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# Bycatch reduction in the deep-water shrimp (*Pandalus borealis*) trawl fishery with a large mesh top panel

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ABSTRACT

In the Northeast Atlantic deep-water shrimp (*Pandalus borealis*) trawl fishery, the bycatch of juvenile fish and shrimp represents a problem. This study evaluated if inserting a 200 mm mesh size top-panel in the last three sections of the tapered upper belly section of the trawl could reduce bycatch of juveniles while maintaining the catch efficiency for deep-water shrimp. The bycatch species investigated were Greenland halibut (*Reinhardtius hippoglossoides*), redfish (*Sebastes* spp.) and polar cod (*Boreogadus saida*). The bycatch of Greenland halibut and the smallest polar cod was significantly reduced, while no effect was found for redfish. The large mesh panel did not lead to a significant loss of deep-water shrimp. The results of this study illustrate how a simple modification of a fishing gear can mitigate the bycatch problem in a shrimp fishery, without significant losses of the target species.

## 1. Introduction

Trawl fisheries targeting shrimp are often associated with high levels of bycatch due to small mesh sizes, which lead to the capture of species that are similar in size to the targeted shrimp (Broadhurst, Brand, & Kennelly, 2012; Campos & Fonseca, 2004; He & Balzano, 2013; Polet, Coenjaerts, & Verschoore, 2004; Sistiaga, Herrmann, Larsen, & Brinkhof, 2019). Large amounts of bycatch imply high mortality of juvenile fish, negative ecological consequences on fish stocks, and operational challenges for the fishing industry (Kennelly, 1995; Larsen, Herrmann, Sistiaga, Brčić et al., 2018).

In the Barents Sea deep-water shrimp (*Pandalus borealis*) trawl fishery, the bycatch of juvenile fish and shrimp represents a problem for fisheries management and commercial fisheries. Current gear regulations for this fishery include the mandatory use of a Nordmøre sorting grid with 19 mm bar spacing and a codend with a minimum mesh size of 35 mm (Norwegian Directorate of Fisheries, 2018a). With this gear, large fish are unable to pass through the narrow bar spacing of the grid and are released through the fish escape opening over the grid (Eayrs, 2007; Larsen, Herrmann, Sistiaga, Brinkhof, & Grimaldo, 2018). The smaller fish that pass through the grid together with the shrimp may be released through the codend meshes (Fig. 1). However, a range of sizes that are small enough to pass through the bar spacings of the Nordmøre grid are too big to subsequently be released through the codend meshes and are therefore retained (Herrmann, Sistiaga, Larsen, & Brinkhof, 2019; Larsen, Herrmann, Sistiaga, Brinkhof, Brinkhof et al., 2018; Larsen, Herrmann, Sistiaga, Brinkhof et al., 2018; Sistiaga et al., 2019).

The selection properties of the gear configuration create bycatch problems in the fishery, where the current regulations allow the capture of low numbers of juvenile fish from regulated species, including a maximum of three redfish (*Sebastes* spp.) and three Greenland halibut (*Reinhardtius hippoglossoides*) per 10 kg catch of shrimp (Norwegian Directorate of Fisheries, 2018a). Exceeding the capture limits for regulated species leads to fishing area closures that can result in significant

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restrictions on the areas where fishermen can operate (Norwegian Directorate of Fisheries, 2018b). In addition to the problems associated with the bycatch of regulated species, the capture of polar cod (*Boreogadus saida*) should be avoided, as it is a key species in the Arctic ecosystem (Laurel et al., 2019).

Several gear modifications have been tested in the Barents Sea deep-water shrimp trawl fishery with the aim of reducing fish bycatch without leading to loss in capture efficiency for the target species. These modifications include changes to codend design (Herrmann et al., 2019; Sistiaga et al., 2019), grid design and configuration (Grimaldo & Larsen, 2005; Larsen, Herrmann, Sistiaga, Brinkhof, Brinkhof et al., 2018, 2019), and the use of LED lights in the trawls (Larsen, Herrmann, Sistiaga, Brinkhof et al., 2017; Larsen, Herrmann, Sistiaga, Brčić et al., 2018). However, none of the modifications tested have led to a reduction in fish bycatch that is not excluded by grid or codend selection, without simultaneously compromising the catch efficiency for deep-water shrimp. Therefore, additional designs need to be tested to address the bycatch problem in the Barents Sea trawl fishery where trawlers are targeting deep-water shrimp.

An alternative strategy to try to solve the fish bycatch problem in shrimp fisheries could be inserting a large mesh panel in the upper panel of the belly section of the trawl. The release of bycatch through a large mesh panel is dependent on contact with the panel meshes (Brčić, Herrmann, & Sala, 2017; Cuende, Arregi, Herrmann, Sistiaga, & Basterretxea, 2020), which depends on factors such as behaviour and swimming capacity of the species, location of the large mesh panel in the trawl, and the mesh sizes used (Herrmann et al., 2009, 2015; Krag, Herrmann, Madsen, & Frandsen, 2011). Studies on the vertical preferences of species at the mouth of the trawl indicate that some bycatch species have a high tendency to rise quickly as they enter the trawl, while the majority of shrimp stay low (He & Balzano, 2013; He, Goethel, & Smith, 2007; Larsen, Kristjansson, & Marteinsson, 1993). Additionally, positioning large mesh panels in the tapered section, as opposed to the non-tapered section of the trawl, has been shown to result in an increased contact probability for certain fish species (Krag, Herrmann, & Karlsen, 2014). Thus, the use of a large mesh panel inserted in the tapered top panel section of a trawl could potentially contribute to the release of juvenile fish that enter the trawl higher up in the water column than the targeted shrimp.

