Fisheries Research 219 (2019) 105337

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Effect of three different codend designs on the size selectivity of juvenile cod in the Barents Sea shrimp trawl fishery

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ARTICLE INFO

Handled by George A. Rose

Keywords:
Shrimp fishery
Bycatch
Cod
Size selectivity
Nordmøre grid
Codend design

ABSTRACT

Shrimp trawlers often use a Nordmøre sorting grid ahead of a small mesh codend to avoid bycatch of juvenile fish while allowing shrimps to be efficiently caught. However, small fish can pass through the grid to enter the codend and risk being retained. The risk of retention for fish of different sizes depends the size selection in the Nordmøre grid and the size selection in the subsequent codend, which makes the process complex and often results in a bell-shaped size selection curve. In the Barents Sea shrimp fishery, cod (*Gadus morhua*) is one of the species of concern because of its great commercial value. We studied the size selection of juvenile cod when the trawl was equipped with the compulsory gear in the fishery: a 19 mm Nordmøre grid followed by a 35 mm diamond mesh codend. As expected, the size selection curve showed a bell-shaped signature, with a certain size range of juveniles having high retention risk, while the risk for smaller and bigger cod was smaller. The retention risk was highest for cod between 12 and 20 cm in length. We also tested two alternative designs in the aft section of the gear: a codend with 35 mm square mesh panels and a square mesh sorting cone section. Neither of these designs affected the size selection in the trawl significantly.

1. Introduction

The deep-water shrimp (*Pandalus borealis*) is a commercially important species that has been widely fished in the Northeast Atlantic for around four decades. Despite efforts made to reduce bycatch, the Norwegian trawl fishery targeting this species is still associated with juvenile fish bycatch issues. Due to the small mesh size used in the shrimp trawl (minimum 35 mm), substantial numbers of juveniles of various fish species may be retained when they are abundant in the shrimp fishing grounds. Introduction of the Nordmøre grid in the trawl in the early 1990s eliminated the bycatch of bigger fish because they could not pass through the 19 mm bar spacing grid and into the trawl codend (Isaksen et al., 1992; Grimaldo and Larsen, 2005; Grimaldo, 2006). However, juvenile fish can pass through the grid and enter the codend together with the targeted shrimp. The retention risk of fish of different species and sizes depends on the size selection in the Nordmøre grid and the size selection in the subsequent codend. Thus, the selection process is complex, and a bell-shaped size selection curve is often the result (Larsen et al., 2018).

The current regulations for the Northeast Atlantic deep-water shrimp fishery allow limited retention of juvenile fish from regulated species. Fishing grounds are closed if, for example, 10 kg of catch contain eight or more juvenile Atlantic cod (*Gadus morhua*). These rather strict bycatch rules have led to the closure of several large shrimp fishing grounds in the Northeast Atlantic over the last 20 years. The closures can last for weeks or months and cause huge operational problems and increased costs for the fishing fleet (e.g., the distances between potential fishing grounds become bigger with increased area closures). Bycatch of juvenile fish also causes practical problems, as it increases the need for sorting onboard the fishing vessel.

Larsen et al. (2018) recently assessed the size selection of the targeted deep-water shrimp as well as redfish (*Sebastes* spp.) and American plaice (*Hippoglossoides platessoides*) for the standard gear configuration used by the commercial fleet, a 19 mm Nordmøre grid combined with a 35 mm diamond mesh codend. They described how the bell-shaped size selection curve of the bycatch species could be modelled and assessed to obtain an estimate of which sizes of these species would have high risk of retention in the shrimp trawls when they are abundant on the fishing grounds. The results showed that specific size ranges of redfish and American plaice would have high risk for retention if they entered the trawl, which raised concerns about other bycatch species in this fishery.

Northeast Arctic cod is one of the largest cod stocks in the world,

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https://doi.org/10.1016/j.fishres.2019.105337
Received 15 March 2019; Received in revised form 22 July 2019; Accepted 25 July 2019

and economically it is the most important species in the Barents Sea fishery (Yaragina et al., 2011). Nevertheless, size selectivity of juvenile cod in the shrimp fishery in this area has not been assessed. Due to the gear setup used in the fishery and based on data for other roundfish (e.g., redfish), selectivity for cod is expected to be bell-shaped (Larsen et al., 2018). Thus, although the smallest and largest cod should escape the gear through the grid escape opening and codend meshes, a certain size range of cod will likely have higher retention probability. Depending on the size range and how high the retention probability for cod is, the shrimp fishery could have considerable impact on the cod stock if shrimp fishing activity increases. For example, Thorsteinsson (1992) estimated that the shrimp fishery in an Icelandic fjord killed gadoid juveniles that would have yielded around 1600 tons of fish some years later.

