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Can a large-mesh sieve panel replace or supplement the Nordmøre grid for bycatch mitigation in the northeast Atlantic deep-water shrimp fishery?

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ABSTRACT

The Nordmøre grid is the principle bycatch mitigation device in many shrimp trawl fisheries. However, in several of these fisheries, bycatch is a problem because small sized fish can pass through the grid and enter the codend together with the targeted shrimp. One such fishery is the Northeast Atlantic deep-water shrimp (*Pandalus borealis*) fishery, where the use of a Nordmøre grid is mandatory. In this fishery, redfish (*Sebastes* spp.) and polar cod (*Boreogadus saida*) are two common bycatch species. Redfish is a commercially important species that at times is captured in great numbers, whereas polar cod is a threatened species that can also be caught in high numbers. Sieve panels are bycatch reduction devices commonly used in shrimp fisheries and their potential to replace or supplement the Nordmøre grid in the Northeast Atlantic deep-water shrimp fishery is of interest. We investigated the size selectivity of redfish, polar cod and deep-water shrimp for the Nordmøre grid and four sieve panel configurations differing in mesh size (182 and 286 mm) and inclination angle (10 and 20°). The sieve panels were unable to replace the Nordmøre grid as a stand-alone device due to greater catches of the bycatch species. However, combining the two devices provided promising results. Specifically, when a large-mesh sieve panel was placed in front of the Nordmøre grid, 20–40% fewer small redfish and polar cod in a specific size range entered the codend, while the loss of targeted shrimp was less than 5%.

1. Introduction

The introduction of the Nordmøre grid in 1991 was one of the main breakthroughs regarding bycatch reduction in shrimp trawl fisheries (Isaksen et al., 1992). The device was not only applied in Scandinavia, where it was originally introduced, but also in many other countries (e.g. He and Balzano, 2007; Thorsteinsson, 1995). Although the introduction of the Nordmøre grid and other types of sorting grids have reduced the fish bycatch problem in shrimp fisheries considerably, small sized fish such as juveniles of various species are still able to pass through the grid and enter the codend together with the targeted shrimp (He and Balzano, 2013, 2007; Larsen et al., 2018a). In some fishing grounds the bycatch issue persists, seriously affecting the activities of commercial trawlers. When the number of small fish of certain species caught with the shrimp gets too high, the respective fishing region can be closed. Furthermore, high concentrations of small fish in the catch can imply inconveniences such as additional sorting work on board and reduction of shrimp quality due to the longer catch processing time (Noell et al., 2018). Finally, high juvenile mortality can have consequences on the fish stocks in addition to the environmental and ethical implications they impose (Chopin et al., 1996).

In the Northeast Atlantic deep-water shrimp (*Pandalus borealis*) fishery, the compulsory selectivity system is composed of a Nordmøre grid with a maximum bar spacing of 19 mm, and a codend with a minimum mesh size of 35 mm (Fig. 1) (Larsen et al., 2018a). Despite the implementation of this selectivity device, high numbers of juvenile fish catch are still frequent. Redfish (*Sebastes* spp.) and polar cod (*Boreogadus saida*) are bycatch species that currently receive special attention in this fishery. Redfish is a commercially important species in the Northeast Atlantic that is slow growing and at times can be caught in

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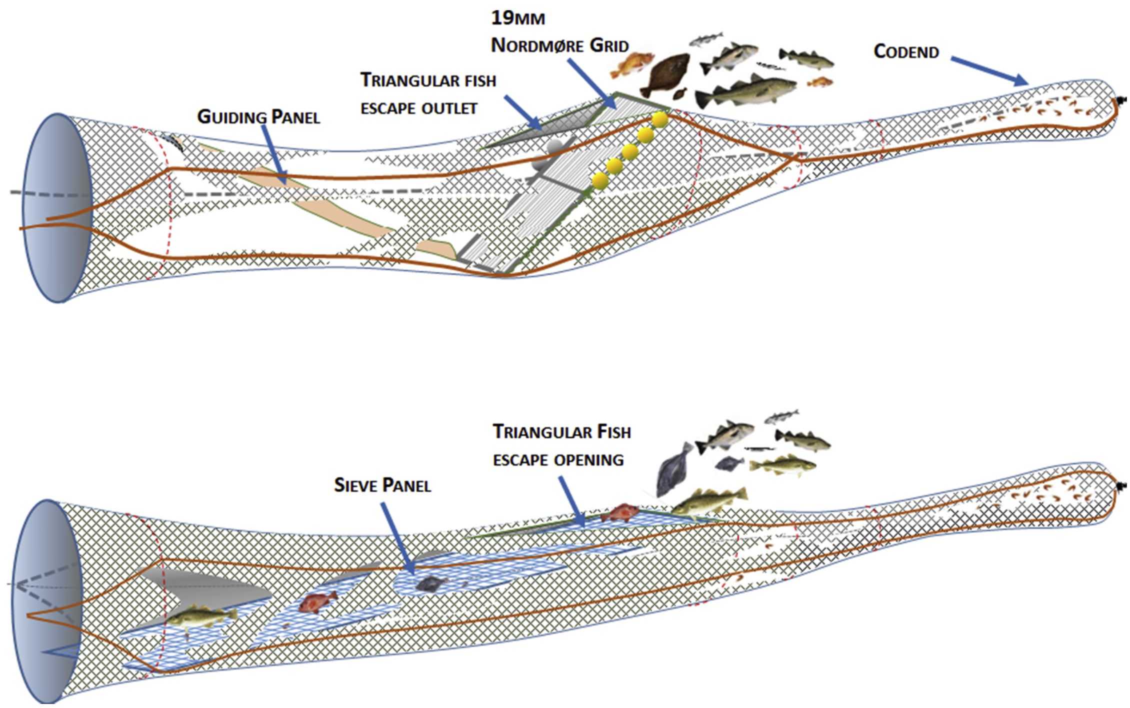

Fig. 1. Working principle of the Nordmøre grid (above) and a sieve panel (below) as bycatch excluders.

high numbers by shrimp trawlers. This leads in many cases to area closures when the maximum acceptable bycatch levels are met, which for redfish is 3 individuals per 10 kg of shrimp (Norwegian Directorate of Fisheries, 2011). The capture of polar cod should be avoided as it is considered a threatened species (Fernandes et al., 2015). However, it is at times caught in great numbers by shrimp trawlers.

Efforts to reduce juvenile fish bycatch in this fishery concentrate mostly on modifications to the Nordmøre grid since most sorting takes place at this point in the gear (e.g. Grimaldo and Larsen, 2005; Grimaldo, 2006; Larsen et al., 2018b). However, other devices that can supplement the selection process by the grid have also been tested in recent years (Larsen et al., 2018c). Together with grids, sieve panels are the most commonly used fish bycatch excluding devices in European shrimp fisheries (CEFAS, 2003; Polet et al., 2004). Sieve panels follow essentially the function of the Nordmøre grid (Fig. 1), with square meshed netting used instead of the rigid metal structure. Recently, Larsen et al. (2018d) investigated and compared the effect of an experimental sieve panel and a Nordmøre grid in the Northeast Atlantic deep-water shrimp fishery. However, the results obtained by Larsen et al. (2018d) using 144 mm square meshes in the sieve panel, installed in front of the grid with an inclination angle of ca. 9°, showed that this design could not be applied in the fishery as the loss of commercial-sized shrimp was between 37 and 56%. Nonetheless, Larsen et al. (2018d) recommended the testing of other sieve panel designs with larger mesh sizes and higher operational angles, because the codend entry probability of juveniles of several commercially important species was significantly reduced when the sieve panel was installed in front of the Nordmøre grid.

