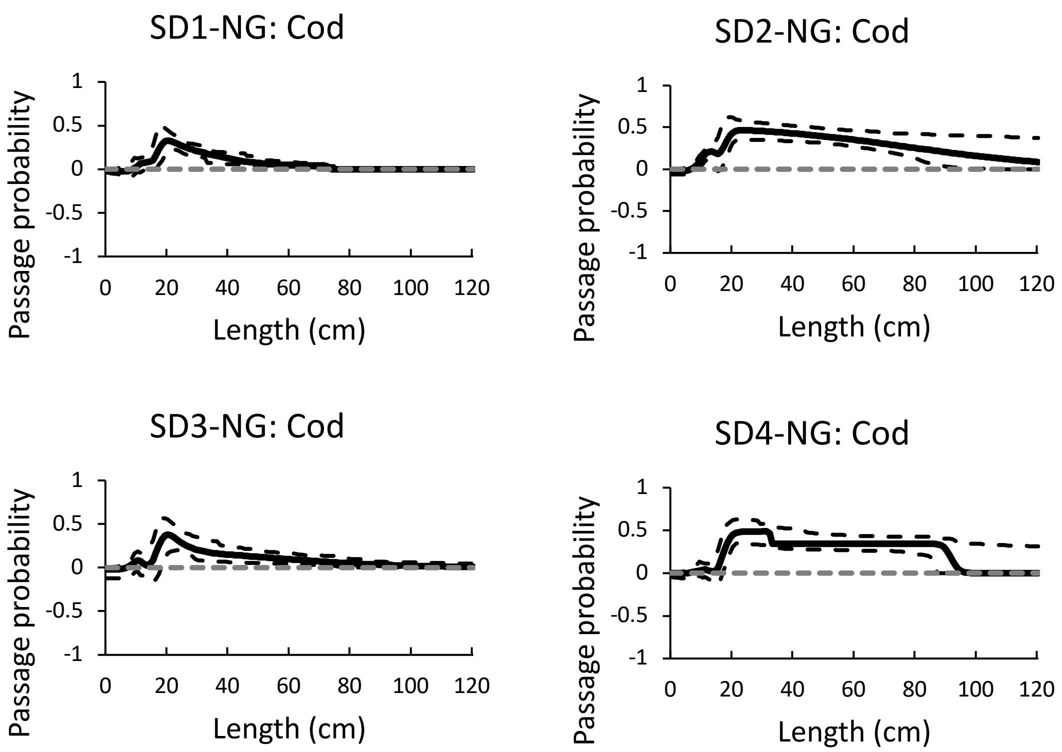

Figure 16. Cod passage differences between the SP and the NG (black line) with 95% confidence bands (dashed black line).

value of 0. Passage of cod below 20 cm again is indifferent among the compared designs and similarly a clear size constraint is observed for larger individuals.

Adding a second BRD to the trawl gear led to a similar response in exclusion efficiency of cod as seen by the classical design across a wide range of cod sizes, excluding significantly more cod within the size range of approximately 10 cm and 18 cm (fig. 18, 19). The SD4 configuration was the most successful, enabling the exclusion of 14% more cod from the codend at its highest point in the comparisons curve (fig. 19). Thus, regarding cod, the addition of a 300 mm mesh size SP has the potential to contribute to bycatch reduction.

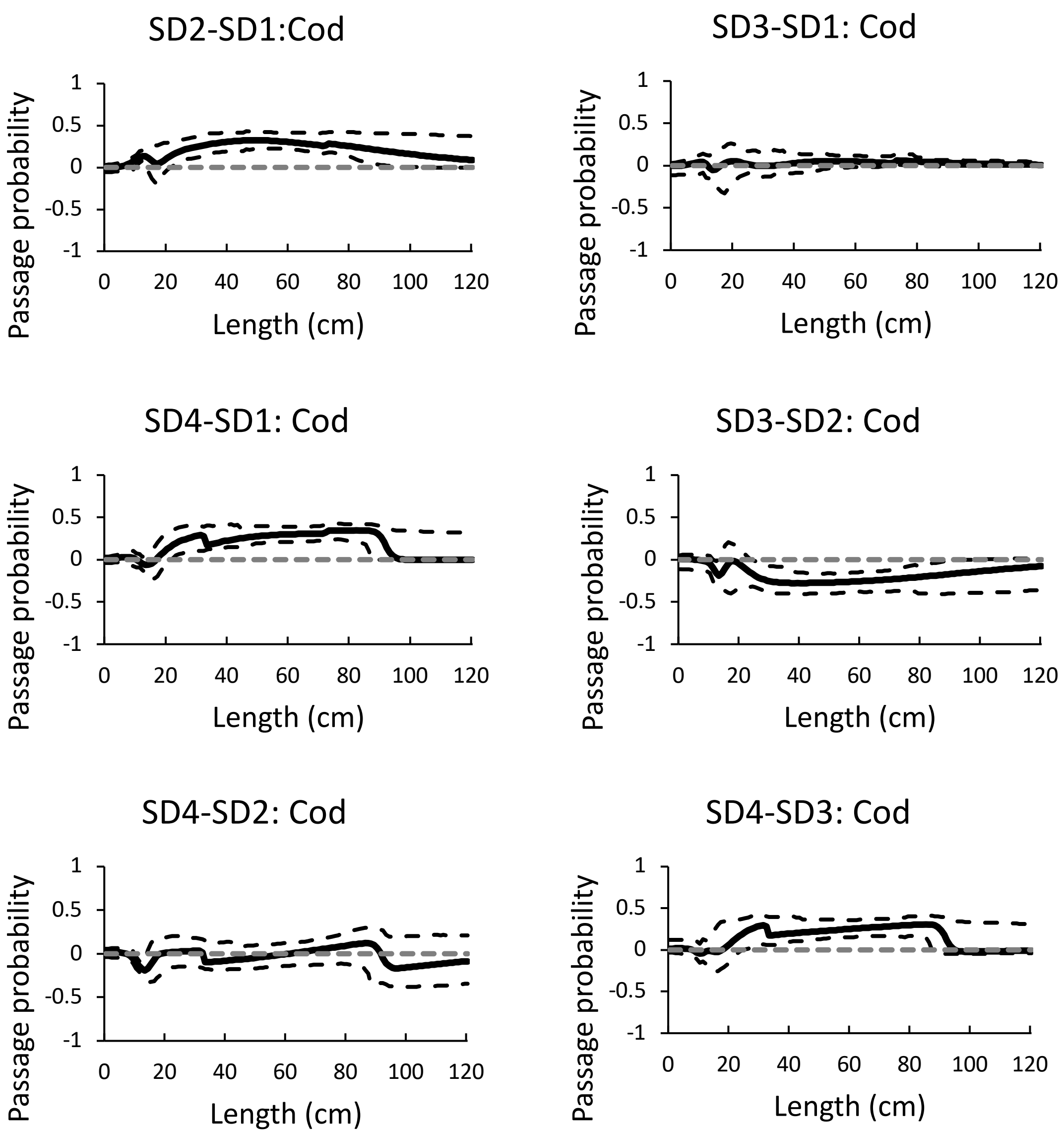

Figure 17. Cod passage differences between SP designs (black solid line) with 95% confidence bands (dashed black line).

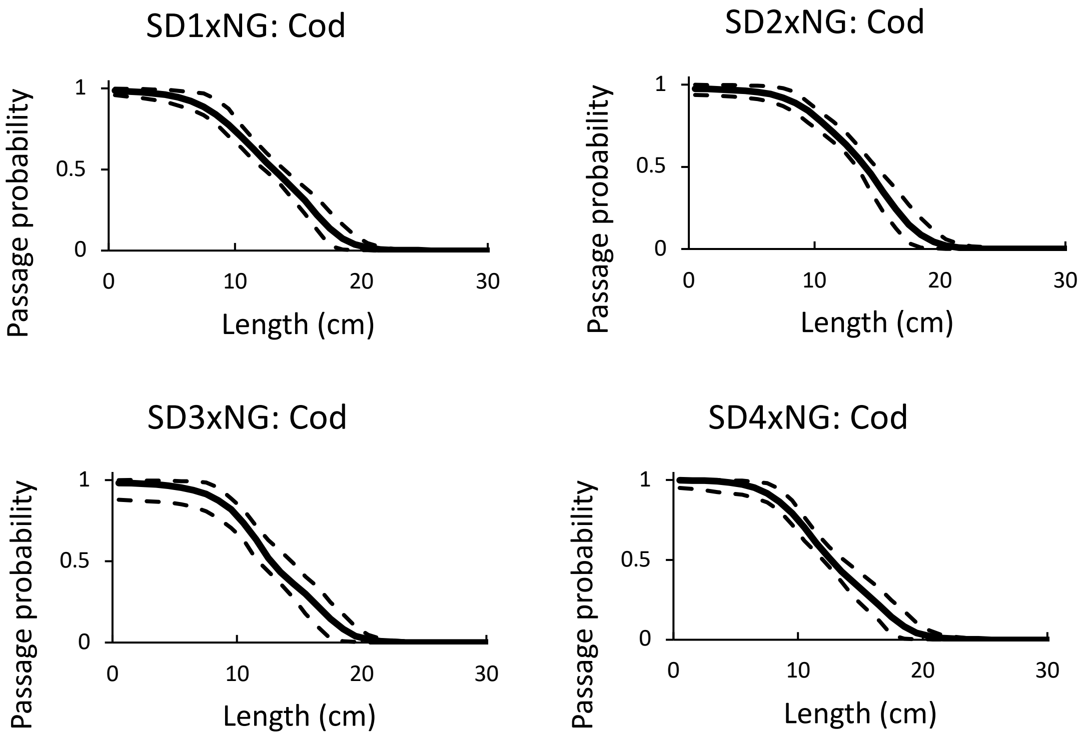

Figure 18. Cod passage through a combined BRD setup (solid line) with 95% confidence bands (dashed lines).