The main objective of this study was to investigate the bycatch size selectivity of juvenile cod in the Barents Sea shrimp fishery. We estimated the size selectivity of the compulsory selection system currently used in the area, a 19 mm Nordmøre grid followed by a 35 mm diamond mesh codend. Further, we investigated the effect of using alternative codend designs. Specifically, a codend with 35 mm square mesh panels and a square mesh sorting cone similar to a device tested in the 1980s (Valdermarsen, 1986, 1989). We addressed the following research questions:

- Does the selectivity for cod in the Northeast Atlantic shrimp trawl fishery follow the expected bell-shaped selectivity curve?
- To what extent is the selectivity of the compulsory 19 mm Nordmøre grid and 35 mm diamond mesh codend satisfactory for cod?
- Can the selectivity for cod be improved replacing the 35 mm diamond mesh codend with 35 mm square mesh panels or a sorting cone?

2. Materials and methods

2.1. Vessel, area, time, and gear set-up

The fishing trials were performed on board the R/V “Helmer Hanssen” (63.8 m LOA and 4080 HP) from 16 to 28 February 2016. The fishing grounds were located east of Hopen Island in the northern Barents Sea. The trials were carried out with two identical Campelen 1800# trawls, used one at a time. The trawls netting was built entirely of polyethylene with twine thickness 2 mm. The inside mesh size was 80 mm in the wings and 40 mm in the belly. Thyborøn T2 (6.5 m^2 and 2200 kg) trawl doors were used, and a 20 m long rope was linked between the warps 80 m in front of the doors, which kept the distance between the doors at 48–52 m while towing. The Campelen trawl has a 19.2 m fishing line and is believed to work at its optimal wingspread (ca. 15 m) and height (ca. 6.5 m) when the door distance is kept in this range. We used 40 m double sweeps and a 19.2 m long rock hopper gear built of three sections equipped with 46 cm rubber discs.

Both trawls were equipped with 4-panel Nordmøre grid sections. Each grid was made of stainless steel with outer dimensions of 1500 mm in height by 750 mm in width. The grid in both trawls was mounted so that it would maintain an angle of 45 degrees while fishing. The fishing trials were conducted using a shrimp trawl with a bycatch reducing system consisting of a Nordmøre grid followed by a size selective codend installed at the rear (Fig. 1). In this study, we present data collected with three different size selection configurations. The Nordmøre grid section in all three gears was identical but the codend differed: a 35 mm diamond mesh codend (mesh size 33.8 ± 1.0 (mean ± SD)), a 35 mm diamond mesh codend with square mesh panels (mesh size 32.2 ± 0.1 mm), and a square mesh sorting cone (mesh size 26.3 ± 0.9) (Fig. 1).

During the trials we used two experimental setups, a test setup and a control setup (Fig. 2). In the test setup, we used the three codends to be tested in this study, whereas in the control setup we used a 35 mm diamond mesh codend with an inner-net (mesh size 18.5 ± 0.9 mm) installed with a low hanging ratio to retain all sizes of shrimp and fish juveniles. The grid in the test setup was measured to be 18.8 ± 1.2 mm (mean ± SD), whereas the grid at the control setup was measured to be 18.8 ± 0.4 mm. In both setups, the grid was covered with a small mesh size cover to capture the fish and shrimp escaping through the escape outlet of the grid. The covers used were the same as those used by Larsen et al. (2018), and the meshes in the covers of the test and control setup, which were installed with a low hanging ratio, were 16.4 ± 0.5 mm and 18.9 ± 1.2 mm, respectively.

The trial period and data used in the present study partly overlapped with Larsen et al.’s (2018) study of the Nordmøre grid and 35 mm codend. However, Larsen et al. (2018) reported results only for the standard codend (35 mm diamond mesh) for shrimp, redfish, and American plaice. Herein we report results for cod for the standard codend and the two alternative codends.