In the present study, we tested two new sieve panels with different mesh sizes (each installed in front of the Nordmøre grid) and two different working angles, making a total of four designs. The main objective was to investigate whether a sieve panel could replace or supplement the selective properties of the Nordmøre grid on redfish and polar cod in the Norwegian trawl fishery targeting deep-water shrimp. Specifically, the investigation aimed at answering the following research questions:

- can sieve panel designs different to those used by Larsen et al. (2018d) avoid the associated shrimp loss and thereby potentially represent a realistic device for bycatch mitigation in the Northeast Atlantic deep-water shrimp fishery?
- which sieve panel size and angle configuration provides both improved bycatch reduction and retains a commercially acceptable amount of shrimp?
- do the sieve panel and Nordmøre grid need to be combined to reduce juvenile fish bycatch while maintaining commercial catches of shrimp?

2. Material and methods

2.1. Experimental design

Data collection was carried out on board the research vessel (R/V) "Helmer Hanssen" (LOA 63.8 m, 4080 HP), a trawler owned and operated by the Arctic University of Norway. The research cruise took place during the 6th–17th of November 2017 within the fishing grounds along the western side of Svalbard (N78°15′–E12°31′). As it took place during the polar night period, all fishing was carried out in the dark.

Fishing tows were carried out with a commercial gear and setup that is typically used for shrimp trawling in the Northeast Atlantic. This was comprised of an Egersund Polar 2800# trawl and a pair of Injector Scorpion trawl doors (8 m^2 and 3100 kg each). The netting of the trawl was made of polyethylene (PE) in the wing sections and polyamide (PA) in the rest of the trawl. The trawl and doors were connected by 40 m 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 59 m long groundgear composed of five rockhopper sections (30 m long in total) with rubber discs that had a diameter (Ø) of 53 cm, and 14.5 m long chains (Ø19 mm) with five Ø53 cm steel bobbins. Scanmar distance and height sensors were attached to the trawl to monitor its geometry during each tow. The belly of the trawl was equipped with a four-panel standard Nordmøre grid section (Norwegian Directorate of Fisheries, 2018). The grid was made from stainless steel (1.5 m high and 0.75 m wide) and was mounted to maintain an angle of approximately 45° during fishing. The bar spacing of the Nordmøre grid was 18.8 mm ± 0.4 mm

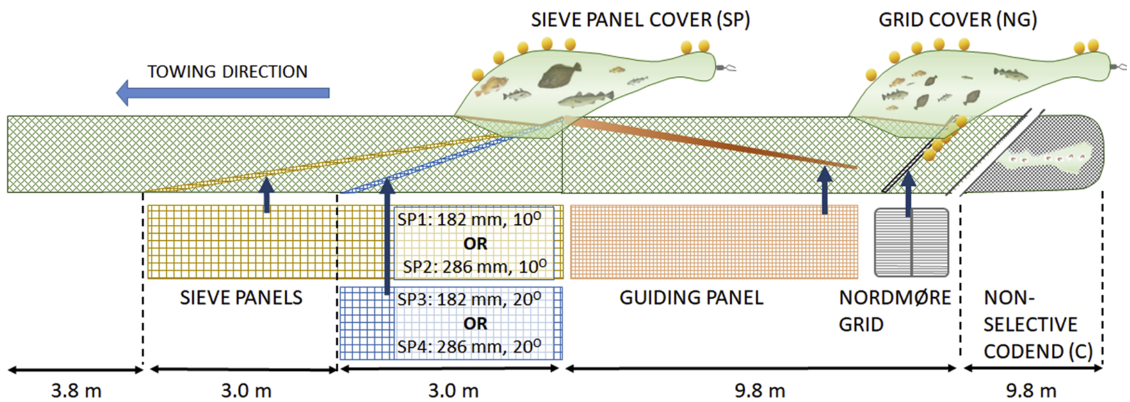

Fig. 2. The experimental gear section with a sieve panel (two angles), a Nordmøre grid, the two escape outlet covers and a non-selective codend used during the trials.

(mean ± standard deviation (SD)).

The grid section had an escape outlet in the upper panel. This outlet measured 35 meshes long and 70 meshes wide, forming a triangle shape approximately 1.6 m long and 0.75 m wide. The 6.5 m long sieve panel, configured with square meshes of either a 182 mm (SD = 1.2 mm) or a 286 mm (SD = 1.1 mm) mesh size (full mesh size, equal to two times the mesh bar length) at either a 10° or 20° angle, was mounted in front of the grid section (Fig. 2). A triangular escape outlet was cut above the sieve panel with dimensions as for that of the Nordmøre grid escape outlet.

The outlets were fitted with small meshed covers (mesh size 18.9 mm ± 1.2 mm) in order to collect all sizes of fish and shrimp escaping through them (Fig. 2) (Wileman et al., 1996). To ensure that the two outlets were not blocked by the covers during trawling, seven detachable Ø200 mm plastic floats supported each cover (each with a 2.7 kg lifting capacity) (Fig. 2). Small individuals that were able to pass through the sieve panel and consecutively the Nordmøre grid were collected in the codend, which was fit with a small meshed inner-net (mesh size 18.5 ± 0.9 mm).

Directly after each tow, the catch from each of the three compartments (sieve panel cover (*SP*), Nordmøre grid cover (*NG*) and non-selective codend (*C*)) was sorted by species, and all redfish and polar cod present were length-measured to the nearest centimetre below. No subsampling was carried out for these two species but the shrimp had to be subsampled. In these instances, a random 1 kg portion of shrimp catch from each compartment was taken. The carapace length for each shrimp was measured to the nearest millimetre below using callipers.

2.2. Modelling and estimation of selection processes in the sorting system

The probability for a fish or shrimp to be retained in the non-selective codend upon entering the experimental gear section depends on the probability that it passes through the sieve panel towards the Nordmøre grid, and that it subsequently also passes through the grid and into the codend. Thus, the combined size selection process in the sorting section with both the sieve panel and the Nordmøre grid installed can be described by the following dual sequential model:

$$p_{combined}(l, \boldsymbol{\nu}_{SP}, \boldsymbol{\nu}_{NG}) = p_{SP}(l, \boldsymbol{\nu}_{SP}) \times p_{NG}(l, \boldsymbol{\nu}_{NG}) \quad (1)$$

Where $p_{combined}(l)$ is the overall retention probability of the selection system, $p_{SP}(l)$ is the passage probability through the sieve panel, and $p_{NG}(l)$ is the passage probability through the Nordmøre grid conditioned passage through the sieve panel. l is the total length for the fish or the carapace length for the shrimp, $\boldsymbol{\nu}_{SP}$ is a vector of parameters for the parametric model used to describe the sieve panel passage probability and the $\boldsymbol{\nu}_{NG}$ is a vector of parameters for the parametric model used to describe the Nordmøre grid passage probability (conditioned entering the zone of the grid).