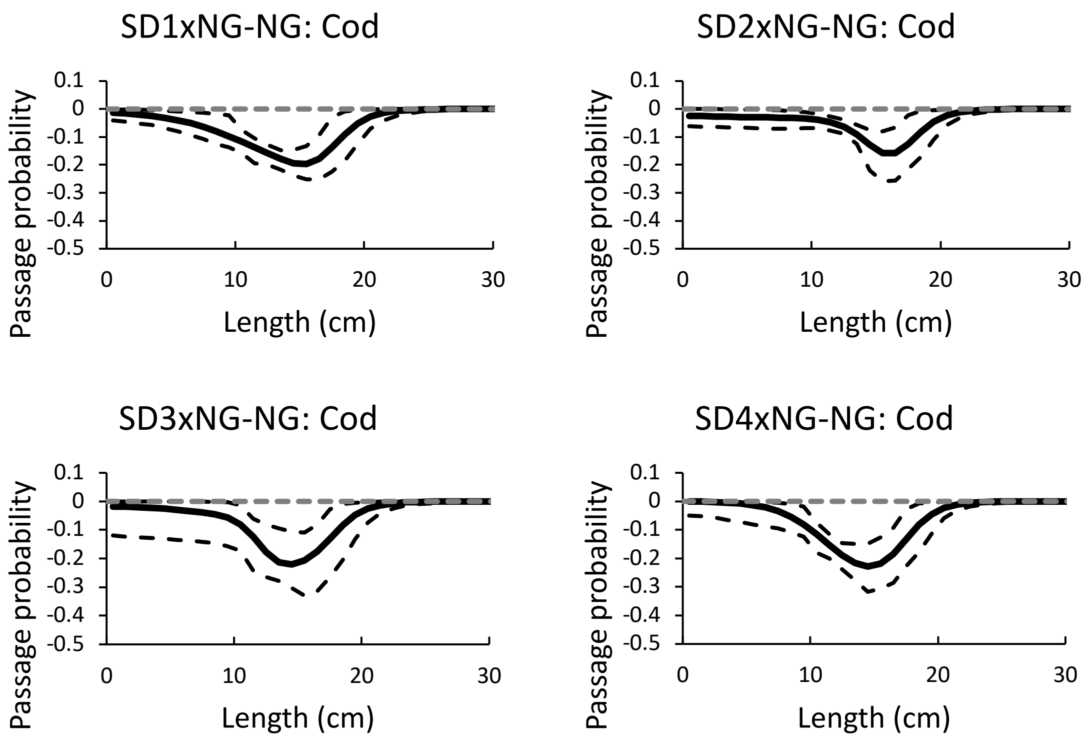

Figure 19. Cod passage differences between the combined BRD setup and the NG stand - alone (solid black line) with 95% confidence bands (dashed black line).

3.2.3 Redfish

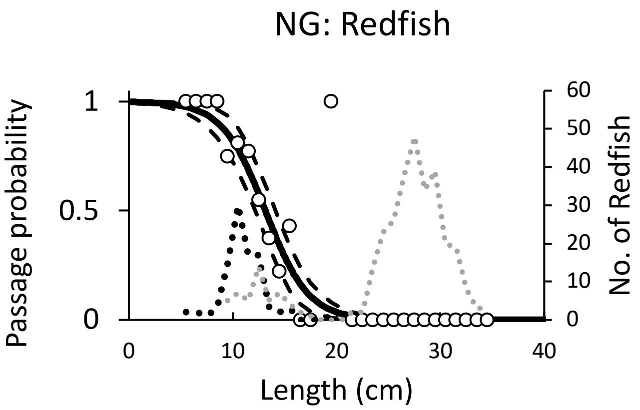

Figure 20. Redfish passage through the NG (black line) with 95% confidence bands (dashed lines) with shrimp counts in compartment one (black dotted line) and compartment two (grey dotted line).

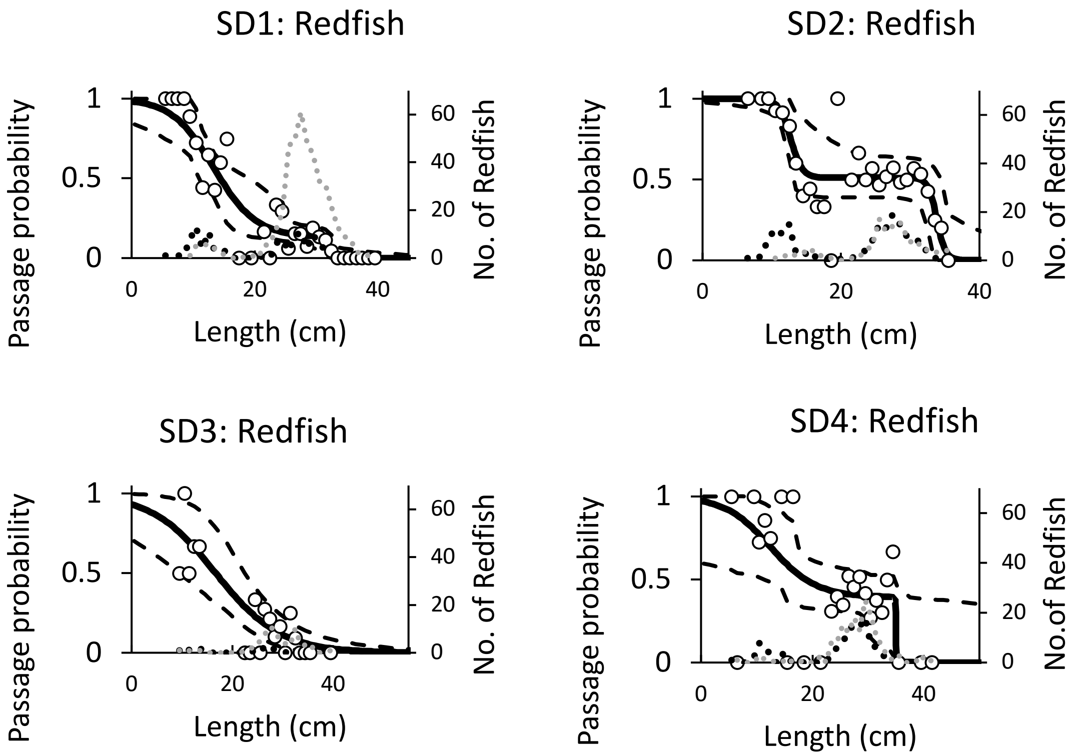

Figure 21. Redfish passage through the SP designs (black line) with 95% confidence bands (dashed lines) with shrimp counts in compartment one (black dotted line) and compartment two (grey dotted line).

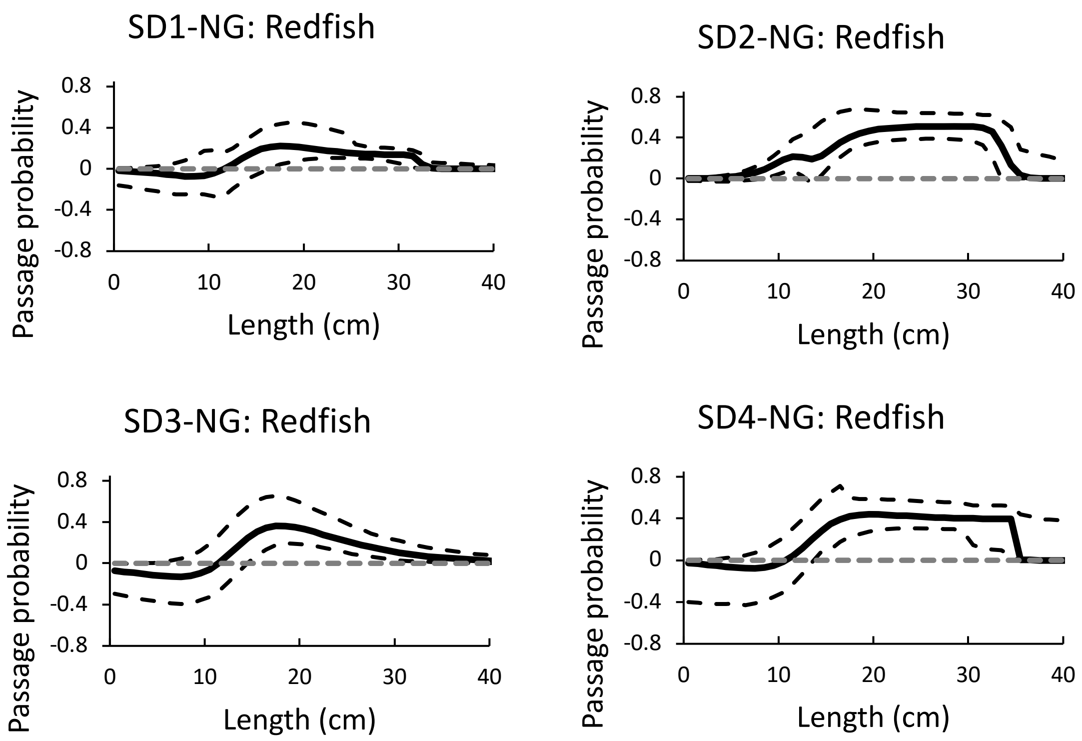

Figure 22. Redfish passage differences between the SP and the NG (black line) with 95% confidence bands (dashed black line).

Difficulties in excluding this red-listed species begins for the year classes below approximately 10 cm. Around 100% of these small redfish passed through the BRDs tested (fig. 20, 21). All of the SP designs tested generated significantly more retention of redfish in the codend than the NG did (fig. 22), being unable to reduce retention in any year classes caught. Wide confidence bands for passage through SD4 shows some potential for excluding more juveniles with a large mesh size and high angle, but a similar outcome has potential for the SD3 design tested so a clear effect of mesh size or angle is unclear (change in angle effect is not evident in the SD1 and SD2 curves). Larger mesh sizes associated with a higher percentage reduction in exclusion (at least 30%) and this was implicated for a wide range of central length classes (approx. 16 cm – 33 cm). Smaller meshed SPs may have more potential for exclusion if the NG is to be replaced, but as discussed below, a combined design may be a more appropriate alternative.