The current study was designed to investigate whether inserting a large-mesh panel in the tapered top panel of a shrimp trawl could reduce fish bycatch without compromising the catch efficiency for the targeted deep-water shrimp.

## 2. Materials and methods

### 2.1. Sea trials and gears

Sea trials were conducted between the 18th – 21st of October 2019 onboard the commercial trawler "Arctic Viking" (IMO:8517437) (4600 HP, 58 LOA, 1720 GT). The area chosen for the sea trials was located on the North-Eastern side of Svalbard near "Kvitøya" (Fig. 2). The vessel was rigged with a twin trawl and we used two identical Vonin shrimp trawls with a 108 m fishing circle (2700 mesh circumference × 40 mm mesh size). The trawls had a 68.7 m long fishing line attached to 58.4 m long ground gear (Ø54 cm rubber discs) and a Ø54 cm bobbin with a 10.4 m long chain on each side. Two 13.2 $m^2$ Sea Hunter trawl doors (5400 kg) and one Sea Hunter central clump (7000 kg) were used to rig the trawls in a twin trawl configuration. The trawl doors and the central clump were attached to the trawls with 30 m long double bridles. Each trawl was fitted with a Nordmøre grid with 19 mm bar spacing. The outer dimensions of the grids were 170 cm (width) and 240 cm (height). The grids were inserted in a 15 m long four panel polyethylene netting section, 500 × 50 mm meshes in circumference. Behind the grids, there were 10 m transitions from four to two panels to match the two panel codends. Two identical 16.9 m long diamond mesh codends of 35 mm nominal mesh size made of double twisted polyamide netting (twine thickness of 2 × 1.6 mm) were attached to the trawls.

### 2.2. Experimental design

The two trawls were towed simultaneously. One of the two trawls was used as baseline as it was equipped with the standard gear configuration used for shrimp trawling in the Barents Sea, comprising a 19 mm Nordmøre grid and a 35 mm diamond mesh codend (Fig. 1). The other trawl was used as a test trawl because it was fitted with a 29.4 m long large mesh panel inserted in the upper aft part of the trawl, i.e., replacing the last three sections of the trawl belly (Figs. 3 and 4). The baseline trawl had a top panel of 50 mm meshes, identical to the bottom panel (Fig. 3). The large mesh panel was mounted as a T90 panel, i.e., the orientation of the meshes was turned by 90 degrees compared to the traditional diamond mesh netting (Herrmann, Wienbeck, Moderhak, Stepputtis, & Krag, 2013). The panel was made of 2.8 mm braided polyethylene twine with a nominal mesh size of 200 mm and was 22 % narrower than the panel that was removed, to enhance lateral mesh opening. Both trawls were simultaneously towed in a twin trawl configuration, therefore, any difference between the two catches could be attributed to the effect of the large mesh panel.

The number of meshes, mesh sizes, and cutting ratios used in the construction of the belly sections of the trawls are provided in the technical specifications (Fig. 3). We used underwater video recordings to inspect the geometry and correct operation of the panel and to obtain the mesh openings (hanging ratios) in the panel, enabling an estimation of the geometry of the sections and tapering angle of the three belly sections where the 200 mm panel was inserted. The estimated tapering angles of the first, second, and third belly sections (T90-S1, T90-S2, and T90-S3) were 7.7°, 4.1°, and 3.1°, respectively (Fig. 4a).

### 2.3. Data collection

Fishing operations were kept as similar to normal commercial fishing activities as possible during the sea trials, with a mean towing time of approximately 5 h (ranging from 4.43 to 5.47 h) and mean towing speed of 2.3 knots. After both trawls were hauled on deck, the codend catches were kept separate. Each catch was sorted by species and the total weight for each species noted. Bycatch species caught in sufficient numbers were included in the data analysis. The length of these individuals was measured and rounded down to the nearest half centimetre. Due to time constraints the whole catch could not be measured, so the catch was subsampled and sampling fractions were included in

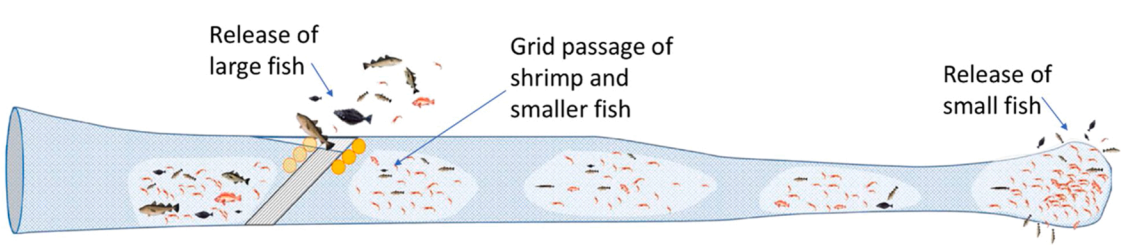


**Fig. 1.** Working principle for the Nordmøre grid and the codend system currently used in the Barents Sea bottom trawl shrimp fishery.