As different species have different morphological characteristics and behaviours, model (1) needs to be applied separately for deep-water shrimp and the two bycatch fish species. Since we are interested in how the sieve panel and the Nordmøre grid perform on average, the analysis was made for data summed across hauls. Thus, expressions (2) and (3) were minimised, which is equivalent to maximizing the likelihood for the observed data:

$$-\sum_{i=1}^{ms}\sum_{l}\left\{\frac{nSP_{il}}{qSP_i} \times ln(1.0 - p_{SP}(l, \boldsymbol{\nu}_{SP})) + \left(\frac{nNG_{il}}{qNG_i} + \frac{nC_{il}}{qC_i}\right) \times ln(p_{SP}(l, \boldsymbol{\nu}_{SP}))\right\} \quad (2)$$

$$-\sum_{i=1}^{m}\sum_{l}\left\{\frac{nNG_{il}}{qNG_i} \times ln(1.0 - p_{NG}(l, \boldsymbol{\nu}_{NG})) + \frac{nC_{il}}{qC_i} \times ln(p_{NG}(l, \boldsymbol{\nu}_{NG}))\right\} \quad (3)$$

Where nC_{li}, nSP_{li}, and $nNG_{li}$are the number of individuals length-measured belonging to length class l in haul i in the codend, sieve panel cover and Nordmøre grid cover, respectively. qC_i, qSP_i, and $qNG_i$are subsampling factors that quantify the fraction of individuals length-measured caught in the respective compartments in each individual haul. The outer summation in (2) is over the hauls conducted (*ms*) with the specific sieve panel investigated and the inner summation is across the length classes in the data. The outer summation in (3) is across all hauls conducted since the sieve panel passage data is not present in (3) and the Nordmøre grid configuration was identical for all hauls conducted. Expressions (2) and (3) are applied independent of each other to estimate the passage probability respectively for the sieve panels and the Nordmøre grid.

To model the length-dependent passage probabilities for the sieve panels and the Nordmøre grid, we considered four different models (Appendix, Eq. (A6)):

$$p(l, \boldsymbol{\nu}) = \begin{cases} rlogit(l, \boldsymbol{\nu}) \\ rclogit(l, \boldsymbol{\nu}) \\ rclogitS2(l, \boldsymbol{\nu}) \\ rclogitS3(l, \boldsymbol{\nu}) \end{cases} \quad (4)$$

The models in (4) and their parameters are thoroughly described in the appendix. $rlogit(l, \boldsymbol{\nu})$ (Eq. (A2)) and $rclogit(l, \boldsymbol{\nu})$ (Eq. (A3)) are similar in structure to those Larsen et al. (2018d) applied to describe the length-dependent passage probability through a smaller mesh sieve panel. Further, $rclogit(l, \boldsymbol{\nu})$ has been applied in several studies to model grid passage probability in shrimp fisheries (Larsen et al., 2017, 2018a,b) and escape through grids in whitefish trawl fisheries (Sistiaga et al., 2010; Herrmann et al., 2013; Grimaldo et al., 2015). Therefore, these models are the natural starting point for modelling the sieve panel and Nordmøre grid length-dependent passage probabilities in this study. However, an initial inspection of the data indicated the need for more complex and flexible models to describe the length-dependent passage probability for some cases. Therefore, $rclogitS2(l, \boldsymbol{v})$ (Eq. (A4)) and $rclogitS3(l, \boldsymbol{v})$ (Eq. (A5) in (4)) were also considered as candidates to describe the passage probability through the sieve panels and the Nordmøre grid.

The implications above mean that we considered four different models for $p(l, \boldsymbol{v})$ for each species and for each of the different sieve panel configurations and the Nordmøre grid passage processes. The combined process (a sieve panel followed by the Nordmøre grid) was then estimated based on the models independently selected for the sieve panel and the Nordmøre grid used in (1).

The estimations for the sieve panels were conducted using each of the models (4), minimizing expression (2) and then selecting the model resulting in the lowest AIC value (Akaike, 1974). Similarly, estimation of the Nordmøre grid size selectivity was conducted testing each of the models (4) minimizing expression (3), and then selecting the model resulting in the lowest AIC value.

Determining the ability of the selected models to describe the experimental data 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 were selected for each sieve panel and the Nordmøre grid and the corresponding model parameters were estimated, the obtained $p_{panel}(l, \boldsymbol{v}_{panel})$ and $p_{grid}(l, \boldsymbol{v}_{grid})$ were applied to quantify the combined size selection and stand-alone size selection in terms of the length-dependent probability for passing through the devices.

Efron 95% percentile confidence bands (Efron, 1982) for the sieve panel and Nordmøre grid passage probability curves were obtained using a double bootstrap method that accounts for both between-haul variation in the process and within-haul uncertainty in the estimation (Herrmann et al., 2012). For each species analysed, 1000 bootstrap repetitions were conducted to estimate the 95% confidence limits (consult Larsen et al., 2017 for further details). For the combined process $p_{combined}(l)$ as modelled by (1), the 95% confidence bands were calculated based on the two bootstrap population results for $p_{SP}(l)$ and $p_{NG}(l)$. As they are obtained independent from each other, two new bootstrap populations for $p_{combined}(l)$ were created using:

$$p_{combined}(l)_i = p_{SP}(l)_i \times p_{NG}(l)_i \; i \in [1\ldots1000] \tag{5}$$

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 (5) using two independently generated bootstrap files (Herrmann et al., 2018).

To infer the effect of replacing the Nordmøre grid with a sieve panel, the difference in the length-dependent passage probability was $\Delta p(l)$estimated:

$$\Delta p(l) = p_{SP}(l) - p_{NG}(l) \tag{6}$$

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

$$\Delta p(l)_i = p_{SP}(l)_i - p_{NG}(l)_{\,i} \; i \in [1\ldots1000] \tag{7}$$

Finally, based on the bootstrap population, Efron 95% percentile confidence limits were obtained for $\Delta p(l)$ as described above. A similar technique was used for evaluating the effect of supplementing the Nordmøre grid with each of the sieve panel designs and for the comparisons made between the sieve panels.

All analyses described above were conducted using the analysis tool SELNET (Herrmann et al., 2012).

3. Results

3.1. Modelling the catch data

During the experimental period, 36 hauls were conducted: 11 with *SP1*, 10 with *SP2*, 5 with *SP3* and 10 with *SP4*. Totals of 13,604 shrimp, 1226 redfish, and 4166 polar cod were length measured (Table 1).

From the four models tested, the model with the lowest AIC value was chosen to represent the data for each device and species. Fit statistics were calculated accordingly (Table 2). The fit statistics calculated were supportive for all species except for the shrimp. For the shrimp, p-values obtained for the sieve panel designs were low (< 0.05) (Table 2), but this was most likely a consequence of over-dispersion in the experimental catch portioning data that resulted from working with pooled and subsampled data with low sampling rates (Alzorriz et al., 2016; Larsen et al., 2017). This is supported by there being no clear pattern in the deviations between the catch data and the fitted grid passage probability curves for shrimp (Fig. 3). Thus, the applied model can be regarded as legitimate in presenting the length-dependent passage probability (Larsen et al., 2018a).

3.2. Passage probability through the Nordmøre grid and the sieve panel configurations

The shrimp passage probability was high for the Nordmøre grid implying a low loss when considered stand-alone (Fig. 3). The two sieve panels with the 286 mm mesh showed the greatest potential to replace the Nordmøre grid as a result of their ability to maintain shrimp catches. This was between 0.96–0.97, and the loss only occurred for the largest length classes (Fig. 3) and compared to the Nordmøre grid there was no additional loss of shrimp (Fig. 4). Shrimp loss began in smaller length classes when the two 182 mm sieve panels were used, where up to 15% of the larger individuals were released (Fig. 3) and for SP1 there was a significant increase in loss compared to the Nordmøre grid (Fig. 4).

The bycatch reduction of the Nordmøre grid could not be matched by the sieve panels (Figs. 3 and 4). Further, a clear difference could be observed between the four configurations. For redfish, replacing the Nordmøre grid with any of the sieve panel designs lead to a significant increase in codend entry probability for a design dependant size span. This increase was dramatic for the 286 mm mesh sieve panel designs. For example, redfish sized between 20 and 30 cm (TL) have an increased codend entry probability of at least 0.35 (Fig. 4). The Nordmøre grid does not allow any entry of these sizes of redfish into the codend (Fig. 3). Observed codend entry through the 182 mm sieve panel reduced in comparison but was still significantly higher than for the Nordmøre grid (Fig. 4). For polar cod, we see a dramatic increase in the codend entry probability for sizes above 16 and 18 cm using the 286 mm mesh sieve panel at 10° and 20° respectively. We did not observe this pattern in codend entry for the 182 mm mesh sieve panel for either angle.