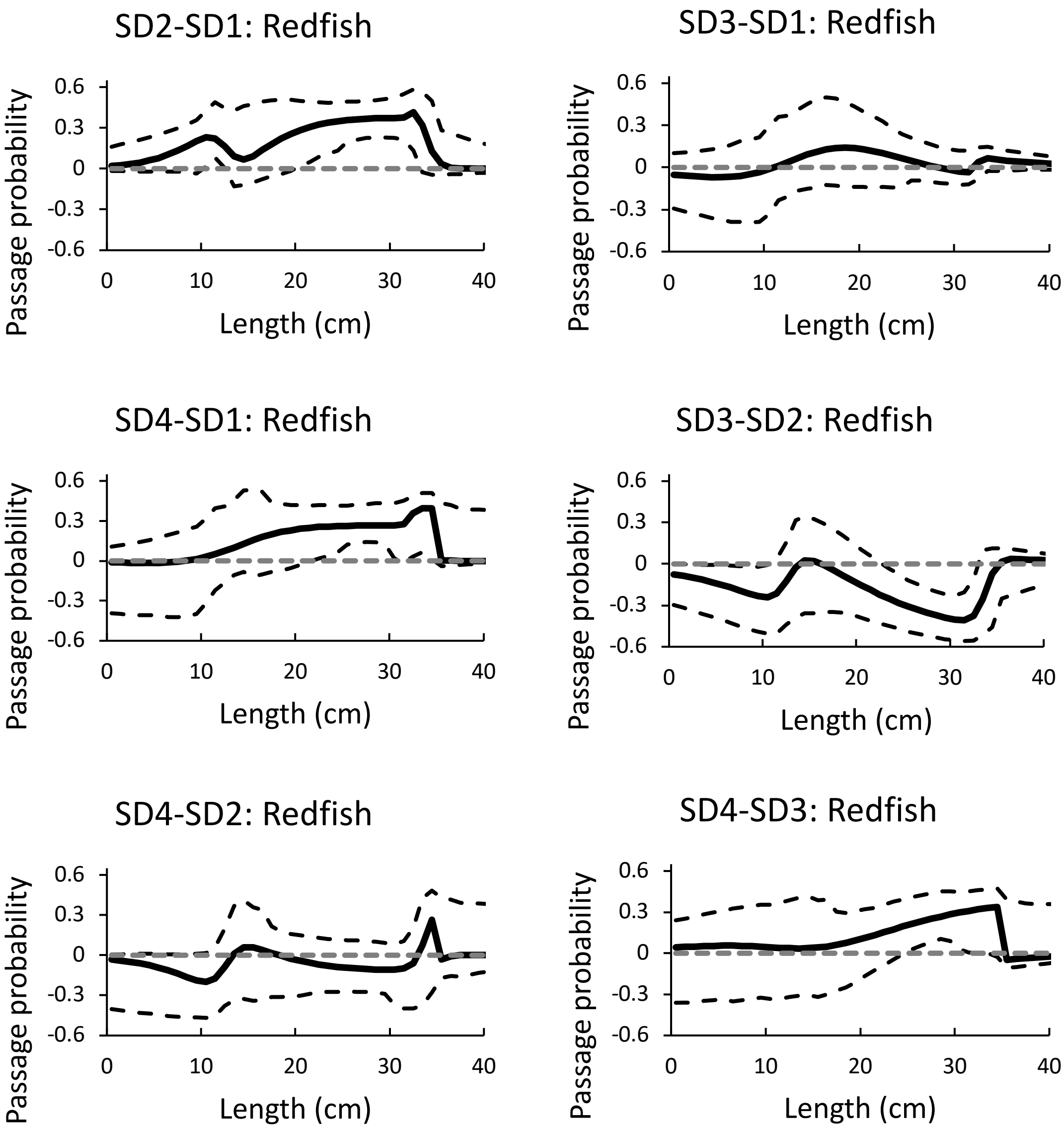

Figure 23. Redfish passage differences between SP designs (black solid line) with 95% confidence bands (dashed black line).

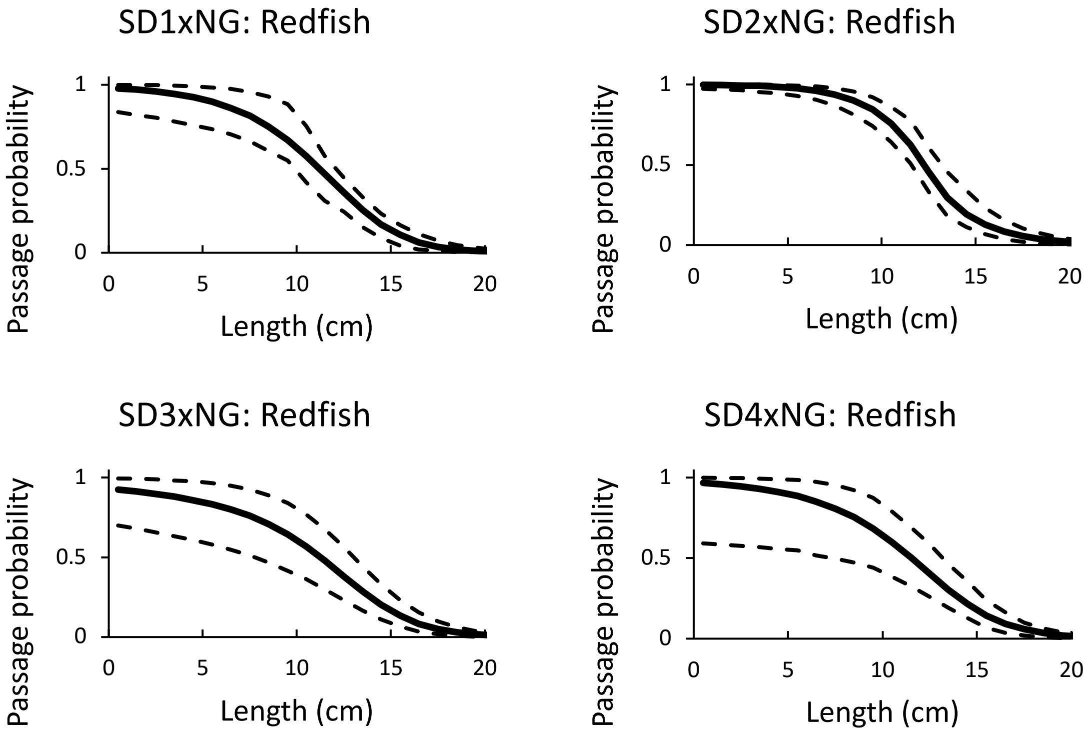

Figure 24. Redfish passage (solid line) through a combined BRD setup with 95% confidence bands (dashed lines).

Some marginal differences in the four SP designs were detected throughout larger year classes (fig. 23), but no such differences could be seen for juveniles below 10 cm, and differences were only found for a narrow range of sizes. These differences always arose when the size in mesh was increased, regardless of sieving angle. Larger meshes as expected allowed significantly more of some larger age-classes to pass through. The trend lines for this species (fig. 23) display a lot of irregularity though and would have a high degree of uncertainty associated with any inferences made. This may owe to the behavioral factors attributed to redfish. Comparatively lower catches of redfish to cod also outline the wider confidence bands shown.

The combined effect however showed some promise over the classical setup (fig. 24, 25). A SP combined with the NG becomes more effective at excluding redfish greater than approximately 10 cm. Below this size, the combined design is still able to exclude significantly more individuals, but the efficiencies are quite similar. A clear dependency on mesh size and/or sieve angle is not clear though as designs that were opposite in structure were both successful at varying degrees. The highest differences in exclusion were seen with a small mesh size and low angle though (fig. 25) where a select range of larger length classes were excluded more (14%) by the combined design. Despite the inability to draw obvious conclusions for this species, a combined design here is still a successful alternative to the NG. Replacing the NG with a SP (fig. 22) though would lead to significantly higher codend entry of medium-sized redfish and potentially also those in smaller length classes.

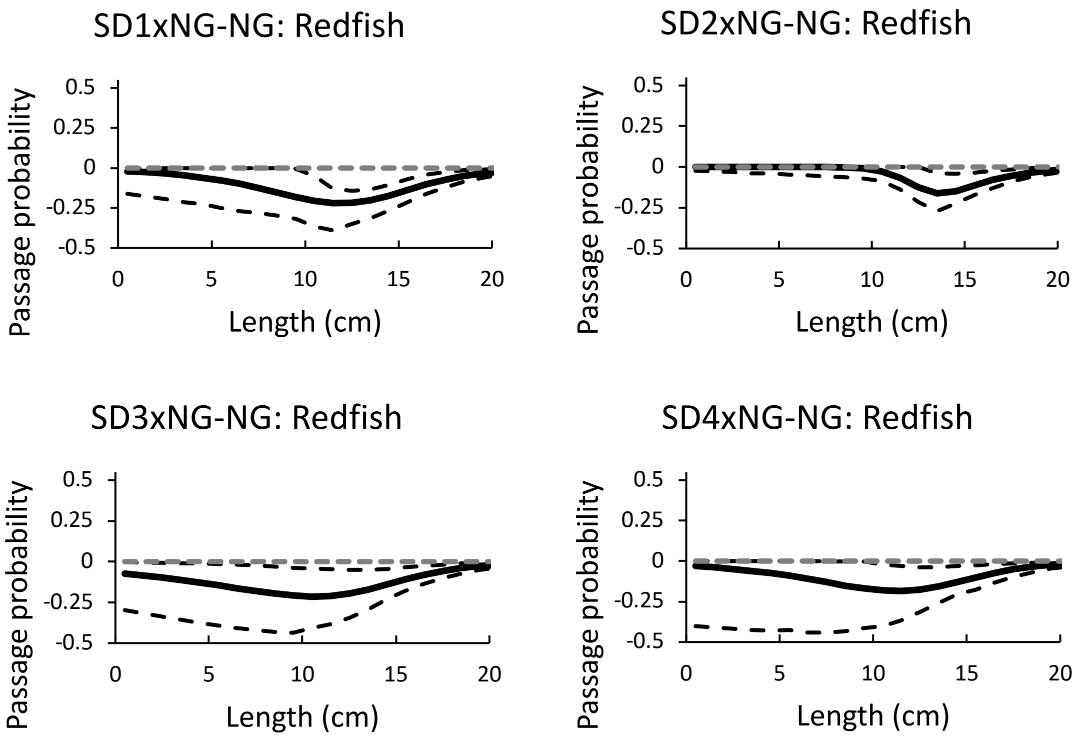

Figure 25. Redfish passage differences between the combined BRD setup (solid black line) and the NG stand- alone with 95% confidence bands (dashed black line).