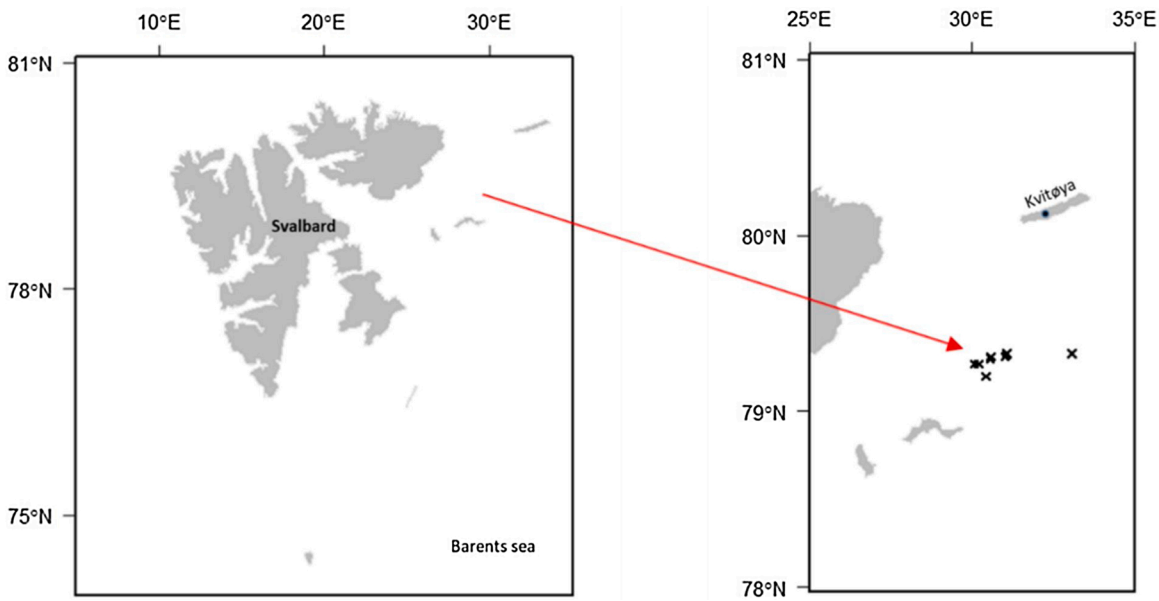


**Fig. 2.** Map showing the area where the sea trials were conducted. Black marks on the right side represent the start positions for the hauls.

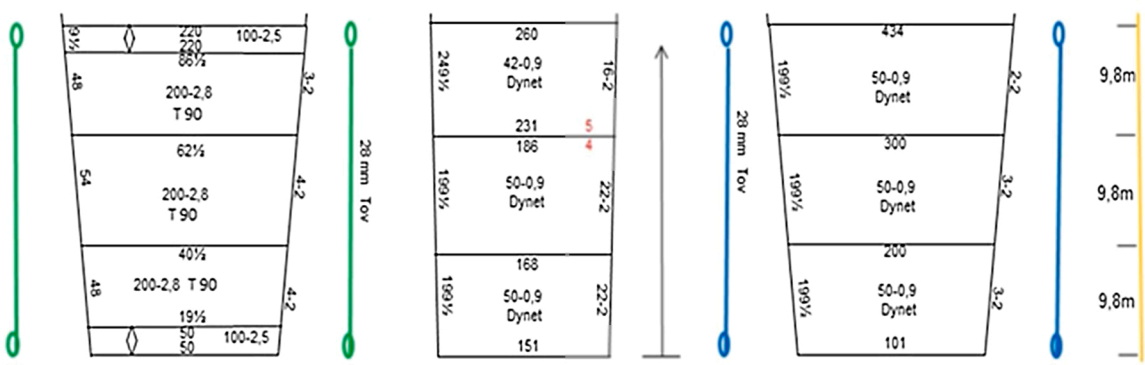


**Fig. 3.** Technical specifications of the belly sections where the 200 mm T90 mesh panel was inserted. From left to right: top, side, and bottom panels.

the analysis. For shrimp, a subsample of approximately 1.5–2 kg was randomly selected from each codend prior to sorting and the carapace length was measured to an accuracy of 0.01 mm. Prior to analysis, the lengths were rounded down to the nearest millimetre.

### 2.4. Data analysis

We used the statistical software SELNET (Herrmann, Sistiaga, Nielsen, & Larsen, 2012) to analyse the paired catch data. We conducted size-dependent catch comparison and catch ratio analysis to determine whether the catch efficiency between the test (trawl with the large mesh panel) and baseline (commercial trawl without the large mesh panel) gears was different, and whether these potential differences were length-dependent. To do this, the number of fish and shrimp in each length class caught in the test and baseline trawl was used. The analysis was carried out independently for all species following the description below.

#### 2.4.1. Modelling the relative length-dependent catch comparison rate and catch ratio of the trawls

To assess the relative length-dependent catch comparison rate ($CC_l$) of changing from baseline to test gear, we used Eq. (1):

$$CC_l = \frac{\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}+\frac{nt_{lj}}{qt_j}\right\}} \tag{1}$$

where $nb_{lj}$ and $nt_{lj}$ are the number (n) of fish of size $l$, caught in paired haul $j$ with the baseline ($b$) and test ($t$) gear, respectively. Parameters $qb_j$ and $qt_j$ are the subsampling ratios that account for the fact that not all of the catch from the baseline and test trawl, respectively, were measured in the pair haul $j$. Parameter $h$ is the total number of paired tows conducted during the study. The catch comparison rate $CC(l,\boldsymbol{v})$ expressed by Eq. (1) was estimated using maximum likelihood estimation by minimizing the Expression 2:

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

In Expression 2, $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\boldsymbol{v})$. The experimental $CC_l$ was modelled by the function $CC(l,\boldsymbol{v})$:

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

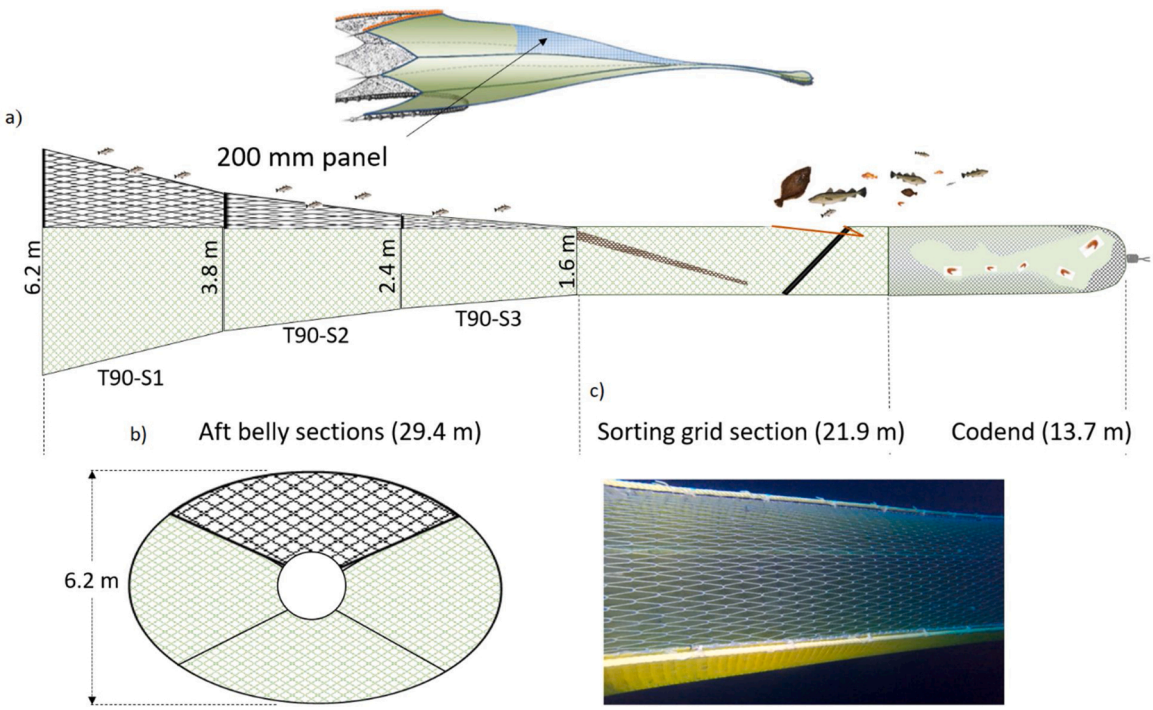


**Fig. 4.** a) A schematic representation of the test trawl and selection devices with an approximation of their estimated dimensions under operation. b) A schematic representation of the front view of the trawl belly illustrating the projected area of the 200 mm panel. c) An image of the panel taken during the underwater video recordings.

In Eq. (3), $f$ is a polynomial of order $k$ with coefficients $v_0$-$v_k$, such that $\boldsymbol{v} = (v_0,\ldots,v_k)$. We considered $f$ of up to an order of 4. Leaving out one or more of the parameters $v_0 \ldots v_4$, at a time resulted in 31 additional candidate models for the catch comparison function $CC(l,\boldsymbol{v})$. Among these models, the catch comparison rate was estimated using the multi-model inference to obtain a combined model (Burnham & Anderson, 2002; Herrmann, Sistiaga, Rindahl, & Tatone, 2017). The ability of the combined model to describe the experimental data was based on the $p$-value, which is calculated based on the model deviance and degrees of freedom (DOF) (Herrmann et al., 2017; Wileman, Ferro, Fonteyne, & Millar, 1996). Thus, suitable fit statistics for the combined model to describe the experimental data sufficiently well should include a $p$-value $> 0.05$. If the $p$-value exceeded 0.05, the deviance and the DOF were assessed to determine whether the result was due to structural problems when modelling the experimental data, or to overdispersion in the data.

To provide a direct relative value of the catch efficiency between the test and the baseline trawls, the following catch ratio $CR(l,\boldsymbol{v})$ equation was used:

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{[1 - CC(l,\boldsymbol{v})]} \tag{4}$$

In this case, if the catch efficiency of both gears is equal, $CR(l,\boldsymbol{v})$ will be 1.0.

We used a double bootstrapping method (1000 bootstrap repetitions) to estimate the 95 % confidence intervals (CIs) for the catch comparison and catch ratio curves following the description in Lomeli, Groth, Blume, Herrmann, and Wakefield (2019). When the catch efficiency of the two trawls is equal, the catch comparison rate is 0.5 and the catch ratio is 1.0.