3.3. Effect of changing mesh size and angle of the sieve panel

The effect of changing the sieve panel mesh size or angle could be inferred from Fig. 5. The Shrimp passage probability was significantly

Table 1
Summary of the number of individuals for shrimp (*Pandalus borealis*), redfish (*Sebastes* spp.) and polar cod (*Boreogadus saida*) that were length-measured in each haul. *nSP*, *nNG* and *nC* denote the number of individuals measured from the sieve panel cover, the Nordmøre grid cover and the codend with a small-meshed inner net, respectively. Values in () are subsampling ratios in percentages (weight ratio), which are provided only if subsampling did take place. "*" denotes counts that were not attainable.

				Deep-water shrimp			Redfish			Polar cod		
Haul ID	*SP* ID	Mesh size (mm)	Incl. angle (º)	*nSP*	*nNG*	*nC*	*nSP*	*nNG*	*nC*	*nSP*	*nNG*	*nC*
1	SP1	182	10	894 (10.6)	5407 (36.29)	238 (1.4)	61	9	4	23	30	147
2	SP1	182	10	1410 (16.39)	2764 (25.13)	186 (1.43)	55	7	3	24	10	72
3	SP1	182	10	1492 (11.3)	2976 (20.96)	209 (1.14)	52	5	4	31	16	67
4	SP1	182	10	863 (7.31)	4923 (38.16)	171 (1.01)	40	8	2	21	12	58
5	SP1	182	10	815 (8.49)	4647 (45.56)	323 (1.7)	26	12	3	19	4	57
6	SP1	182	10	1058 (8.67)	3865 (29.73)	257 (1.24)	58	8	6	40	12	72
7	SP1	182	10	1124 (10.04)	6153 (49.26)	182 (1.19)	31	8	1	43	19	83
8	SP1	182	10	1630 (14.17)	3113 (30.22)	173 (1.33)	23	1	3	25	24	100
9	SP1	182	10	1071 (10.5)	2365 (16.31)	158 (0.98)	24	4	0	31	33	91
10	SP1	182	10	614 (5.39)	20.29 (17.49)	173 (0.96)	29	5	4	19	15	88
11	SP1	182	10	2343 (18.16)	2373 (29.3)	208 (1.68)	38	9	5	32	14	77
12	SP2	286	10	7276 (94.49)	11,231 (89.85)	684 (5.03)	17	10	2	2	5	23
13	SP2	286	10	*	*	*	17	21	9	19	25	111
14	SP2	286	10	5300 (35.57)	4830 (30.38)	142 (0.95)	9	19	5	30	76	107
15	SP2	286	10	5961 (43.51)	3457 (26.19)	252 (1.68)	23	9	4	17	24	48
16	SP2	286	10	3207 (30.54)	4416 (37.11)	222 (1.66)	8	11	2	14	22	80
17	SP2	286	10	3308 (24.69)	2452 (19.16)	249 (1.37)	6	20	2	30	20	59
18	SP2	286	10	1892 (14.33)	3730 (28.69)	161 (1.05)	17	16	7	4	22	96
19	SP2	286	10	2594 (20.75)	17,282 (89.8)	222 (1.52)	12	6	3	25	9	71
20	SP2	286	10	6021 (44.6)	3660 (27.52)	342 (2.18)	15	12	1	12	29	56
21	SP2	286	10	8664 (91.2)	3406 (28.38)	310 (1.87)	5	11	1	6	16	90
22	SP3	182	20	2820 (24.74)	7049 (81.02)	177 (1.36)	20	2	2	28	5	30
23	SP3	182	20	5617 (49.71)	6200 (100)	536 (2.82)	13	2	3	0	6	64
24	SP3	182	20	4898 (45.78)	5500 (100)	411 (2.27)	11	1	0	12	7	63
25	SP3	182	20	4345 (49.38)	2415 (17.63)	292 (1.79)	14	7	0	7	12	28
26	SP3	182	20	1668 (12.54)	7700 (100)	969 (6.17)	18	1	2	15	8	29
27	SP4	286	20	8768 (88.57)	4877 (82.66)	246 (1.86)	15	10	0	21	4	38
28	SP4	286	20	2584 (19.14)	2639 (23.15)	118 (0.82)	11	7	1	36	10	91
29	SP4	286	20	5430 (40.52)	4101 (31.79)	255 (1.45)	11	12	3	18	14	108
30	SP4	286	20	8262 (64.05)	3831 (42.1)	297 (1.98)	10	8	0	31	12	116
31	SP4	286	20	4593 (41.75)	3531 (34.62)	180 (1.33)	37	13	2	18	11	73
32	SP4	286	20	10938 (88.21)	2989 (24.7)	203 (1.31)	15	21	6	30	19	110
33	SP4	286	20	12374 (86.53)	3335 (30.32)	189 (1.18)	11	5	0	24	12	78
34	SP4	286	20	5081 (51.85)	3398 (31.76)	147 (1.1)	12	10	4	12	8	84
35	SP4	286	20	7477 (80.4)	1937 (14.79)	201 (1.21)	14	12	1	27	15	160
36	SP4	286	20	4069 (34.19)	7046 (59.71)	245 (1.71)	23	7	1	6	6	103

higher through the 286 mm sieve panel design for sizes between 19 mm and 27 mm at the 10° angle and 21 mm and 27 mm at 20° (Fig. 5, row 1 and 2). However, we do not have evidence to support an effect on shrimp passage when the sieve panel angle is changed (Fig. 5, row 3 and 4). For redfish, increasing mesh size led to a significant increase in passage probability for a specific size range of redfish. At a 10° angle this was for individuals between 10 cm and 12 cm and between 20 cm and 33 cm. For the 20° sieve panel, increasing mesh size increased passage for individuals between 25 cm and 32 cm (Fig. 5, row 1 and row 2). Regarding the effect of changing angle (Fig. 5, row 3 and 4), no significant effect was detected. For polar cod, when the sieve panel was installed at 10°, increasing mesh led to a size dependant increase in the codend entry probability (Fig. 5, row 1). When the sieving angle increased to 20° we did not see a significant effect of mesh size (Fig. 5, row 2). Contrary to this, increasing the sieve panel angle while configured with a 182 mm mesh size, led to an increase in codend entry probability for polar cod between 15 and 18 cm (Fig. 5, row 3). Changing the angle when the 286 mm mesh size sieve panel was used had no significant effect on the codend entry probability (Fig. 5, row 4).

Table 2
Fit statistics for selected models for shrimp (*Pandalus borealis*), redfish (*Sebastes* spp.) and polar cod (*Boreogadus saida*).