3.2.4 Polar cod

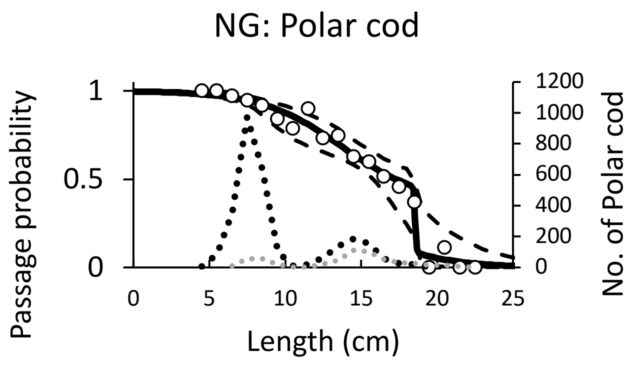

Figure 26. Polar cod passage through the NG (black line) with 95% confidence bands (dashed lines) with shrimp counts in compartment one (black dotted line) and compartment two (grey dotted line).

The NG alone operates similarly with polar cod as it does for redfish (fig. 26). It has a lesser ability of excluding juveniles, but the selection curve in this case lacks the steepness, therefore many more larger individuals of this species are at risk of becoming bycatch. The SP designs tested varied in their exclusion efficiencies, but the smaller mesh size, particularly when coupled with a low angle, when implemented indicated potential to match the NG in efficiency (fig. 27). Increasing the mesh size alone resulted in a much lower exclusion rate from the trawl while increasing the sieving angle alone had less of an effect on exclusion, but this statement is non-conclusive due to the high increase in uncertainty. Like the increase in mesh size, the combined effect of increasing mesh size and angle was detrimental to polar cod exclusion, with no more than 30% of individuals from any length class being able to escape the net.

If it were to be installed alone in the gear (fig. 28), analysis showed that the SP made no significant impact on bycatch reduction compared to the NG when the mesh size was kept

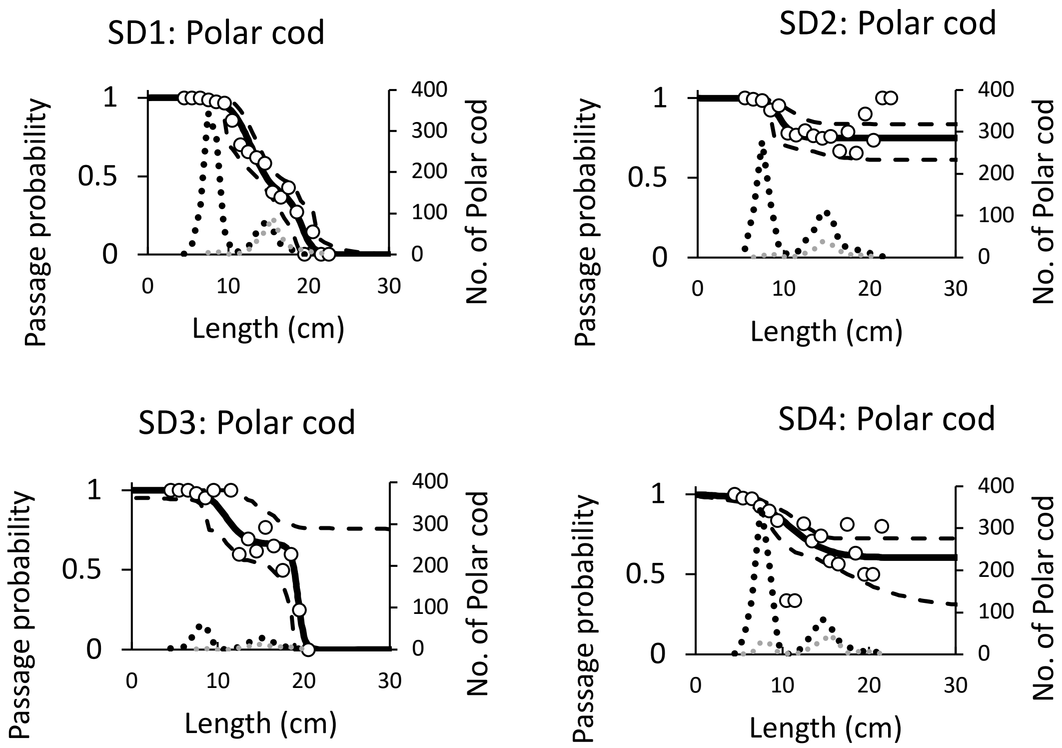

Figure 27. Polar cod passage through the SP designs (black line) with 95% confidence bands (dashed lines) with shrimp counts in compartment one (black dotted line) and compartment two (grey dotted line).

low, regardless of sieving angle. When the mesh size was increased, significantly more polar cod were retained when the length exceeded 16 cm at a low sieving angle and after 19 cm at a higher sieving angle. Thus, replacing the NG with a SP including large meshes would not be detrimental to younger polar cod, but will result in unnecessary catch of some larger individuals.

Comparisons drawn between the four SP designs (fig. 29) indicated a considerable effect of changing mesh size at a low sieving angle (SD2-SD1) as well as the combined effect (SD4 – SD1) of changing mesh size and sieving angle, whereby larger meshes gave rise to lower exclusion. Changing mesh size did not affect polar cod exclusion when a high angle was used (SD4-SD3). This effect was seen for individuals larger than 15 cm. Some marginal reduction in exclusion was seen when the angle was increased at a small mesh size (SD3-SD1) when individuals were within the 15 cm – 18 cm size range.

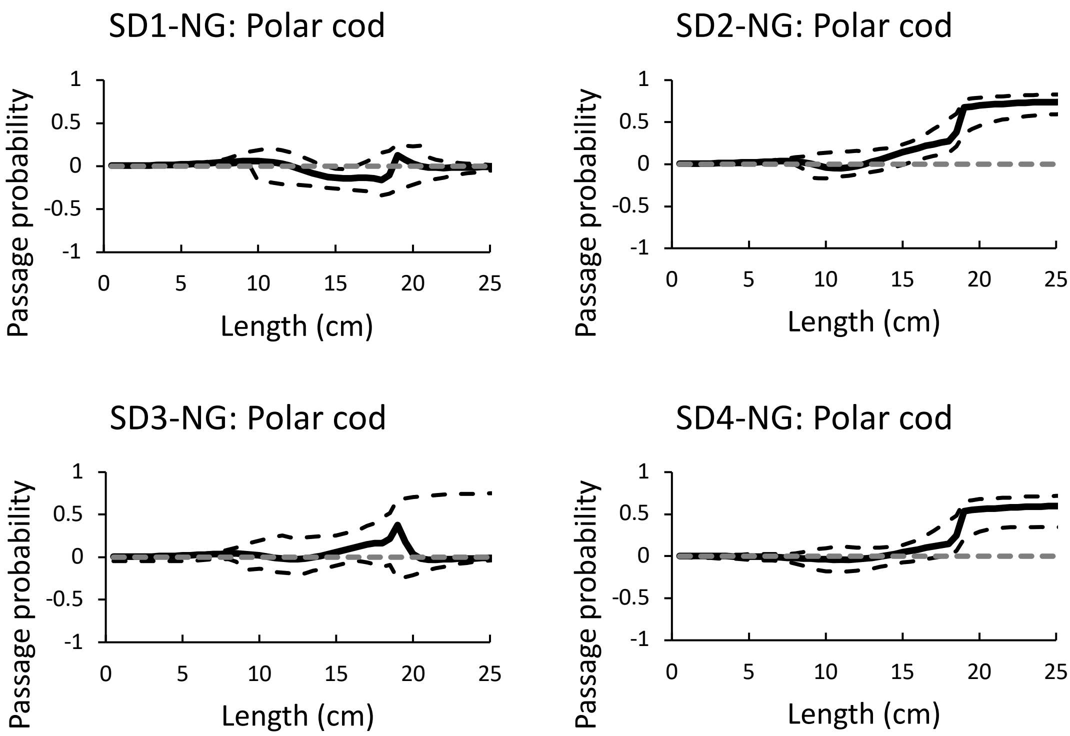

Figure 28. Polar cod passage differences between the SP and the NG (black line) with 95% confidence bands (dashed black line).

The potential for a combined, NG and SP (fig. 30, 31), setup to exclude more polar cod than the current setup was significant for all SP designs but limited to individuals in some central length classes. Perhaps unexpectedly, a larger mesh size and sieving angle (SD4) gave rise to the widest size-range in individuals being excluded when compared to the NG alone. But an additional BRD does not influence juvenile polar cod escapement from these selectivity devices below 8 cm.

Therefore, following from results observed by the shrimp, the SD4 design combined with a NG can be identified as a possible candidate in improving bycatch selection. The sieve panel still remains unsuccessful along with the NG in excluding the smallest juveniles of the species tested here, but nevertheless has good potential in addressing bycatch across larger year classes, that otherwise are able to pass through the size selective devices used today.