2.2. Data analysis and parameter estimation

Two different experimental setups were used for the hauls conducted during the sea trials. In the test hauls, the Nordmøre grid followed by one of the three experimental codends was fished. In those hauls a small meshed cover collected fish and shrimp escaping in front of the Nordmøre grid, and we used no cover over the codend (Fig. 2). A number of hauls were conducted with this setup for each of the three experimental codends. In the control hauls, the codend contained a small mesh inner-net to prevent fish and shrimp from escaping through the codend. For this setup, fish and shrimp that escaped in front of the Nordmøre grid were collected in a small mesh cover as in the test setup (Fig. 2).

Test and control hauls were conducted in the same fishing area and during the same cruise. Together the catch data from these groups of hauls were applied to estimate the size selectivity for cod for each of the three experimental designs tested. In the test setup, the catch was collected in the grid cover (GT) and in the codend (CT), respectively, whereas for the control setup the catch was collected in the grid cover (GC) and the blinded codend (CC), respectively. For each haul, cod retained in compartments GT and CT or in GC and CC were measured and sorted into 1 cm wide length groups. Thus, the catch data consisted of count numbers (n) representing the number of cod in each length group in each of the compartments. This experimental setup and procedure for analyzing the collected data, which were used to estimate the size selectivity for each of the three different trawl configurations, followed the method described in Larsen et al. (2018). The overall ($r_{combined}(l, v_{grid}, v_{codend})$) and individual size selection for the Nordmøre grid ($p_{grid}(l, v_{grid})$) and codend ($r_{codend}(l, v_{codend})$) were described by the model:

$$
\begin{aligned}
r_{combined}(l, v_{grid}, v_{codend}) &= p_{grid}(l, v_{grid}) \times r_{codend}(l, v_{codend}) \\
p_{grid}(l, v_{grid}) &= C_{grid} \times (1.0 - logit(l, L50_{grid}, SR_{grid})) \\
r_{codend}(l, v_{codend}) &= logit(l, L50_{codend}, SR_{codend})
\end{aligned} \quad (1)
$$

where l denotes the length of cod and $p_{grid}(l, v_{grid})$ is the length-dependent passage probability through the Nordmøre grid. The length-dependent passage probability through the Nordmøre grid considers that some shrimp or fish may not contact the grid at all or do so with such a poor orientation that they will not be subjected to a length-dependent probability of passing through it. This is modeled by the length-independent parameter C_{grid}. For a cod contacting the grid with sufficiently good orientation to provide a length-dependent chance of passing through it, Eq. (1) assumes the traditional *logit* size selection model with parameters $L50_{grid}$ and SR_{grid} (see Wileman et al., 1996). For the codend size selection, Eq. (1) assumes that the retention probability can be modeled by a *logit* model with parameters $L50_{codend}$ and SR_{codend}.

To estimate the average size selection of the Nordmøre grid and each specific codend in the test trawl, we paired the pooled catch data