		NG	*SP1*	*SP2*	*SP3*	*SP4*
Shrimp	Model	*rclogitS3*	*rclogitS3*	*rclogitS3*	*rclogitS3*	*rclogitS3*
	p-value	0.4274	0.0001	< 0.0001	0.0068	0.0177
	Deviance	15.34	43.51	56.59	27.4	24.44
	DOF	15	14	15	12	12
Redfish	Model	*rlogit*	*rclogitS2*	*rclogitS2*	*rlogit*	*rclogitS2*
	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
Polar cod	Model	*rclogitS2*	*rclogitS2*	*rclogit*	*rclogitS2*	*rclogit*
	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

3.4. Passage probability through the combined sieve panel and Nordmøre grid configurations compared to the Nordmøre grid (stand - alone)

When a sieve panel supplemented the Nordmøre grid, bycatch exclusion was significantly increased across a given length span for both bycatch species (Fig. 6). For redfish, combining the Nordmøre grid with the 182 mm mesh sieve panel at 10° led to a peak in reduced codend entry probability at length 13 cm of 0.22 (95% CI: 0.14–0.35). For the remaining sieve panel designs the estimated peak values were 0.15 (95% CI: 0.04–0.27), 0.21 (95% CI: 0.05–0.39) and 0.18 (95% CI: 0.03–0.36) for *SP2xNG*, *SP3xNG* and *SP4xNG* respectively. For polar cod the significance covered a wider length span than for redfish.

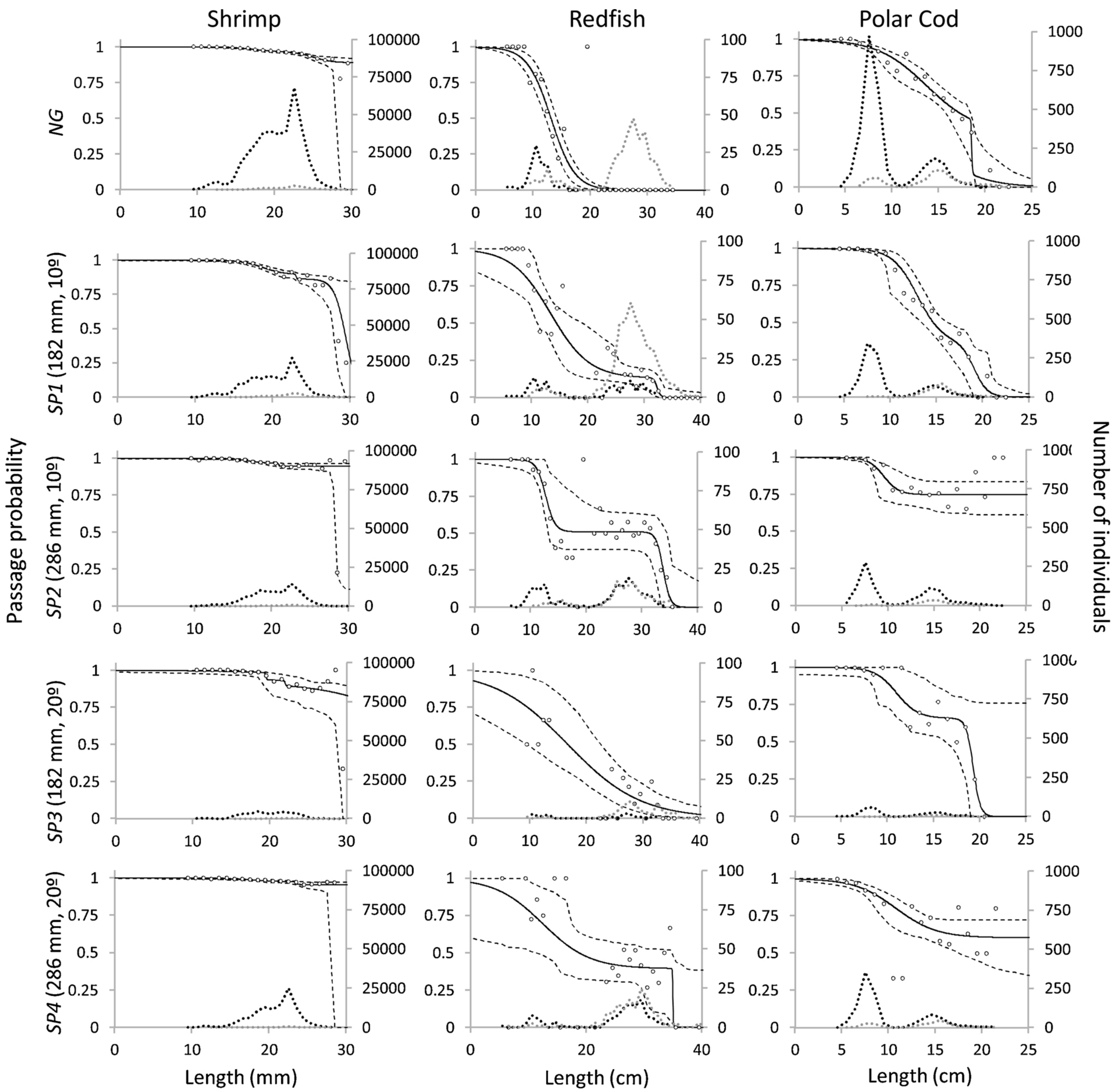

Fig. 3. Passage probability through the Nordmøre grid (*NG*) and the four sieve panel configurations tested (*SP1*, *SP2*, *SP3*, *SP4*). Experimental rates (circle marks), estimated probability curves (black solid line) with 95% confidence bands (dashed black lines). The black dotted line represents counts for the individuals that passed through the respective device (Nordmøre grid or sieve panel) and the grey dotted line represents counts for the individuals that were presented to the device but did not pass through it for shrimp (left), redfish (centre) and polar cod (right).

Individuals with lengths between 11 cm and 19 cm were excluded at the highest rate, with peak estimated reduction in codend entry probabilities of 0.39 (95% CI: 0.27–0.40), 0.18 (95% CI: 0.08–0.25) 0.21 (95% CI: 0.03-0.32) and 0.21 (95% CI: 0.16-0.28) for *SP1xNG, SP2xNG, SP3xNG* and *SP4xNG* respectively. Therefore, regarding bycatch it would be advantageous to supplement the Nordmøre grid with one of the sieve panel designs, however the effect on the target shrimp must be considered.

Combining the Nordmøre grid with any of the sieve panel designs resulted in a significant reduction in codend entry for shrimp (Fig. 6). In particular, combining the 182 mm sieve panel at 10° resulted in the highest increase in exclusion for large individuals. When this sieve panel was used, shrimps with a length of 27 mm underwent a reduction in codend entry of 0.17 (95% CI: 0.10–0.25) demonstrating a severe loss when using this design of sieve panel in front of the Nordmøre grid. When the 286 mm sieve panel was used the reduction in codend entry probability was as low as 0.03 (95% CI: 0.03–0.07) when installed at 10° and 0.02 (95% CI: 0.02–0.07) when installed at 20°. Therefore, in order to avoid an unacceptable level of target catch loss while improving bycatch selectivity it would be most acceptable to use the *SP4* sieve panel design in front of the Nordmøre grid.