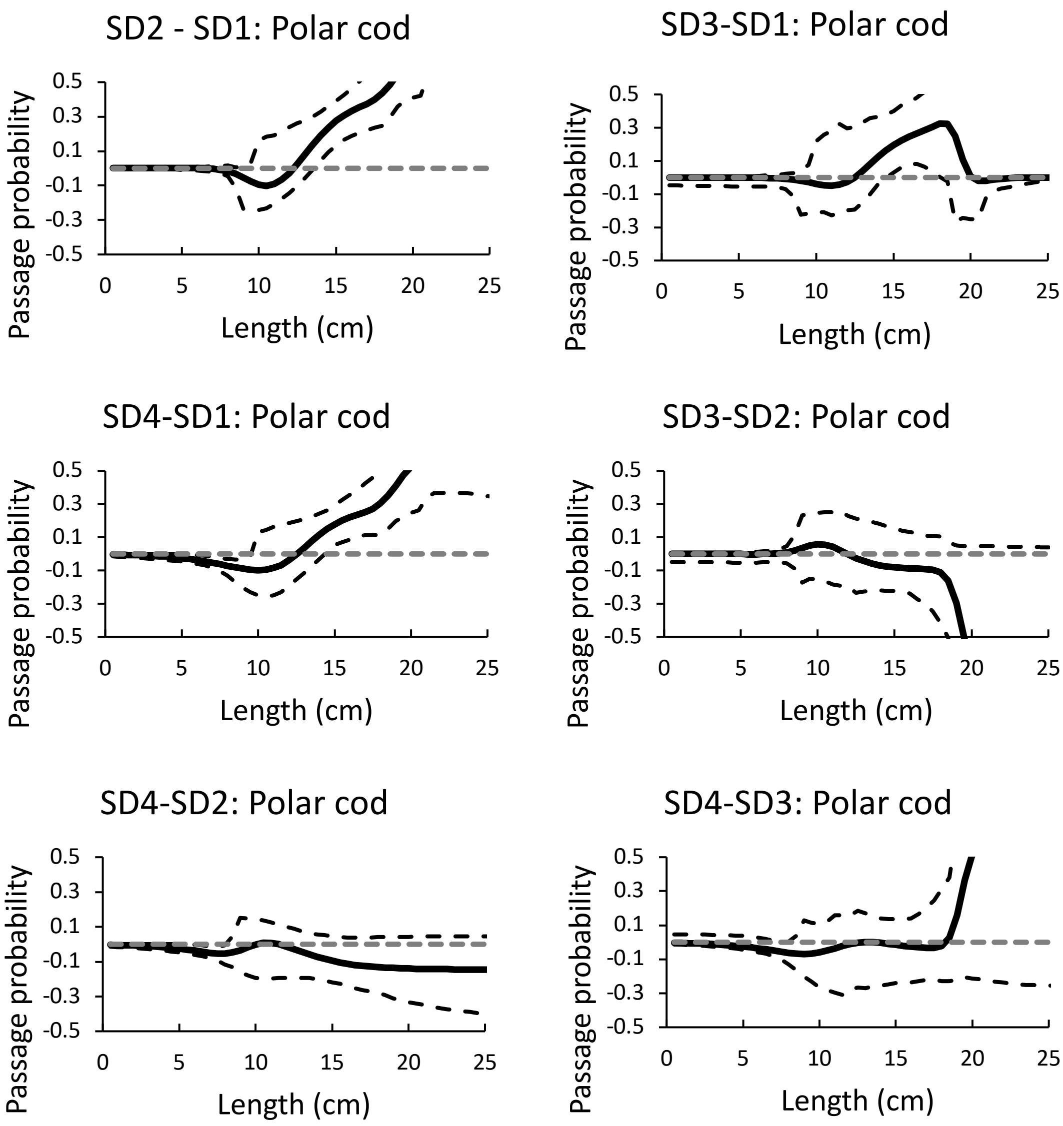

Figure 29. Polar cod passage differences between SP designs (black solid line) with 95% confidence bands (dashed black line).

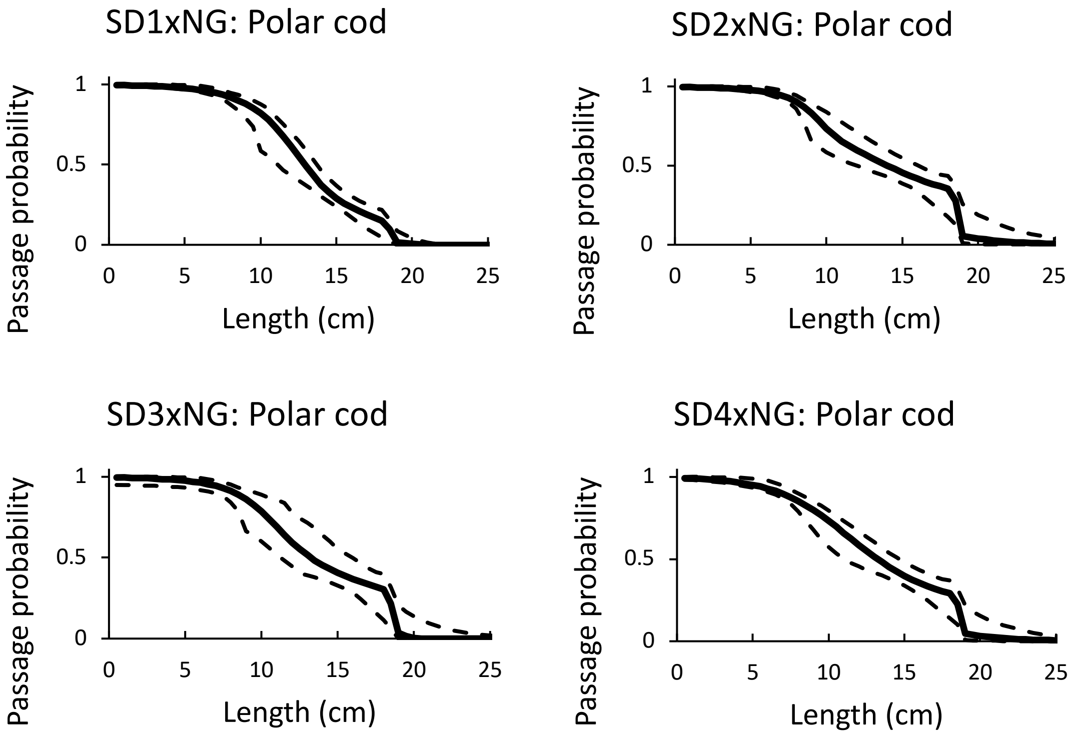

Figure 30. Polar cod passage (solid line) through a combined BRD setup with 95% confidence bands (dashed lines).

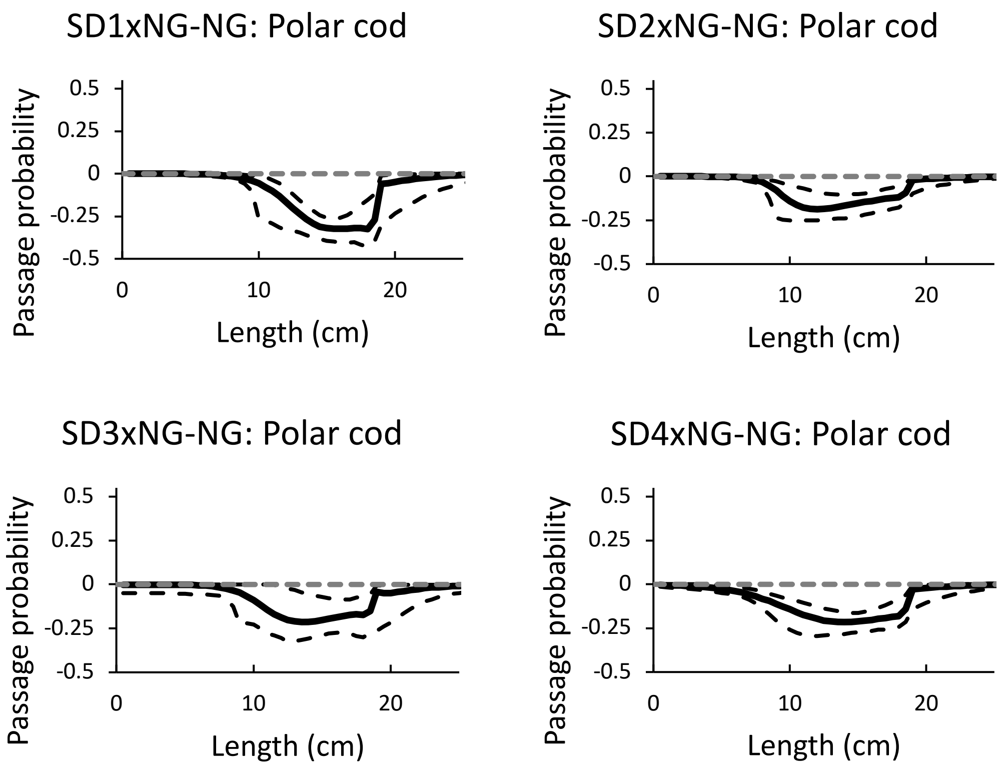

Figure 31. Polar cod passage differences between the combined BRD setup (solid black line) and the NG stand- alone with 95% confidence bands (dashed black line).

3.3 Sieve design – wise comparisons

3.3.1 NG (stand-alone) compared to a SP (stand-alone) (fig. 10, 16, 22, 28)

The target species, shrimp, was indifferent in its exclusion by the NG or the varying SP designs. From these results, in respect to the shrimp, the SP has some potential to replace the NG but a clear dependence on a large mesh size is seen as a determinant for shrimp passage through the panel. But when simultaneously aiming to exclude bycatch from the codend, the SP designs tested were unsuccessful, without exception, in being able to exclude more individuals from the codend than otherwise would be possible by the NG. The two different selectivity devices were indifferent when addressing small year classes (<10 cm), but in terms of some larger length classes, particularly for cod, the NG operated more efficiently. Thus, as a stand-alone device, the SP may be regarded as inadequate to replace the NG due to the added degree of fish retention that was observed.