### 2.4.2. Estimating the length-integrated average catch ratio

Length-integrated average values for the catch ratio ($CR_{average}$) were estimated directly from the experimental catch data using the following equations:

$$CR_{average-} = \frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\right\}}$$
$$CR_{average+} = \frac{\sum_{l\geq MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l\geq MLS}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\right\}} \tag{5}$$

where the outer summations include the size classes in the catch during the experimental fishing period that were under (for $CR_{average-}$) and over (for $CR_{average+}$) the minimum landing size ($MLS$ = 15 mm carapace length) of deep-water shrimp. For bycatch fish species $CR_{average}$ was estimated summed over all sizes such that Eq. (6) aggregates to one value. In contrast to the length-dependent evaluation of $CR(l,\boldsymbol{v})$, $CR_{average-}$ and $CR_{average+}$ are specific to the population structure encountered during the experimental trials and cannot be extrapolated to other scenarios in which the size structure of the shrimp and bycatch fish species may be different (Wienbeck, Herrmann, Feekings, Stepputtis, & Moderhake, 2014).

### 2.4.3. Estimating the discard ratio

Discard ratios for the shrimp were estimated directly from the experimental catch data by using Eq. (6):

$$NDRatio_{Test} = 100 \times \frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}$$
$$NDRatio_{Baseline} = 100 \times \frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nb_{bj}}{qb_j}\right\}}{\sum_{l}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\right\}} \quad (6)$$

The outer summations include the length classes that were under the minimum targeted size of deep-water shrimp (in the nominator) and over-all length classes (in the denominator). *NDRatio* quantifies the fraction of the catch (in percentage) that consists of undersized shrimp (i.e., below the MLS of 15 mm carapace length) (Norwegian Directorate of Fisheries, 2018a). Ideally, *NDRatio* should be as low as possible. The value of *NDRatio* is affected by both the size selectivity of the gear and the size structure of the shrimp in the fishing grounds. Therefore, it provided an estimate that is specific to the population fished and cannot be extrapolated to other areas and seasons (Veiga-Malta, Feekings, Frandsen, Herrmann, & Krag, 2020).

Uncertainty in terms of 95 % CIs was estimated for both $CR_{average}$ and *NDRatio* by incorporating the estimation of these measures in the double bootstrapping method described above.

## 3. Results

A total of nine valid paired hauls were carried out, resulting in length measurements of 5090 shrimp, 1645 Greenland halibut, 8402 polar cod, and 5556 redfish. The number of length-measured individuals in test and baseline trawls are shown in Table 1.

First, we examined whether the use of a large mesh panel compromised catch efficiency for deep-water shrimp. For shrimp, the catch comparison model fit between the baseline trawl and the trawl with the large mesh panel showed that the model was able to describe the experimental data (*p*-value of 0.28 (Table 2)). The size distributions of shrimp caught had a similar structure for both trawl configurations (Fig. 5). The catch comparison ratio $CC(l,\boldsymbol{v})$ and the catch ratio $CR(l,\boldsymbol{v})$ did not show any significant difference between the test and baseline trawls (Fig. 5). The results indicate a lower retention of shrimp of larger length classes, however, this result was not statistically significant (Fig. 5, Table 2). The catch ratio averaged over all length classes ($CR_{average}$) was estimated at 96.3 % (95 % CI: 87.3 %–106.3 %) and did not differ significantly between the test and baseline gears. The discard ratio (*NDRatio*), representing the proportion of shrimp below the MLS, did not differ significantly between the test and baseline trawls. $NDRatio_{test}$ and $NDRatio_{baseline}$ were 6.6 % (95 % CI: 4.3 %–8.8 %) and 6.4 % (95 % CI: 4.3 %–8.4 %) for the test and baseline trawls, respectively (Table 2).

**Table 2**
Estimated catch ratio values $CR(l,\boldsymbol{v})$ for specific length classes, average catch ratio $CR_{average}$ results and fit statistics for shrimp. Values within parenthesis are the 95 % CIs. DOF = degrees of freedom. $NDRatio_{test}$ and $NDRatio_{baseline}$ represent discard ratios (%) for the test and baseline trawls, respectively.

| Length (mm) | Catch ratio (%) |
|---|---|
| 10 | 76.40 (32.24–244.15) |
| 15 | 101.26 (79.81–122.95) |
| 20 | 97.66 (86.15–111.43) |
| 25 | 89.91 (77.18–103.10) |
| 30 | 56.01 (21.74–192.29) |
| *p*–value | 0.28 |
| Deviance | 43.64 |
| DOF | 39 |
| $CR_{average-}$ | 99.59 (70.20–136.66) |
| $CR_{average+}$ | 96.31 (87.33–106.28) |
| $NDRatio_{Test}$ (%) | 6.61 (4.28–8.79) |
| $NDRatio_{Baseline}$ (%) | 6.40 (4.28–8.41) |

For all fish bycatch species, the *p*-values obtained (Table 3) were lower than 0.05 and were assumed to be caused by over-dispersion in the experimental data (Wileman et al., 1996). Thus, the model was believed to be appropriate to represent the main trends in the experimental data. The frequency distribution of Greenland halibut and polar cod differed between the test and baseline trawls, with less individuals of these species being caught by the test trawl with the large mesh panel (Fig. 6). For redfish, both length frequency distributions were almost identical (Fig. 6).

The size-dependent catch comparison and catch ratio analysis showed highly significant length-dependent catch efficiency for Greenland halibut, with larger number of fish between 5 and 14 cm being released by the test trawl (Fig. 6, Table 3). When averaged over all the length classes, the test trawl retained significantly fewer (31.7 % (CI: 23.2 %–50.4 %)) Greenland halibut than the baseline trawl (Table 3). For polar cod, we estimated a significant reduction for fish between 5 and 9 cm, but when averaged over all length classes this reduction was not found to be significant ($CR_{average}$ = 80.8 % (95 % CI: 65.8 %–106.8 %)) (Table 3). There was no significant difference in capture efficiency between the test and baseline gears for redfish (Fig. 6).