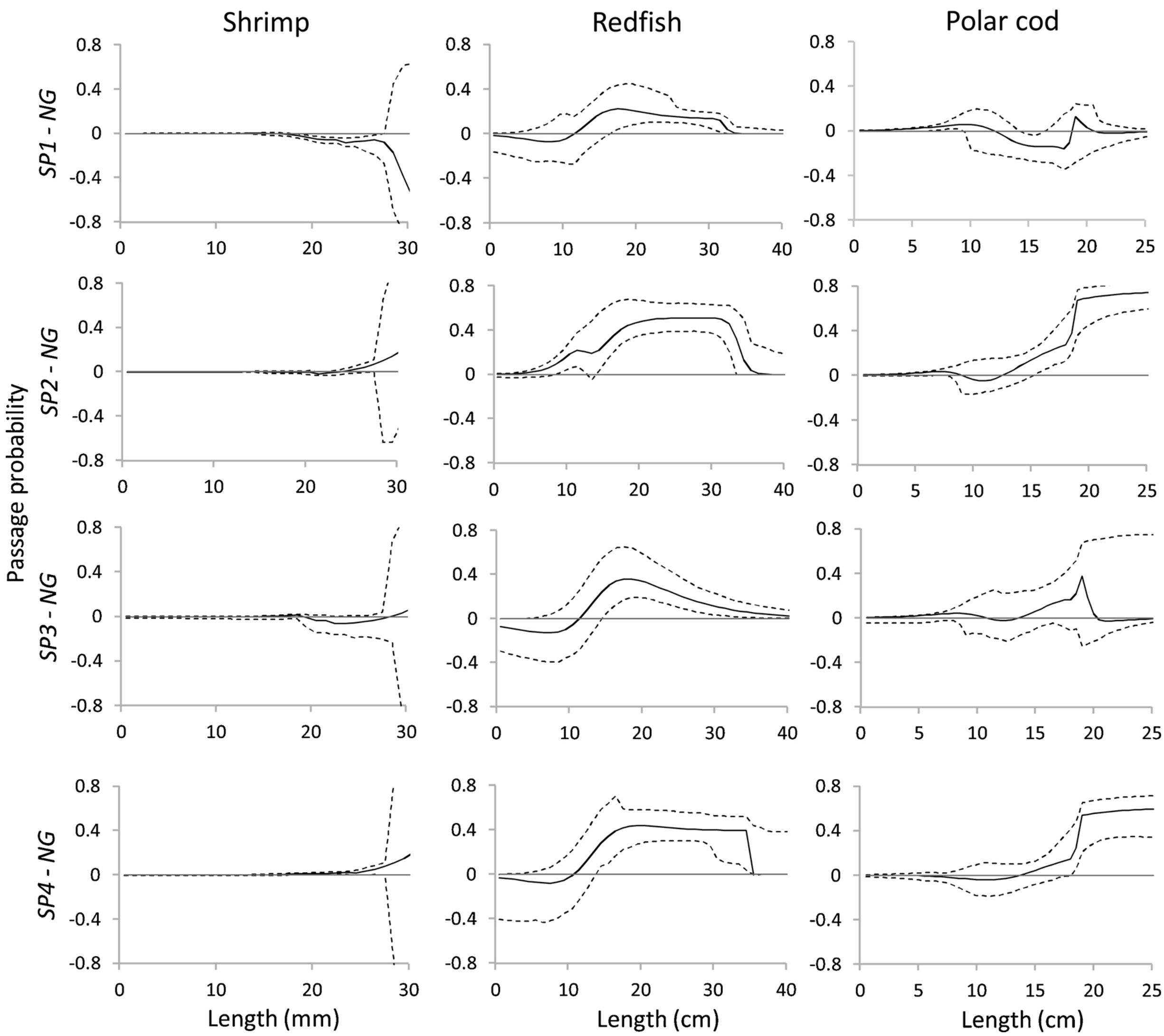

Fig. 4. Passage differences between the four sieve panel configurations (*SP1*, *SP2*, *SP3*, *SP4*) and the Nordmøre grid (*NG*) (solid black line) with 95% confidence bands (dashed black lines) for shrimp (left), redfish (center) and polar cod (right).

4. Discussion

The implementation of the Nordmøre grid (Isaksen et al., 1992) has been successful in the northeast Atlantic. The grid efficiently sorts large fish from the shrimp catch (He and Balzano, 2013, 2007; Larsen et al., 2017). However, due to the persisting juvenile fish bycatch problem in the area, additional sorting measures are still sought.

Sieve panels have been implemented to reduce bycatch of fish in different shrimp fisheries worldwide (Broadhurst and Kennelly, 1996; Polet et al., 2004; Revill et al., 1999; Revill and Holst, 2004; Sabu et al., 2013), however, limited studies address the use of a sieve panel followed by other selective devices. Larsen et al. (2018d) tested a 144 mm square mesh sieve panel installed at 9° followed by a Nordmøre grid in a similar manner to the present study, within the same fishery. Results from that study showed an exclusion of up to 56% of the largest and most valuable shrimp, which made the implementation of the specific panel tested unviable in the fishery. However, as the codend entry probability for several commercially important species was significantly reduced, the study recommended the additional testing of other sieve panel designs with larger mesh sizes and higher operational angles.

Based on the experience and recommendation in Larsen et al. (2018d), we tested sieve panels with mesh sizes of 182 mm to 286 mm, with operation angles of 10 and 20° (Fig. 2). These four sieve panel designs performed differently regarding the size dependent passage probability of shrimp and the bycatch species investigated. Increasing the mesh size from 182 mm to 286 mm resulted in a length-dependent increase in codend entry probability for all three species analysed. However, the effect of changing sieve panel angle was unclear (Fig. 5). These results show the importance of carefully considering the design of new selectivity devices within a fishery. The high entry probability for the largest shrimp obtained with the Nordmøre grid (96%–97%) could only be maintained by the sieve panels with 286 mm meshes (*SP2* and *SP4*). However, for some sizes of redfish and polar cod, where the