3.3.2 SP design comparisons while holding the configuration of the NG constant (fig. 11, 17, 23, 29)

Changes in SP design had very minimal effects on shrimp passage. Only when mesh size alone at a low angle and the combined effect of increasing the two variables was compared did shrimp passage increase for an interval of larger year classes. Wide length class intervals of cod showed strong dependency on the size of the meshes implemented in the selectivity device, indicating no response when angle alone was changed. Size dependency for escapement as shown by the cod was not obvious for redfish. Differences that were revealed by comparisons could only be assured for an interval of length classes but were guaranteed in that interval when meshes were altered, and not seen when angle alone was changed. Polar cod selectivity looked different throughout different SP designs. Strong effects were demonstrated when mesh size was increased at a low angle and the combined increase of mesh size as well as sieving angle where exclusion of larger fish was significantly lower. Exclusion however did not change when larger meshes were implemented at a high angle. Any change in angle alone affected quite narrow length intervals only but only when meshes were small, indicating some dependency on that variable. Thus, increasing the mesh size was shown to have a noticeable effect on bycatch exclusion in the codend. Although this is not constant in all year classes of each species tested, it can help to illustrate the way in which the species interact with these SP designs, as previous studies testing this type of device (Polet, 2002; Revill and Holst, 2004a) have used mesh sizes of much smaller sizes. Shrimp retention and bycatch exclusion still indicates dependency on mesh sizes as big as 200 mm and 300 mm.

3.3.3 NG (stand - alone) compared to the combined SP and NG performance

When the new SP designs were combined with the NG in general there was a size interval in which the added bycatch excluder improved selectivity for all bycatch species tested. But many year classes that are of particular concern to fishery managers were unsuccessfully excluded from the catch using the added BRD. However, using a combined model simultaneously can positively contribute to bycatch reduction of some larger sized fish while limiting larger shrimp exclusion to less than 5% with a 300 mm mesh SP, leaving small shrimp exclusion unchanged. Improved cod exclusion from the SP designs was only attained for a select margin of length classes (between 10 cm and 20 cm). Individuals outside of this did not exhibiting any difference to exclusion efficiency compared to the NG alone. Improved redfish exclusion was quite minimal for the designs tested but the probability of improved efficiency is high, particularly by SD4 for the smallest juveniles, seen by the wide confidence bands. The smallest mesh size and lowest angle of SD1 was most successful in excluding some larger individuals, but comparatively shows less promise for the smallest juveniles, and since the confidence bands remain below the null axis across all curves in figure 25, SD4 performance may be favourable due to its added possible efficiency for the smallest individuals. Contrary to expectation, polar cod responded best when SD4 was implemented, as it improved exclusion from the catch of individuals as small as 6 cm despite the larger mesh size and sieving angle. A SP configured with meshes around 300 mm large therefore shows good potential to improve the catch quality of many species. An additional loss of 3% in shrimp is regarded as acceptable in this setting (Isaksen et al., 1992), thus, including a soft excluder as well as the rigid excluder offers a viable alternative for fishermen through improving ecological conservation as well as the guarantee for economic return through more efficient fishing practice.

4 Discussion

The aim of this study was to investigate the potential for the SP to improve selectivity of deep-water shrimp and bycatch through either replacing or adding to the current NG excluder device used in the fishery. When sorting devices are not effective in avoiding bycatch of juvenile fish species, the risk of growth overfishing is exacerbated. Due to the multi-species nature of these fishing grounds, a solution to these sieving efficiency difficulties also demands for inter-species adaptability for the varying sieving characteristics, therefore four different configurations of the SP were tested. A challenge regularly faced is the ability to avoid the high losses seen in shrimp catches (Gorman and Dixon, 2015; Larsen pers. comm) when selectivity devices are implemented that strongly select against bycatch (Polet, 2002; Wienbeck and Rauck, 1992). The above results outline how this can occur and simultaneously be mitigated.

Selectivity studies in this fishery since they began with rigid sorting devices (i.e.; grids) in the early nineties (Isaksen et al., 1992) have continued to develop the fields explored to improve the fishery's efficiency and sustainability (Grimaldo and Larsen, 2005; He and Balzano, 2007; Larsen et al., 2018; Polet, 2002). This study is inspired through the challenges that persist in many shrimp fisheries as the sorting ability of rigid bycatch excluder devices remains to be suboptimal. The varying designs of rigid grids such as that of the NG (Isaksen et al., 1992) have had successful implementation in the NEA with the intention to separate large individuals from the catch (He and Balzano, 2007, 2013; R B Larsen et al., 2017a). Investigations concerning the NG functionality were carried out in the Newfoundland *Pandalus* shrimp fishery by Brothers & Boulos (1996). These addressed the unwanted catch of small shrimp and approaches to reduce these with a shrimp sorting system installed after shrimp pass through the NG. The percentage of larger shrimp in the catch was increased when a 10 mm bar spacing was used in the shrimp sorting system compared to an 8 mm bar spacing while smaller shrimp passage remained high. Addressing juvenile shrimp catch remained unattainable in the present study also. The widely recognized findings by Isaksen et al. (1992) observed these tendencies when testing the NG, but agreeable exclusion of marketable sizes of these species led to the success of this selectivity device in the following years.

Prior to the implementation of the NG in NEA fisheries, SPs were already being used to enable fishermen to fish in areas for shrimp where there would otherwise be large volumes of bycatch (Karlsen, 1976). One of the first explorations of the applicability for the SP in the shrimp fishery was by Kurc, Faure, & Laurent, (1965). These experiments were developed further in the Netherlands (Boddeke, 1965) and later experimentation with SPs in the NEA *Pandalus* shrimp fishery in Norway initiated (Rasmussen, 1973). Central challenges during these stages of experimentation were in relation to clogging of the net in areas with high amounts of benthic material and maintaining fish loss while retaining the shrimp of most favorable size (Besançon, 1973; Rasmussen, 1973; Thorsteinsson, 1973). Reducing incidental catch when using a SP persisted as fish such as small redfish (8-14 cm) would simply pass through while larger individuals would build up, become entangled and eventually contribute to clogging of the device (Karlsen, 1976; West et al., 1984).

As the demand for shrimp catches is still high and fishing fleets become more competitive with increasing efficiency in fishing practices, the need from industry to improve the relative target catch and bycatch ratios increases. The research design implemented here has shown itself to be largely successful to portray this. Catch data analyzed using the above techniques has allowed presentation of the results in straightforward and clear manner. Including all four r*logit* models in this study (*rlogit*, *rclogit*, *rclogitS2* and *rclogitS3*) with their added contact parameters was the first time they had been applied in connection with the shrimp fishery to our knowledge. These were applied because traditional models could not describe the data that was collected sufficiently. Furthermore, the applied models allowed for an appropriate range of behavioral as well as length – dependent differences to be accounted for across the species in a systematic way. This is shown by the fit statistics yielded after selecting the most appropriate model using the AIC method. Excepting for shrimp (as outlined in section 3.1), most BRD fit statistics calculated, using their respectively selected models, indicated a good overall fit with the experimental rates.

Furthermore, each set of confidence intervals calculated in respect to each length dependent trend fitted well with the selection curves. Including the more sophisticated *rclogitS2* and *rclogitS3* models also revealed for the first time, that shrimp selectivity data can in fact be best described by the additional modes of contact in the parameters that the *rclogitS3* model accounts for. Thus, the understanding in contact by shrimp with such excluder devices can be added to. The process of portraying the difference between one SP design and the NG, or similarly another SP design, was well achieved through the methodology applied (section

2.2). These curves enabled clear distinction between the effect of altering mesh size or sieving angle between the four designs and likewise, the combined impact of these variables. The curves produced provide a form of map that allows detailed insight into which lengths of shrimp or bycatch are at risk and the degree at which this risk exists. Furthermore, quantitative comparisons can then be drawn between the two potential scenarios (stand-alone or combined efficiencies) as well as superiorities that one SP design may have over another in exclusion or retention ability and an accurate reading of the length classes that these apply to.

Optimal configuration of the SP was observed with the SD4 design. A 300 mm mesh size implemented at 20° compromised high shrimp loss with low bycatch retention most desirably. While angle played an apparent underlying role in improving selectivity (as the combined effect of changing mesh size and angle was more pronounced for shrimp and polar cod (fig. 11, 29), in particular, while changing mesh size at a high angle had no effect (i.e.; SD4-SD1), changing mesh size proved to have the most impact on passage probability for each species. While the effect of angle contributes in some instances to improved selectivity, angle (fig. 11, 17, 23 and 29) does not improve selectivity for the selected species on its own (i.e.; SD2-SD1 and SD4-SD3). Mesh size was also found to be most influential in the German Crangon fishery to improve SP efficiency (Wienbeck and Rauck, 1992). A loss of 40% of shrimp using a 44 mm mesh size was initially documented. When a SP with larger meshes was tested (50 mm, 60 mm and 88 mm) the loss of target catch was just 6-15% (Wienbeck and Rauck, 1992).

Shrimp passage through the SP as depicted in figure 9 and comparatively in figure 10 show some indication by small mesh sizes to give rise to shrimp loss but the upper bounds do not begin at unacceptable levels. It is the lack in exclusion ability of bycatch species, when the

SP replaces the NG in figures 16, 22 and 28 that determine this arrangement to be detrimental to vast majorities of length classes, particularly in the case of cod and polar cod, and therefore, not useful in practice. The success of the SP in the brown shrimp fishery as a stand-alone device may be attributed to the size difference between the bycatch and the target species being higher in these more southern regions (Broadhurst, 2000; Revill and Holst, 2004b), as long as operations are not carried out in popular nursing grounds. Operating a SP in the brown shrimp fishery in Belgium obtained good catch results in comparison to the NG, although these showed to be highly seasonal (44% change in shrimp catch seasonally), but confirmed the applicability of this device, particularly with the positive response received from fishermen (Polet, 2003).

The combined design in the NEA may offer an easy-to-apply added means of escape for fish before they come into contact with the NG for regions containing higher bycatch concentrations. Results for the combined design in this study offer good indication to achieve this. Potential was shown by the combined design to improve bycatches of all species trialed while contributing shrimp loss of just 3% when SD4 was used (fig. 13). Adding this SP improved cod exclusion by at least 30% in central length classes (fig. 19), up to 45% for the smallest and central length classes of redfish (fig. 25) and up to 30% for central length classes of polar cod. The compromise made to select the SD4 design rather than SD1 which improved bycatch reduction beyond that described for SD4 can be observed in figure 32 and 33. Gorman and Dixon, (2015) outline the insistency acted out by industry members to reject any change to selectivity devices that compromises the target catch. Finding a balance between the resulting shrimp and bycatch in this study when selecting optimal configurations is therefore important for its future application. Introducing a new selectivity configuration that adds just 3% in shrimp loss would not be expected to face opposition. Regulations to include either a NG or a SP in the European Crangon fishery has revealed the preference that fishermen have for the SP over the NG in their gear setup due to the ease-of-handling, low complexity and affordability associated with it (Polet et al., 2004; Van Marlen et al., 2001). Concern arises however in relation to reluctance that fishing industry members might have towards a combined design in terms of practicality during trawling, due to the complexity of a second device in the setup (Broadhurst, 2000).