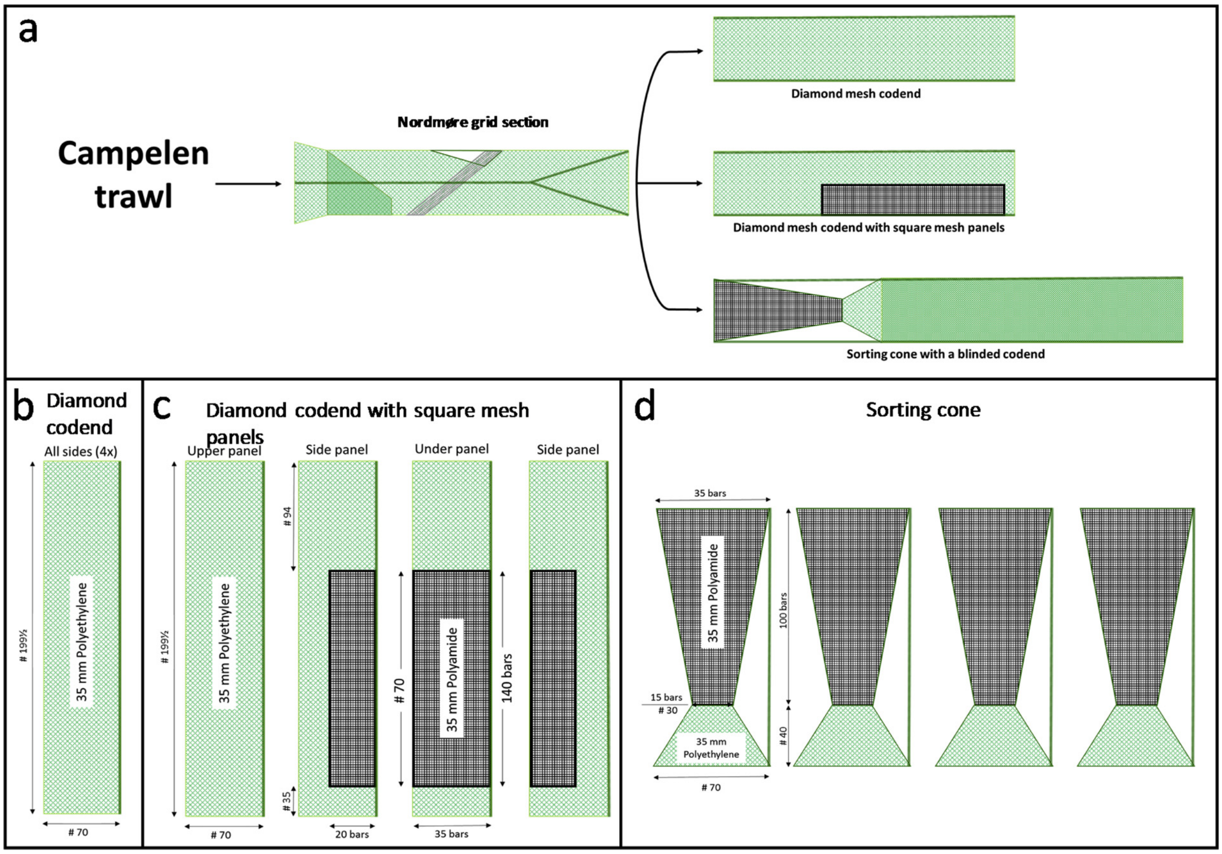

Fig. 1. Schematic view of the three gear configurations tested during the experiments (a): diamond mesh codend (b), diamond mesh codend with square mesh panels (c) and square mesh sorting cone (d).

from the test hauls with the pooled catch data from the control hauls. Based on this approach, the experimental data in the analysis were treated like three compartment data. Cod caught were observed in GT, CT, or (GC + CC). For the estimation based on the size selection model (1), we needed to express the probabilities p_{GT}, p_{CT}, and p_{GC+CC} for a cod of length l to be observed in each of these three compartments conditioned they were caught (Larsen et al., 2018):

$$\begin{aligned} & p_{GT}(l, \boldsymbol{v}_{grid}, \boldsymbol{v}_{codend}, SP) \\ & = \frac{SP \times (1.0 - p_{grid}(l, \boldsymbol{v}_{grid}))}{1.0 + SP \times (r_{combined}(l, \boldsymbol{v}_{grid}, \boldsymbol{v}_{codend}) - p_{grid}(l, \boldsymbol{v}_{grid}))} \\ & p_{CT}(l, \boldsymbol{v}_{grid}, \boldsymbol{v}_{codend}, SP) \\ & = \frac{SP \times r_{combined}(l, \boldsymbol{v}_{grid}, \boldsymbol{v}_{codend})}{1.0 + SP \times (r_{combined}(l, \boldsymbol{v}_{grid}, \boldsymbol{v}_{codend}) - p_{grid}(l, \boldsymbol{v}_{grid}))} \\ & p_{GC+CC}(l, \boldsymbol{v}_{grid}, \boldsymbol{v}_{codend}, SP) \\ & = \frac{1.0 - SP}{1.0 + SP \times (r_{combined}(l, \boldsymbol{v}_{grid}, \boldsymbol{v}_{codend}) - p_{grid}(l, \boldsymbol{v}_{grid}))} \end{aligned} \quad (2)$$