## 4. Discussion

In this study, we demonstrated the ability of a 200 mm mesh size panel inserted in the trawl belly to effectively reduce the bycatch of fish species in a deep-water shrimp fishery. In particular, the panel significantly reduced the bycatch of juvenile Greenland halibut, which is a commercially important fish species in the Barents Sea, and polar cod. From a fisheries point of view, the exclusion of a non-target species is

**Table 1**
The number of individuals measured in the test and baseline trawls. The numbers in parentheses represent the percentage of individuals measured in test and baseline codends in each haul. Where the percentage measured is not provided, 100 % of the catch was measured.

| | Shrimp | | Greenland halibut | | Redfish | | Polar cod | |
|---|---|---|---|---|---|---|---|---|
| Haul | Test | Baseline | Test | Baseline | Test | Baseline | Test | Baseline |
| 1 | 328 (0.09) | 335 (0.08) | 174 (17.12) | 250 (7.94) | 0 | 53 (36.96) | 410 (7.06) | 440 (4.23) |
| 2 | 324 (0.08) | 282 (0.08) | 91 (43.64) | 177 (34.44) | 214 (99.47) | 257 (98.23) | 404 (14.73) | 442 (9.49) |
| 3 | 385 (0.09) | 207 (0.09) | 73 (45.25) | 123 (40.85) | 171 (80.53) | 182 (85.05) | 582 (29.76) | 645 (23.74) |
| 4 | 241 (0.06) | 303 (0.03) | 20 (35.00) | 22 (40.71) | 582 (96.72) | 347 (89.92) | 368 (33.93) | 383 (43.05) |
| 5 | * | * | 9 | 17 | 226 | 265 | 435 | 366 (76.36) |
| 6 | 350 (0.12) | 312 (0.15) | 11 (16.67) | 23 (26.33) | 394 (97.1) | 428 (98.48) | 450 (17.12) | 476 (25.84) |
| 7 | 386 (0.06) | 338 (0.06) | 120 (38.27) | 143 (8.39) | 471 (93.59) | 678 (92.31) | 479 (23.96) | 362 (24.95) |
| 8 | 328 (0.13) | 271 (0.09) | 84 (47.01) | 123 (35.43) | 197 (96.73) | 297 (94.61) | 508 (12.71) | 488 (9.1) |
| 9 | 313 (0.06) | 387 (0.09) | 41 (54.20) | 144 (36.15) | 456 (74.28) | 338 (89.17) | 557 (16.28) | 607 (13.41) |
| Total | 2655 | 2435 | 623 | 1022 | 2711 | 2845 | 4193 | 4209 |

* Samples were not available.

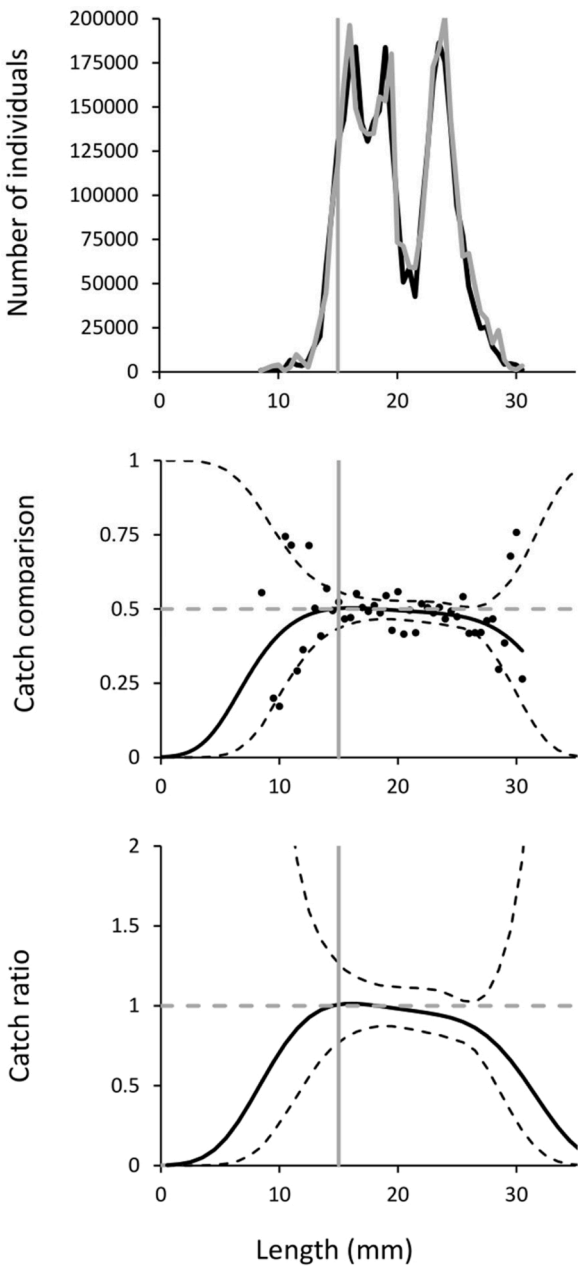


**Fig. 5.** Upper graph: The length frequency distribution of shrimp caught by the test (black line) and the baseline trawls (grey line). Middle: The modelled catch comparison rate (black line) with 95 % CI (black stippled curves). Black circles represent the experimental rate. The grey horizontal line at 0.5 represents the point at which both trawl gears have equal catch rates. Bottom: The estimated catch ratio curve. The horizontal grey line at 1.0 represents the point at which both trawl gears have an equal catch rate. The black stippled curves represent 95 % CI for the estimated catch ratio curve. The vertical grey line represents MLS for shrimp in this fishery.

helpful because it reduces the sorting time and potential loss of shrimp during the mechanical sorting process. The recruitment of polar cod has decreased in recent years in certain parts of the Barents Sea (ICES, 2019). The impact from fisheries is unknown, but as the large mesh panel removed a large fraction of polar cod, it is obvious that its use would contribute to a reduction in the mortality for this species.