Shrimp loss was not exhibited in the present study possibly due to the size of the meshes used being significantly larger than those from past studies. As shrimp selection is believed to be predominantly length-dependent, the degree of behavioral interaction taking place with this type of device cannot be quantified using this study design. Despite the *rclogtiS3* model selected for shrimp containing enough complexity to account for this, the analysis performed subsequently displayed exclusively the length-dependent relationship with the likelihood of passing through the devices. Due to the minor as well as inconsistent degree of change observed in shrimp and bycatch species as a result of changing SP angle alone, it could be interpreted that behavioral interactions with this device are minimal. As the sieving angle in the net increases it was expected to give rise to increased passage by species holding the capability to react to visual stimuli as the meshes become less accumulated in the vertical plane of sight. But as changes in catch did not reflect the change in sieving angle, this cannot be concluded.

For larger shrimp, their orientation at the time of contact as well as length-dependent avoidance behavior with the device are important factors requiring consideration in selectivity modelling. Pre-conceived notions that shrimp make contact with selectivity devices in a random fashion as a result of the high towing speeds and weak swimming capabilities has been falsified in selectivity studies of krill in Antarctica (Krag et al., 2014). Modelling selectivity of diamond meshes revealed that krill (having quite similar swimming tendencies with shrimp) made contact with the device in a way that suggested that they had an ability to orientate themselves so as to increase the likelihood of escape. The angle of attack that the krill made on the selectivity device was an important factor that should be explored in light of the present study's findings. Shrimp that approach the net at a low angle, as portrayed by Krag et al. (2014), were subjected to a much smaller escape opening. This factor could describe a degree of the shrimp selection when square meshes are used for the effect of changing angle as described above.

Successful implementation of new selectivity devices in the NEA are also largely dependent on their adaptability for the wide length distribution of species, particularly as many deep-water shrimp fishing grounds are established areas for several fish populations. When accounting for this, combining the NG with the SP configured with larger (300 mm) meshes shows the best potential for application (fig. 32). In the Dutch beam trawler fleet of the Crangon fishery, a SP that separated shrimp into an upper codend and fish into a lower counterpart was able to improve shrimp catches by 35.4% (in weight), with 13.8% less undersized shrimp and an 82.7% reduction of bycatch (Boddeke, 1965). Collective experiments throughout 547 hauls in the European Crangon fishery, a part of the DISCRAN project (Reduction of Discards in Crangon Trawls) (Van Marlen et al., 2001) found acceptable bycatch reduction as well as shrimp loss to be attained using a 77 mm mesh size in the SP. Trials in Belgium for this project however (77 mm mesh size) observed a loss of shrimp on average of approximately 37%. This could have been due to fishery-specific factors as well as seasonal differences. Comparatively, Revill and Holst (2004b) reported that bycatch exclusion in the UK Crangon fishery was high while shrimp exclusion was maintained low when SPs with just 53 mm, 64 mm and 68 mm mesh sizes were used. Despite the setup differences unique to each study, some common ground can be established in the consequence of changing mesh size. Significant differences observed when meshes were in the range of 200 mm and 300 mm may have been unexpected in respect to the articles mentioned above but considering the diversity in size and species in this fishery some clarification may be made.

This capability of the SP to adopt such large meshes so adequately in terms of selectivity alludes strongly to a behavioral factor likely to be affecting some species. Significant results for polar cod were calculated for length classes as small as 7 cm. This implies a likelihood for fish to be interacting with the net in a way that is not solely length-based, as, in order to reach the escape opening above the SP, there is a requirement for a certain degree of input in swimming ability by the fish to avoid the large meshes. Broadhurst (2000) describes the importance of behavioral, morphological and physiological differences between species in determining their escape probability. The size range able to be targeted by the added net for cod in this study was much narrower (proportionately) to that observed for polar cod, but still indicated up to 30% higher exclusion when the SP was included. The implementation of a BRD that excludes fishes via a behavioral response requires extensive testing as they must harness single or multiple stimuli (Broadhurst, 2000), thus explaining differences between these two species requires an array of behavioral variables to be considered.

Some potential exists through harnessing differences in swimming patterns of juvenile fish in relation to the shrimp for selectivity purposes (Rose and Hammond, 2014; Sistiaga et al., 2017). BRDs inserted in the aft section of the trawl that rely on behavioral responses may be constrained as many small fishes arrive there already relatively fatigued. But due to the towing speed usually used in shrimp trawls being faster than that of most small fish (Beamish, 1978), positioning the BRD in the section of the trawl where relative water flow is lowered (Broadhurst and Kennelly, 1997) or alternatively including components near the BRD that reduce water flow (Rogers et al., 1997) may assist in escapement-related behavior to occur. Boddeke (1965) was able to separate mature shrimp from juveniles with the addition of an upper and lower codend in a modified French otter shrimp trawl, harnessing some identified modes of contact differences between the two groups. In spite of this, selecting against small shrimps in the Gulf of Maine pink shrimp fishery using an added size sorting grid in front of the NG had detrimental effects simultaneously on catch rates of the target shrimps (He and Balzano, 2007). Although it is unlikely to be significant (due to the limited obstruction by the large meshes), the square meshed SP may contribute to differences in water flow, assisting the smaller, less – capable bycatch individuals towards the escape opening that would otherwise not have the swimming capacity to do so. Eayrs, (2007) describes the potential for an added tactile response due to the flow of water through a selectivity device when selecting against bycatch. Those that escape without being selected for based on their length must have the swimming capability in a moving trawl to turn in the direction of tow and move towards the opening. Escapement of larger individuals becomes much more dependent on size rather than behavior due to the obstruction by the meshes. Regarding those in central length classes however, if the selective device is not inserted too far into the aft of the codend, the potential to improve exclusion of these may be much more plausible with an appropriate SP.

The possibility for combining BRDs to target a wider interval of length classes has been explored by coupling devices that harness specifically behavioral characteristics with those that function through length-based selectivity, together (Karlsen and Larsen, 1989; Kenney et al., 1990). Application of the combined setup described in the present study could be improved if, for example, the length interval of cod excluded further could be increased. Karlsen and Larsen, (1989) was able to exclude smaller shrimp, snake blenny (*Lumpenus lampretaeformie, Lumpenidae*) and polar cod more often by releasing individuals through added HH panels (35 mm diamond mesh hung on the bar) to traditional Norwegian shrimp

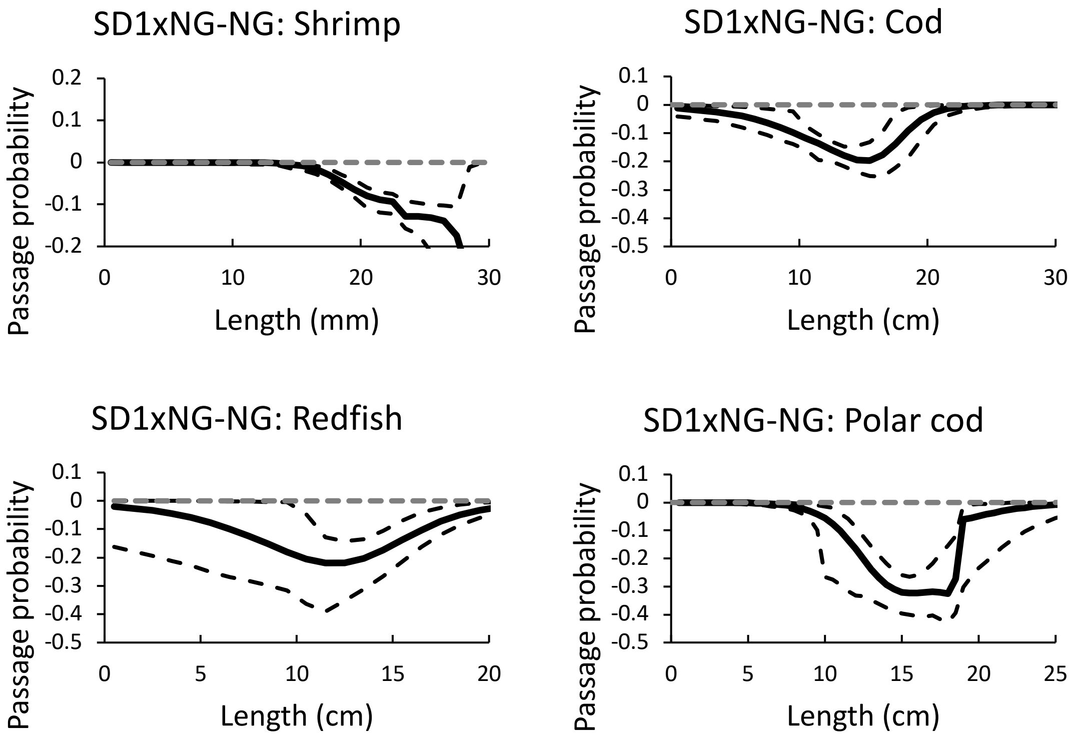

Figure 32: Passage probability comparisons for shrimp, cod, redfish and polar cod between the combined setup using SD1 and the NG stand - alone (solid black line) with 95% confidence bands (dashed black line).