SP is the split parameter, which quantifies the probability that cod

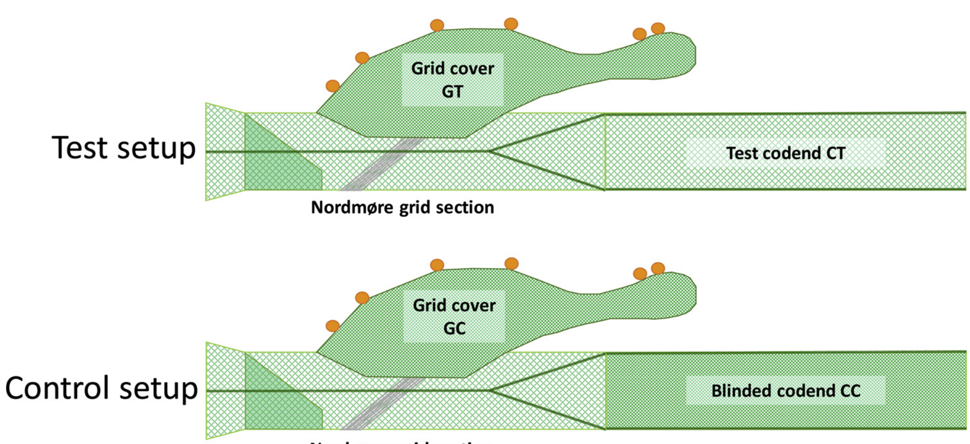

Fig. 2. Experimental gear setups used during the trials: test setup (top) and control setup (bottom).

will enter the selection section in one of the test hauls provided that it entered either in these test hauls or in one of the control hauls. *SP* is traditionally accounted for in paired-gear data analysis (Wileman et al., 1996). Using Eq. (2), the values for the parameters in selection model (1) can be estimated from the collected experimental data by minimizing the following function with respect to $\boldsymbol{v}_{grid}$, $\boldsymbol{v}_{codend}$ and *SP* (Larsen et al., 2018):

$$\sum_{i=1}^{a}\sum_{l}\{nGT_{li}\times ln(p_{GT}(l,\boldsymbol{v}_{grid},\boldsymbol{v}_{codend},SP))+nCT_{li}\times ln(p_{CT}(l,\boldsymbol{v}_{grid},\boldsymbol{v}_{codend},SP))\}+\sum_{j=1}^{b}\sum_{l}\{(nGC_{lj}+nCC_{lj})\times ln(p_{GC+CC}(l,\boldsymbol{v}_{grid},\boldsymbol{v}_{codend},SP))\} \tag{3}$$

where the inner summations are over length classes *l* in the experimental data, and the outer summations are over experimental fishing hauls *i* (from *1* to *a*) and *j* (from *1* to *b*) with, respectively, the specific test codend and control setup. nGT_{li}, nCT_{li}, nGC_{lj}, and nCC_{lj} are the number of cod of length class *l* caught in haul *i* and *j* in the respective compartment. Minimizing (3) with respect to the parameters in it is the same as maximizing the likelihood for the observed experimental data based on a multinomial model, assuming that formulated model (1) describes the experimental data sufficiently well. The observed experimental length-dependent portioning of the catches between the three compartments GT, CT, and GC + CC, which model (2) is expected to describe, are given by (Larsen et al., 2018):

$$\hat{p_{GTl}}=\frac{\sum_{i=1}^{a}nGT_{li}}{\sum_{i=1}^{a}(nGT_{li}+nCT_{li})+\sum_{j=1}^{b}(nGC_{lj}+nCC_{lj})}$$

$$\hat{p_{CTl}}=\frac{\sum_{i=1}^{a}nCT_{li}}{\sum_{i=1}^{a}(nGT_{li}+nCT_{li})+\sum_{j=1}^{b}(nGC_{lj}+nCC_{lj})}$$

$$\hat{p_{GC+CCl}}=\frac{\sum_{j=1}^{b}(nGC_{lj}+nCC_{lj})}{\sum_{i=1}^{a}(nGT_{li}+nCT_{li})+\sum_{j=1}^{b}(nGC_{lj}+nCC_{lj})} \tag{4}$$

Due to the experimental procedure followed, there was no obvious way to pair the data from the individual test and control hauls. Hence, to estimate the mean selectivity parameters for the experimental gear, the length-dependent expected total catches for the test hauls were combined and compared with the combined expected total catches for the control hauls (function (3)). The confidence limits for the parameters and curves for the size selection model were estimated using a double bootstrap method that accounts for the uncertainty resulting from this unpaired nature of the data collection (Larsen et al., 2018). We performed 1000 bootstrap repetitions to calculate the 95% percentile confidence limits (Efron, 1982; Chernick, 2007) for the selection parameters and curves.