The reduction of the smallest length classes of Greenland halibut (5–14 cm) and polar cod (5–9 cm) by the panel may be explained by three processes acting simultaneously. One process is related to the vertical distribution of these species in the water column. The second

**Table 3**
Estimated catch ratios $CR(l, v)$ for specific length classes, average catch ratio $CR_{average}$ results and fit statistics for Greenland halibut, redfish, and polar cod. Values within parenthesis are the 95 % CIs. DOF = degrees of freedom. $CR_{average}$ is the size-integrated average value for the catch ratio of all length classes.

| Length (cm) | Greenland halibut | Catch ratio (%) Redfish | Polar cod |
|---|---|---|---|
| 5 | 4.92 (0.07–115.61) | 99.95 (99.03–100.87) | 37.20 (13.17–94.65) |
| 10 | 20.55 (11.94–41.49) | 99.26 (85.53–114.88) | 78.55 (63.00–107.89) |
| 15 | 40.65 (30.95–61.22) | 96.30 (45.32–201.87) | 102.94 (75.72–145.99) |
| 20 | 57.76 (33.86–98.57) | 88.76 (8.20–920.86) | 104.00 (47.24–437.10) |
| 25 | 190.16 (9.85–814.49) | — | — |
| $CR_{average}$ | 31.70 (23.18–50.37) | 95.08 (70.99–123.04) | 80.83 (65.79–106.80) |
| *p*-value | <0.0001 | <0.0001 | <0.0001 |
| Deviance | 81.71 | 58.37 | 66.16 |
| DOF | 33 | 21 | 26 |

deals with the endurance and swimming ability of the fish to avoid contacting the trawl panels, while the third is related to the length and angle of attack of the 200 mm mesh panel and how it improves escape probability.

Regarding the differences between the vertical distribution of shrimp and fish species in the water column, previous studies have documented that shrimp density is highest close to the seabed and more than 90 % would be expected to enter the trawl in the lowest three metres (De Louche, Hiscock, & Legge, 2006; Larsen et al., 1993). Consequently, inserting a large mesh panel in the upper part of the trawl would not contribute to a significant reduction of the shrimp catch (Broadhurst, Kennelly, & Isaksen, 1996; Broadhurst, 2000; Campos & Fonseca, 2004). Our results are in line with previous studies, as we demonstrated a non-significant impact on the catch efficiency of shrimp by adding the large mesh panel in the upper section of the trawl belly.

In contrast to shrimp, surveys have shown that small Greenland halibut (two years of age and less) can occur higher in the water column than shrimp and can even have a pelagic distribution (Huse, Gundersen, & Nedreaas, 1999; Jørgensen, 1997). Greenland halibut frequently come in contact with the upper part of the gear in shrimp trawls (Huse et al., 1999; Larsen, Herrmann, Sistiaga, Grimaldo et al., 2017), and are therefore susceptible to being sorted out by a large mesh panel if it is inserted in the upper part of the trawl. Polar cod and redfish are pelagic and/or semi-pelagic species and, therefore, able to contact sorting panels in the upper part of the shrimp trawls (Höffle, 2020; Skaret, 2020).

Swimming ability and endurance of fish is positively correlated with fish size (Breen, Dyson, O'Neil, Jones, & Haigh, 2004). In this context, large fish have a better swimming capacity than small fish and can therefore actively avoid the trawl netting (Breen et al., 2004). In our study, this length dependant swimming ability could explain the fish bycatch reduction when using the large mesh panel, especially for Greenland halibut. Small Greenland halibut with limited swimming capacity are unable to actively avoid trawl panels and are consequently excluded through the large-meshed panel in the tapered section with water flow. Larger Greenland halibut would be able to avoid the large mesh panel and be retained in the codend. This was also the case for the smallest length classes of polar cod.

Having a long-tapered panel in the upper section of the trawl belly increased the probability of fish coming into contact with the panel, consequently sorting out most of the smallest fish. Small Greenland halibut, polar cod and redfish entering the trawl at the same hight as the panel had a large probability of being released by the panel, provided that they were also were correctly oriented in respect to the panel