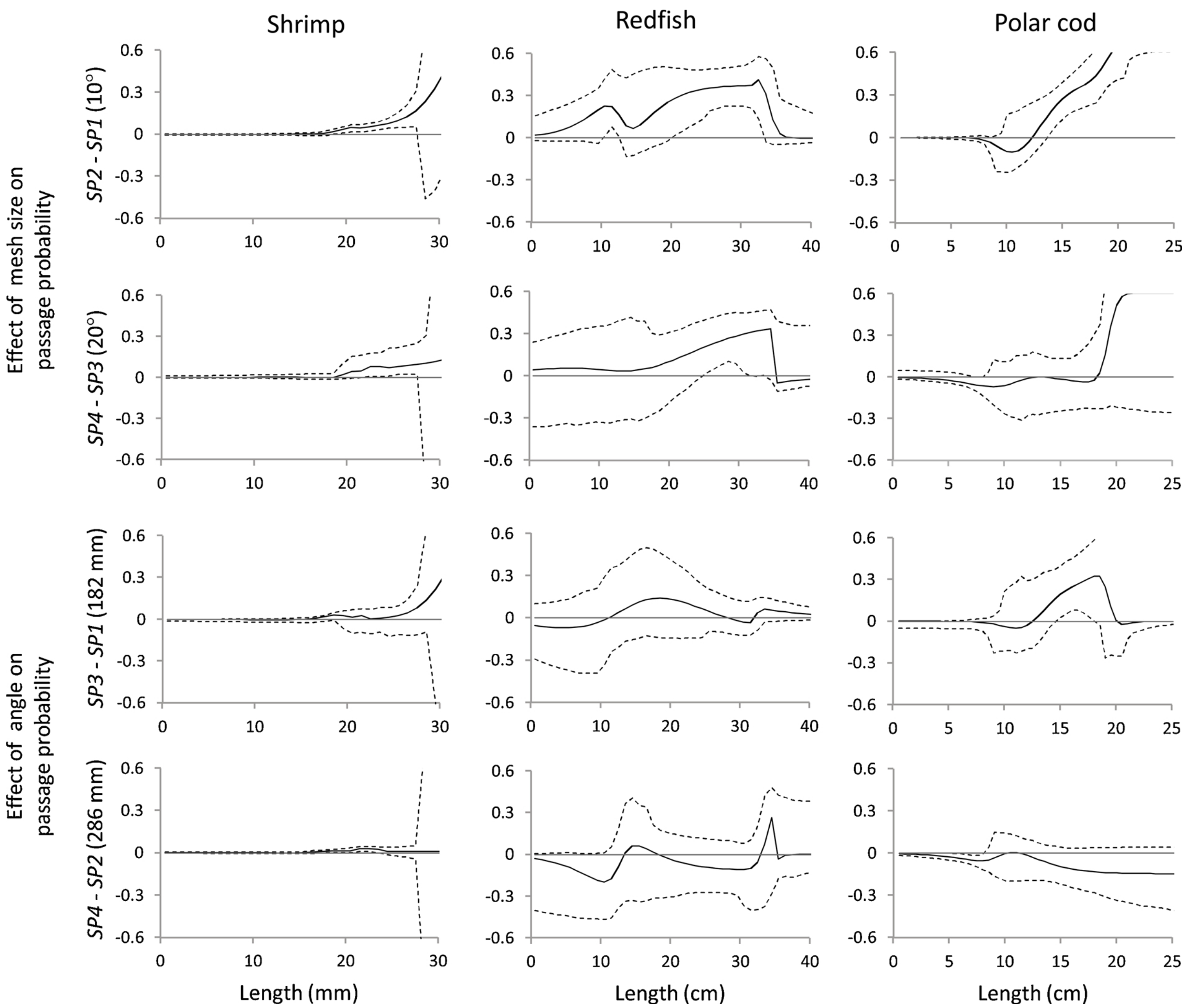

Fig. 5. Differences in passage probability between the four sieve panel designs (*SP1*, *SP2*, *SP3*, *SP4*) (solid black line) with 95% confidence bands (dashed black lines). Comparing the effect of changing mesh size and the effect of changing angle on selectivity of shrimp (left), redfish (center) and polar cod (right).

Nordmøre grid would prevent codend entry, this large mesh design led to an estimated codend entry probability of more than 30%, making it unacceptable for commercial application.

The Nordmøre grid performs better than the sieve panels tested alone. However, combining the *SP4* sieve panel design with the Nordmøre grid resulted in the entry probability of polar cod and redfish to substantially reduce while maintaining a shrimp codend entry probability of 97% (Fig. 3). For the other sieve panel designs (*SP1, SP2* and *SP3*) combined with the Nordmøre grid, the passage probability for the largest shrimp was negatively affected, especially with the 182 mm mesh size panels (*SP1* and *SP3*). Therefore, among the different designs tested, the *SP4* sieve panel would be the best alternative to supplement the Nordmøre grid in this fishery.

The data in this study was collected using small meshed covers. The use of such covers could potentially affect the performance of the sorting devices or fish behaviour. However, these types of covers have been successfully used in several other earlier experiments (e.g. Larsen et al., 2017). Moreover, underwater recordings carried out during the trials showed that they stayed clear from the sieve panel and Nordmøre grid outlets. Regarding fish behaviour, the underwater recordings did not show any peculiarities for any of the species interacting with the gear tested. Therefore, there was no indication that the covers affected the performance of the selective devices tested in the study in any way and we assume that the results obtained are reliable.

The experimental design used in this study allowed for a systematic investigation into the size selective potential of sieve panels in the Northeast Atlantic shrimp trawl fishery. The analysis approach used for the data (as described above), included four models *rlogit*, *rclogit*, *rclogitS2* and *rclogitS3* (Appendix). The last two, which to our knowledge were applied for the first time to a shrimp fishery, enable considering that the net and grid passage probabilities potentially are a complex process. Fish and shrimp may contact the sieve panel or grid in several ways and therefore, need more than a simple s-shaped size selection model to describe the overall process. Frandsen et al. (2010) have previously described net size selection for *Nephrops* based on such a modelling approach. Indeed, our results showed that for several of the cases in this study the passage probability was better described using *rclogitS2* and *rclogitS3* than the more traditional *rlogit* and *rclogit* models, which only consider one s-shaped size selection process.

Fishermen have expressed their preference for non-rigid selective

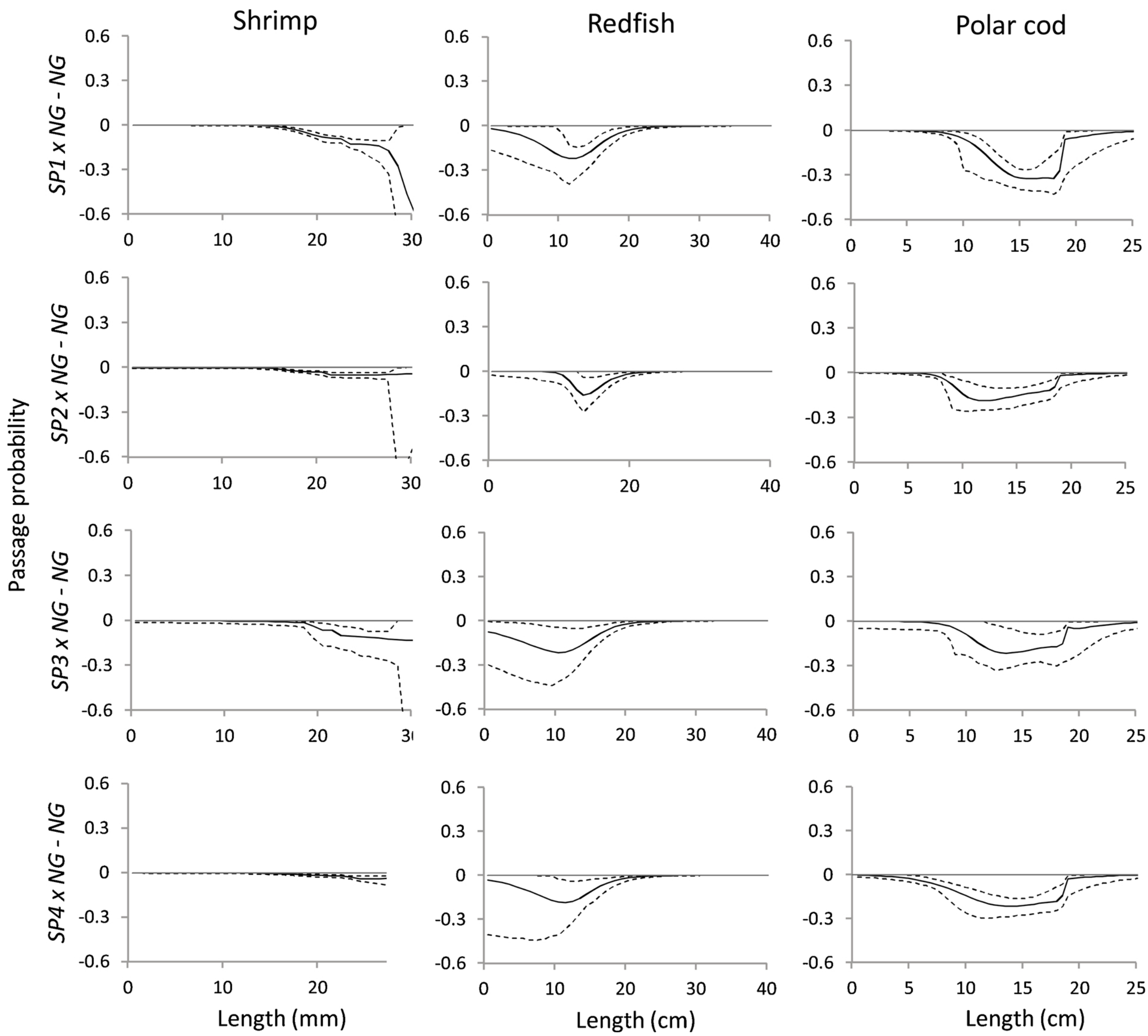

Fig. 6. Differences in passage probability for the four sieve panel designs (SP1, SP2, SP3, SP4) each combined with the Nordmøre grid compared to the Nordmøre grid (NG) stand- alone (solid black line) with 95% confidence bands (dashed black lines) for shrimp (left), redfish (center) and polar cod (right).

devices such as sieve panels because operations such as shooting, retrieving and storing the gear on board are easier (Polet et al., 2004). Sieve panels are cheap and easy to install (Polet et al., 2004; Van Marlen et al., 2001), and imply lower risk of becoming blocked during towing compared to rigid devices like sorting grids (CEFAS, 2003). For instance, in areas with large numbers of American plaice (*Hippoglossoides platessoides*) or other flatfish species, jellyfish (*Cyanea* spp.) and large animals like Greenland sharks (*Somniosus microcephalus*), a sieve panel would be beneficial to avoid blockage of the grid face. Blockages of the grid surface can reduce the sorting capacity of the grid and lead to damages in the sorting system (guiding funnel and grid).