The model's ability to describe the experimental data was evaluated based on the p-value, model deviance versus degrees of freedom (DOF), and inspection of how the model curve reflects the length-based trend in the data (Wileman et al., 1996). The p-value expresses the likelihood of obtaining at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. The analysis was carried out using the software SELNET (Herrmann et al., 2012, 2013a,b), which implements the models and the bootstrap method described above.

2.3. Indicators for bell-shaped retention probability

Because the bell-shaped retention risk (probability) of juvenile cod as given by $r_{combined}(l,\boldsymbol{v}_{grid},\boldsymbol{v}_{codend})$ is a very important issue in fisheries management, parameters related to the bell-shaped retention curve were examined. Indicators RW_{05}, RW_{25}, RW_{50}, RW_{75}, RW_{95}, *Rmax*, *LRmax*, and RA_{05} (Fig. 3) were calculated by a numerical technique implemented in the software tool SELNET.

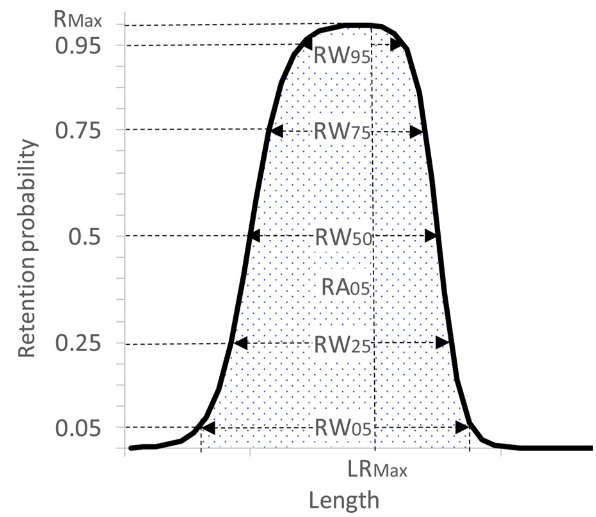

Fig. 3. Bell-shaped retention curve with indicators.

Table 1
Overview of the hauls included in the data analysis. Haul number, Towing time (min), depth (m), the position at trawl start (Latitude and Longitude), and the number of cod captured in the grid cover (*nG*) and codend (*nC*) with each of the setups are provided.

Haul No	Codend	Tow time (min)	Depth (m)	LAT	LONG	nC	nG
H202	Square	61	267	7605.6N	03523.1E	8	43
H204	Control	60	268	7604.9N	03526.9E	11	21
H205	Control	61	257	7605.4N	03517.8E	8	17
H206	Square	59	277	7606.6N	03533.9E	2	8
H207	Square	60	265	7606.0N	03518.2E	2	7
H208	Control	60	278	7605.3N	03511.1E	9	58
H210	Control	60	271	7605.9N	03533.8E	7	12
H211	Square	60	257	7604.5N	03516.4E	9	18
H212	Square	61	267	7604.2N	03507.6E	6	18
H213	Control	63	266	7605.9N	03521.9E	9	28
H214	Control	61	271	7606.5N	03531.9E	12	8
H215	Square	62	267	7606.1N	03520.8E	3	14
H216	Square	60	285	7607.4N	03533.0E	6	21
H217	Control	60	271	7606.6N	03521.9E	12	12
H218	Control	63	272	7606.5N	03531.9E	12	18
H220	Square	63	276	7606.4N	03532.4E	11	38
H221	Diamond	60	268	7606.1N	03522.3E	14	38
H225	Diamond	62	265	7605.4N	03523.3E	9	46
H226	Diamond	64	268	7605.8N	03525.1E	22	114
H229	Diamond	62	265	7605.7N	03522.1E	13	29
H230	Diamond	63	274	7605.9N	03523.4E	22	26
H233	Diamond	60	256	7604.7N	03516.8E	7	25
H234	Diamond	63	252	7604.0N	03512.9E	23	117
H238	Diamond	66	269	7606.1N	03517.2E	9	38
H244	Sort. Co	60	276	7606.9N	03534.1E	10	29
H246	Sort. Co	62	262	7604.7N	03533.9E	20	48
H249	Sort. Co	60	261	7605.8N	03521.3E	12	43
H250	Sort. Co	30	263	7604.9N	03531.5E	1	9
H254	Sort. Co	60	268	7604.6N	03536.4E	11	22
H255	Sort. Co	60	266	7605.6N	03523.8E	13	41
H258	Sort. Co	62	269	7604.1N	03537.5E	25	62
H259	Sort. Co	60	264	7605.0N	03528.4E	25	45