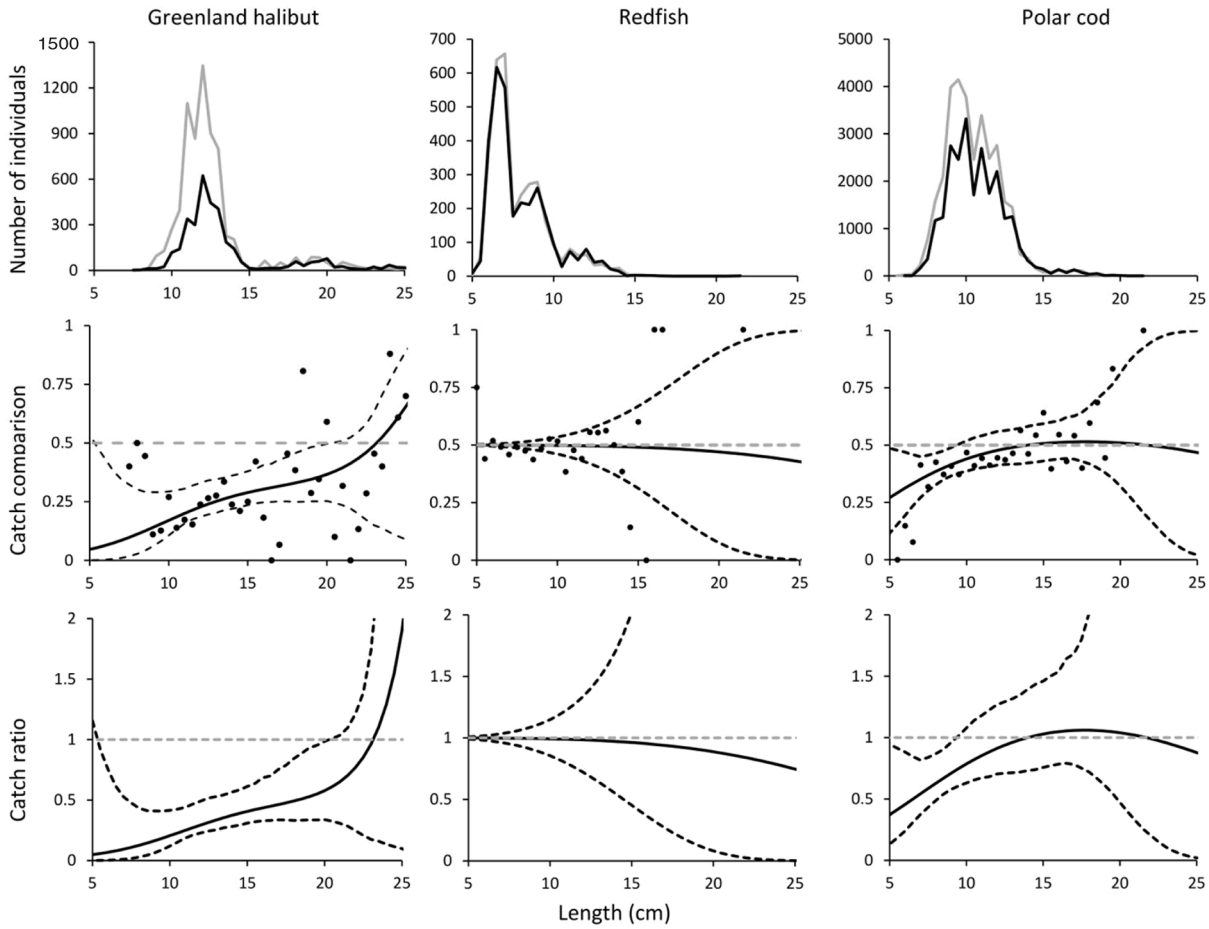


**Fig. 6.** Catch comparison and catch ratio analysis for Greenland halibut, polar cod, and redfish. Upper graphs: The length frequency distribution of bycatch fish caught by the test trawl (black line) and baseline trawl (grey line). Middle: The modelled catch comparison rate (black line) with 95 % CI's (black stippled curves). Black circles represent the experimental rate. The grey horizontal stippled line at 0.5 represents the point at which both trawl gears have equal catch rates. Bottom: The estimated catch ratio curve (black curve) with 95 % CI's (black stippled curves). The grey stippled line at 1.0 represents the point at which both gears have an equal catch rate.

meshes (Herrmann, Sistiaga, Larsen, Nielsen, & Grimaldo, 2013). Cuende, Arregi, Herrmann, Sistiaga, and Aboitiz (2020) demonstrated the importance of the angle of attack to enhance the contact probability and size selectivity in bottom trawls. Additionally, a steep tapering may also reduce the guiding effect, leading to larger fractions of fish passing through the panel (Santos et al., 2018). Since the large mesh panel tested in this experiment had three different tapering angles, we expected that sorting efficiency of the panel was larger when the tapering angle was 7.7 °and smaller when the tapering angle was 3.1°. Unfortunately, our experimental design does not allow for separate analysis of individual panel sorting efficiencies.

Some precaution should be taken regarding the results obtained due to limited number of fishing hauls collected over one season. However, the trials for this study were performed on a commercial fishing vessel thus following the commercial fishing practices. We performed nine valid paired hauls that are included in this study. The conditions for this experiment represented the typical conditions for this fishery. Moreover, the fishing depth was ranging between 200−300 m, thus we assume that season would not make difference in light conditions.

In conclusion, a large mesh panel in shrimp trawls could reduce fish bycatch of some species (e.g., Greenland halibut, and smaller-sized polar cod) without compromising the catch of target species and possibly avoid the closure of fishing areas. This also illustrates the need for more studies related to the reduction of the hight of the trawl in relation to vertical shrimp distribution. Several studies have investigated low opening or topless trawls in other fisheries (Eayrs, Pol, Caporossi, & Bouchard, 2017; Eayrs, Pol, Knight, & Ford, 2020; He et al., 2007; Krag, Herrmann, Karlsen, & Mieske, 2015) Since shrimp are generally distributed low in the water column, thus entering the trawl close to the seabed, reducing the hight of the headline would also limit the drag and reduce the associated fuel costs.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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