The present study provides new knowledge on the performance of sieve panels compared to rigid sorting devices like sorting grids. Considering the objective of simultaneously maintaining the high entry probability for the largest shrimp and low passage probability for bycatch species, our results demonstrate that replacing the rigid Nordmøre grid with a soft sieve panel is not simple. Specifically, like Larsen et al (2018d) and other comparable earlier studies (Watson and Taylor, 1986; Karlsen and Larsen, 1989; Kendall, 1990), we were unable to find a soft sieve panel design that could replace the rigid Nordmøre grid.

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Appendix A. Models for describing sieve panel and Nordmøre grid passage probability

This appendix describes the models considered for quantifying the length dependent passage probabilities for fish and shrimps through the sieve panels and the Nordmøre grid. The starting point for this 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 (Grimaldo and Larsen, 2005; Wileman et al., 1996):

$$logit(l, L50, SR) = \frac{\exp\left(\frac{ln(9)}{SR} \times (l - L50)\right)}{1 + \exp\left(\frac{ln(9)}{SR} \times (l - L50)\right)} \quad (A1)$$

L50 and *SR* are parameters of the model (A1), where *L50* quantifies the length of the fish or carapace length of the shrimp that have a 50% probability of being retained. *SR* measures the steepness of the curve by the difference in *L75* and *L25* (Wileman et al., 1996). $logit(l, L50, SR)$ provides an s-shaped curve with a monotonous increase in retention probability with size of the organism in terms of its length. In our case we want to model the length dependent sieve panel or Nordmøre grid passage probability, therefore the probability of being released needs to be expressed as 1 – the probability of being retained. Based on the $logit(l, L50, SR)$model we use the following model as a starting point for modelling the length dependent sieve panel or grid passage probability:

$$p(l, \boldsymbol{\nu}) = rlogit(l, L50_1, SR_1) = 1 - logit(l, L50_1, SR_1) = \frac{1}{1 + \exp\left(\frac{ln(9)}{SR_1} \times (l - L50_1)\right)}$$
$$where$$
$$\boldsymbol{\nu} = (L50_1, SR_1) \quad (A2)$$

As well as considering the use of (A2) to model the sieve panel and Nordmøre grid passage probabilities, we also considered three additional models (A3–A5) which account for that not all fish or shrimp contact the sieve panel or grid. This provides a size-dependent probability of passing through the gear. The simplest of these models, denoted the *rclogit* model, includes one contact parameter C_1, which has a value in the range of 0.0–1.0. An estimated C_1 value of 1.0 for a species means that every individual of that species contacts the sieve panel or Nordmøre grid in a way that provides them with a length-dependent probability of passing through the device. In case a fish or shrimp does not contact the sieve panel or grid, or is poorly oriented during the contact, it is going to be reflected in the C_1 value. Larsen et al. (2018d) used the following *rclogit* model to describe the size dependent probability of a shrimp or a fish passing through the Nordmøre grid or a sieve panel:

$$p(l, \boldsymbol{\nu}) = rclogit(l, C_1, L50_1, SR_1) = C_1 \times rlogit(l, L50_1, SR_1) = \frac{C_1}{1 + \exp\left(\frac{ln(9)}{SR_1} \times (l - L50_1)\right)}$$
$$where$$
$$\boldsymbol{\nu} = (C_1, L50_1, SR_1) \quad (A3)$$

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

$$p(l, \boldsymbol{\nu}) = rclogitS2(l, C_1, L50_1, SR_1, L50_2, SR_2) = C_1 \times rlogit(l, L50_1, SR_1) + (1 - C_1) \times rlogit(l, L50_2, SR_2)$$
$$= \frac{C_1}{1 + \exp\left(\frac{ln(9)}{SR_1} \times (l - L50_1)\right)} + \frac{1 - C_1}{1 + \exp\left(\frac{ln(9)}{SR_2} \times (l - L50_2)\right)}$$
$$where$$
$$\boldsymbol{\nu} = (C_1, L50_1, SR_1, L50_2, SR_2) \quad (A4)$$

And

$$p(l, \boldsymbol{\nu}) = rclogitS3(l, C_1, C_2, L50_1, SR_1, L50_2, SR_2, L50_3, SR_3) = C_1 \times rlogit(l, L50_1, SR_1) + C_2 \times rlogit(l, L50_2, SR_2) + (1 - C_1 - C_2) \times rlogit(l, L50_3, SR_3)$$
$$= \frac{C_1}{1 + \exp\left(\frac{ln(9)}{SR_1} \times (l - L50_1)\right)} + \frac{C_2}{1 + \exp\left(\frac{ln(9)}{SR_2} \times (l - L50_2)\right)} + \frac{1 - C_1 - C_2}{1 + \exp\left(\frac{ln(9)}{SR_3} \times (l - L50_3)\right)}$$
$$where$$
$$\boldsymbol{\nu} = (C_1, L50_1, SR_1, L50_2, SR_2, L50_3, SR_3) \quad (A5)$$

The rationale behind also considering the two much more complex models (A4)-(A5) for the passage probabilities is that they can account for not all individuals of fish or shrimp making contact with the netting or grid with the same orientation (contact mode, see Frandsen et al. (2010) for details on this concept of modelling). With different orientations, different size ranges of the species would be able to pass through. To account for this, each contact model has its own set of selection parameters ***L50*** and ***SR***. In the case of (A4 and A5) two or three contact modes are accounted for respectively. In (A4) the fraction of individuals that are sorted by with these modes are C and $1 - C$ respectively. In (A5) the fraction of individuals that are sorted with these contact modes are C_1, C_2 and $1 - C_1 - C_2$ respectively. The sum of these fractions will always be equal to 1. For sieve panels with bigger meshes as in this study compared to in Larsen et al. (2018d) allowing the potential for passage with different orientations may be necessary with so much more complex models to be able to describe the length dependent passage probability sufficiently well.

The above considerations mean that we will consider four different models for $p(l, \boldsymbol{\nu})$ for each of the different sieve panels and the Nordmøre grid passage processes for each species that can be summarized by:

$$p(l, \boldsymbol{\nu}) = \begin{cases} rlogit(l, \boldsymbol{\nu}); \quad \boldsymbol{\nu} = (L50_1, SR_1) \\ rclogit(l, \boldsymbol{\nu}); \quad \boldsymbol{\nu} = (C_1, L50_1, SR_1) \\ rclogitS2(l, \boldsymbol{\nu}); \quad \boldsymbol{\nu} = (C_1, L50_1, SR_1, L50_2, SR_2) \\ rclogitS3(l, \boldsymbol{\nu}); \quad \boldsymbol{\nu} = (C_1, L50_1, SR_1, C_2, L50_2, SR_2, L50_3, SR_3) \end{cases} \quad (A6)$$

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