trawls configured with the NG. This configuration was able to improve shrimp retention while additionally excluding a large percentage of the bycatch. Kenney et al. (1990) added various excluder devices (such as horizontal separator twine panels and deflecting grids) to traditional prawn trawls to target the behavior of finfish being retained. Investigations into the ability for behavioral BRDs to operate posterior to the grid (Broadhurst et al., 1997; Watson, 1996) concluded varied success as the majority of the catch was more impacted by the NG due to the species composition in the fishery as well as external factors. But bycatch escapement was maximized in these studies when a NG was followed by a fisheye excluder (a rigid grid inserted in the top section of the codend harnessing reduced water flow to release fish). While the SP allows for fish to actively swim up and out of the trawl opening, it functions chiefly through passive selection of fish. The fisheye excluder relies on a fish's

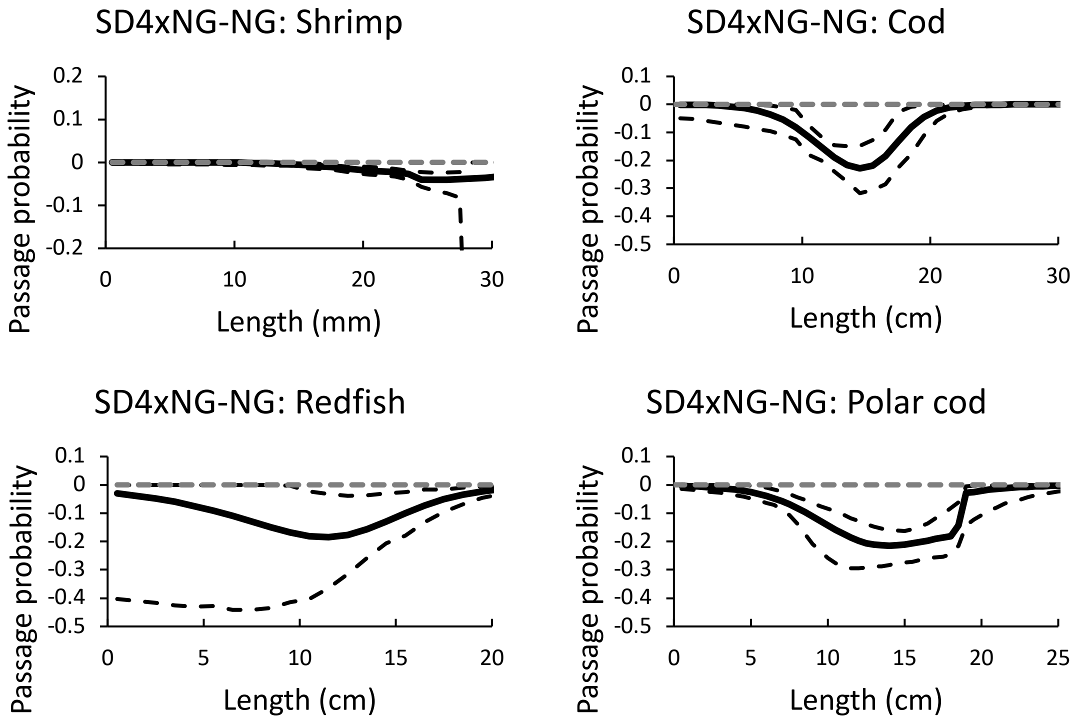

Figure 33: Passage probability comparisons for shrimp, cod, redfish and polar cod between the combined setup using SD4 and the NG stand - alone (solid black line) with 95% confidence bands (dashed black line).

ability to harness the flow of water as a primary means to escape.

Limited studies address the use of a SP followed by a NG in the shrimp fishery. In the present study, shrimps above 18 mm begin to be released by the NG. When the SD4 is added, the selection curve flattens significantly for larger shrimps, allowing approximately 5% more passage through the device. The relative reduction in exclusion of the NG alone of redfish and polar cod makes these species more vulnerable if no selection device is added. The combined design curves for comparisons between species in figure 33 highlight the potentially wider interval of length classes that may be addressed under this design's implementation.

The catch curves presented indicate a strong inability of both selectivity devices to target bycatch below 10 cm. A biological and economic modelling exercise in the brown shrimp fishery (Revill et al., 1999; Revill, 2000) noted that the risk associated with fishing these smaller length classes may be lower than expected and that more consideration for the next largest length class should be had as targeting these excessively by the BRDs contributed the worst impact on future stock durability. If the exclusion of the lowest length classes of species in this study can be disregarded for this reason, the value of the SD4 may be added to. Developments of varying designs of BRDs have accelerated to address the problem of juvenile bycatch however. Over-fishing of these vulnerable year classes before they are able to recruit can be elemental in some fisheries to insure the future availability of certain stocks.

The potential for SPs to be a more effective tool in avoiding capture of benthic species was acknowledged (Revill and Holst, 2004b). The believed capabilities of the SP to release benthic organisms and other material that enter the trawl are high and would be beneficial for reducing catch quality as well as unnecessary compression of the target catch in the codend. This is due to the nature of the SP being able to separate certain catch immediately after capture, thereby improving its chances of survival, and preventing accumulation of it in the codend.

A susceptibility for soft BRDs to become clogged should also be noted, particularly when meshes are too small (Polet et al., 2004; Wienbeck, 1998), as excessive marine detritus can build up as well as the occurrences of gilling and tangling by fish in the SP meshes. Consequently this can add to exclusion of target catch with fewer openings for shrimp to pass through, obscuring the device’s measured effectiveness (Boopendranath et al., 2010). Awareness of this occurring during the present study’s trials was not known though, possibly owing to the large meshes used, significantly larger than those trialed in publications where clogging became problematic. If clogging of the SP can be averted, the motivation by industry members to adopt the device may also be improved. The growing momentum of concepts such as environmental stewardship and ecosystem-based management (Fletcher et al., 2010) has been observed to be a good incentive for industry to accept technologies that promote this.

Furthermore, particularly in tropical nations, non-selective fishing techniques threaten the ecological structure within the food web as shrimp fisheries can occupy highly diverse ecosystems (Stobutzki et al., 2001). Introducing a soft panel combined with a rigid grid configuration in these regions could circumvent destructive fishing practices that threaten this diversity. Ethical implications also arise in regions where shrimp fisheries compete for resources directly depended upon by developing societies in their respective regions as commercial trawl fleets catch too much bycatch (Alverson, 1994). Encouraging the uptake of a SP could raise the depleting value of the shrimp fishery in these regions as improved selectivity will improve the quality of the catch while keeping larger proportions of their associated bycatch species untouched for utilization by communities that depend on them.

The alterations made to the selectivity device presented in this study offer some promising results and, based on uptake success in other fisheries, would be a change that would be welcomed by fishery managers as well as vessel operators (Van Marlen et al., 2001). The dependence of fishing industry on science initiatives to develop more sustainable methodologies for fisheries practice is expected to grow in the coming years (Crowder et al., 2008; Dixon et al., 2013; Pikitch et al., 2004). Historically, the most successful improvements made to selectivity devices used today have been through those that provide the maximum benefit at the lowest cost to the fishery, literally and figuratively speaking. The improvement observed by replacing the currently used NG with the SP would be inefficient to reduce discards, but the combined alternative showed improvements in bycatch reduction while not impacting the catch already achieved by the NG. While soft BRDs still require extensive testing and reporting through academia, they offer an attractive alternative to bycatch reduction techniques currently used. This is through their ease-of-handling, affordability for the commercial industry and potential to improve the quality of the catch.

4.1 Recommendations for the future

- Future analysis of catches from these SP configurations should include the tendencies for flat fishes to be excluded. American plaice is a common species occurring in the NEA and would be expected to behave very differently due to its physiology. Wienbeck and Rauck (1992) reported that mesh sizes exceeding 70 mm, while having good potential to retain shrimp, give rise to a much higher retention of flatfish in the codend. This may pose an added downfall to catch quality and sorting efficiency if implemented in subareas 1 and 2. Data collected from American plaice was not included in this study due to time and reporting restrictions involved with the analysis.
- Shrimp selectivity has been shown to not be as simple as expected. Adopting more complex models in modelling of shrimp selectivity in the future may enable more thorough and concise understanding of how BRD designs interact with the target catch during trawling operations. The bootstrap intervals implementing the *rclogitS3* model, despite their complex theory, enabled more clear understanding of shrimp selection to be made from the data.
- Replacing the NG with SP was not observed to incur high shrimp loss in all four designs. With this knowledge, exploring the potential for viable shrimp catch using the SP combined with other technologies that do not impact shrimp, but rather the bycatch alone could provide a more valuable contribution to the final product.
- Additionally, including the codend selectivity in the analysis would be a valuable extension to this study. This could be displayed by multiplying the combined selectivity

calculated here with that arising in the codend in order to attain total escapement from the gear. Quantifying shrimp loss and/or consequential survival through the codend may be an important factor affecting the final catch. This has been done in past research but publications with a third compartment when a SP is tested are limited.

- Underwater video recordings added in the analysis proceedings could help to facilitate this as well as build a more detailed map of the behavioral responses that this device arrangement causes in the target as well as the bycatch species.
- Importance for further understanding of this selectivity device for application in this fishery would demand for further testing in different areas of subareas 1 and 2. This study took place just in one large fjord in the west of Svalbard. Areas composed of differing catch compositions and abiotic factors during operation of the device may give rise to different trends seen in catches of bycatch as well as shrimp.
- As shown, the influence of angle on shrimp and bycatch selectivity is minimal. Knowledge on how the angle of a SP affects exclusion is incomplete in academia (Herrmann pers. Comm) and demands more understanding in order for this device to be successfully applied. The function of the SP as a device selecting catch based on size is well recognized but there is belief that behavioral influence is involved during selectivity by this device as well (Herrmann pers. Comm). Changes in the selectivity device's angle during setup could affect this for certain species as a change in angle may change its appearance to the fish as it approaches the device due to the shadowing of the horizontally-facing lines.
- Replication of the testing done is most definitely a requirement to improve statistical guarantee in the results, but this should also be spread to include a range of fishing grounds as well as seasons. As noted previously (Polet et al., 2004), variation can be high throughout trials in different times of year.

- Gaps in the knowledge also surround the influence of catch composition when the SP is used and how this device interacts under a diversity of behaviors as well as lengths and physiologies. This would demand a wide – spanning data set but would add great value to chances of application throughout tropical fisheries.

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