RW_{05}, RW_{25}, RW_{50}, RW_{75}, and RW_{95} quantify the length span (in cm) with, respectively, at least 5, 25, 50, 75, and 95% probability of retention. *Rmax* is the maximum retention probability on the bell-shaped curve, and *LRmax* is the corresponding cod length (in cm). RA_{05} quantifies the area of the retention bell-shaped curve when the probability is ≥ 5%. For each of the indicators, 95% confidence bands were estimated using the double bootstrap method described above.

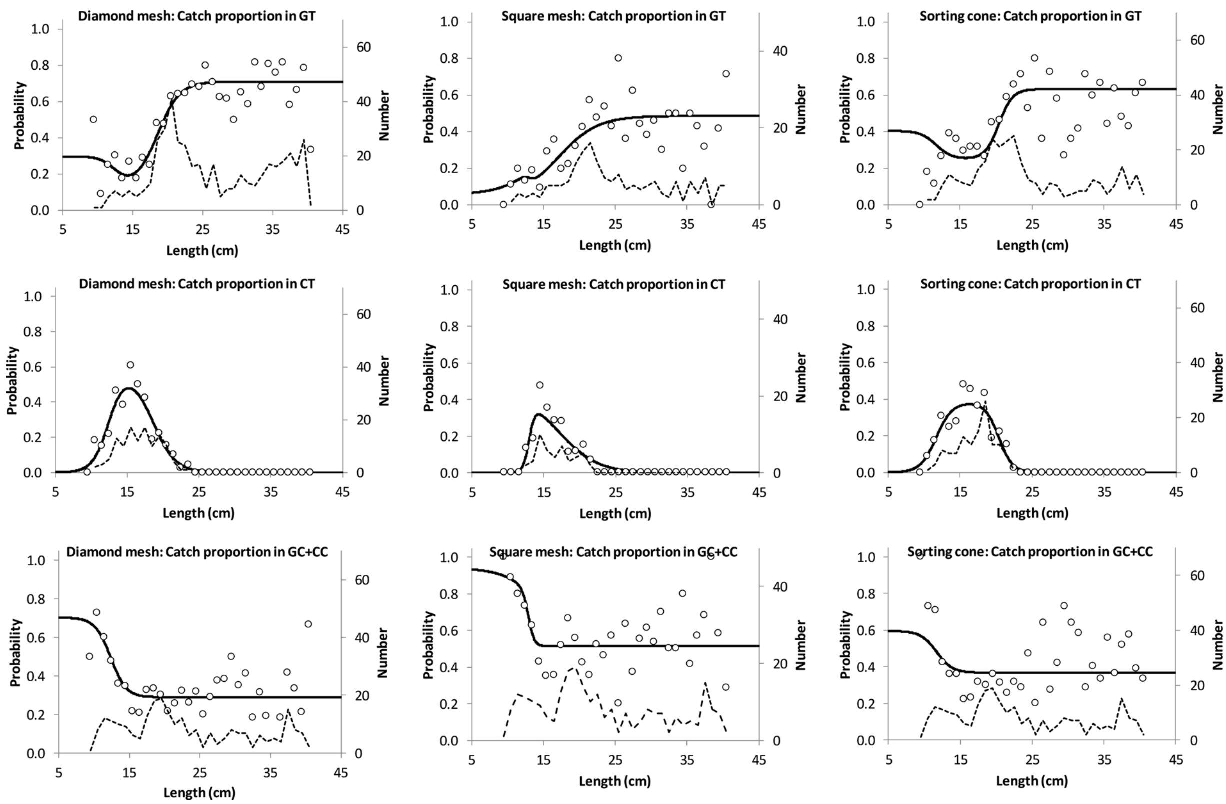

Fig. 4. The plots show the catch proportion of cod observed in the test grid cover (GT), test codend (CT) and control grid cover + control codend (GC + CC), and the model fitted to the data (solid black line) for the diamond mesh codend, square mesh codend and sorting cone. The stippled grey line in the plots show the size distribution of cod present in each compartment(s).

Table 2
Selectivity results and indicators obtained for the three gear setups tested during the experiments: Grid and diamond mesh codend, grid and square mesh panel codend, and grid and a sorting cone. Values in () are 95% confidence bands.

	Diamond M. Codend	Square M. P. Codend	Sorting Cone
C_{grid}	0.83 (0.62–0.98)	0.94 (0.59–1.00)	0.61 (0.44–0.97)
$L50_{grid}$ (cm)	18.51 (16.98–20.54)	17.02 (13.86–20.60)	20.38 (18.19–21.75)
SR_{grid} (cm)	3.46 (1.55–5.01)	5.98 (0.10–13.71)	2.10 (0.10–4.94)
$L50_{codend}$ (cm)	13.38 (11.13–22.05)	13.16 (12.04–14.53)	12.23 (9.98–14.83)
SR_{codend} (cm)	2.42 (0.10–23.14)	0.90 (0.10–2.04)	2.42 (0.10–6.24)
SP	0.71 (0.58–0.82)	0.49 (0.35–0.62)	0.63 (0.51–0.74)
LR_{max} (cm)	15.80 (13.49–17.99)	15.13 (13.00–19.50)	17.63 (0.00–20.94)
R_{max}	0.63 (0.29–0.81)	0.63 (0.40–0.88)	0.58 (0.06–0.74)
RW_{05} (cm)	12.60 (10.21–21.48)	12.85 (8.82–20.65)	13.29 (9.87–17.61)
RW_{25} (cm)	7.38 (3.54–9.57)	7.01 (5.53–8.67)	8.91 (6.66–11.31)
RW_{50} (cm)	3.72 (0.00–6.38)	3.04 (0.00–7.12)	4.88 (0.00–8.63)
RW_{75} (cm)	0.00 (0.00–2.72)	0.00 (0.00–2.24)	0.00 (0.00–0.00)
RW_{95} (cm)	0.00 (0.00–0.00)	0.00 (0.00–0.00)	0.00 (0.00–0.00)
RA_{05}	4.21 (2.87–5.72)	4.01 (3.22–5.23)	4.83 (3.59–6.07)
DOF	58	58	58
Deviance	33.10	55.51	52.39
p-value	0.9965	0.5686	0.6831

2.4. *Inference of difference in codend size selection and combined retention between designs*

To infer the effect of changing from one codend (A) to another (B) on the codend size selection curve $r_{codend}(l, \boldsymbol{v}_{codend})$ and on the combined selection curve $r_{combined}(l, \boldsymbol{v}_{grid}, \boldsymbol{v}_{codend})$, the length-dependent change $\Delta r(l)$ in the values was estimated by:

$$\Delta r(l) = r_B(l) - r_A(l) \tag{5}$$

where $r_A(l)$ represents the value for $r_{codend}(l, \boldsymbol{v}_{codend})$ or $r_{combined}(l, \boldsymbol{v}_{grid}, \boldsymbol{v}_{codend})$ for codend design A, and $r_B(l)$ represents the value for codend design B. Efron 95% percentile confidence limits for $\Delta r(l)$ were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) for both $r_A(l)$ and $r_B(l)$. As they were obtained independently, a new bootstrap population of results was created for $\Delta r(l)$ by:

$$\Delta r(l)_i = r_B(l)_i - r_A(l)_i \; i \in \; [1...1000], \tag{6}$$

where i denotes the bootstrap repetition index. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on (6) using the two independently generated bootstrap files (Herrmann et al., 2018). Based on the bootstrap population, Efron 95% percentile confidence limits were obtained for $\Delta r(l)$ as described above.

3. Results

3.1. *Experimental data*

We conducted 32 hauls using the Nordmøre grid with three different codends. We obtained a sufficient number of cod to be included in the data analysis for eight hauls with the diamond mesh codend, eight hauls with the square mesh panel codend, eight hauls with the sorting cone, and eight control hauls. All cod present in the covers and codends were measured, which resulted in a total of 1436 cod measurements (Table 1).

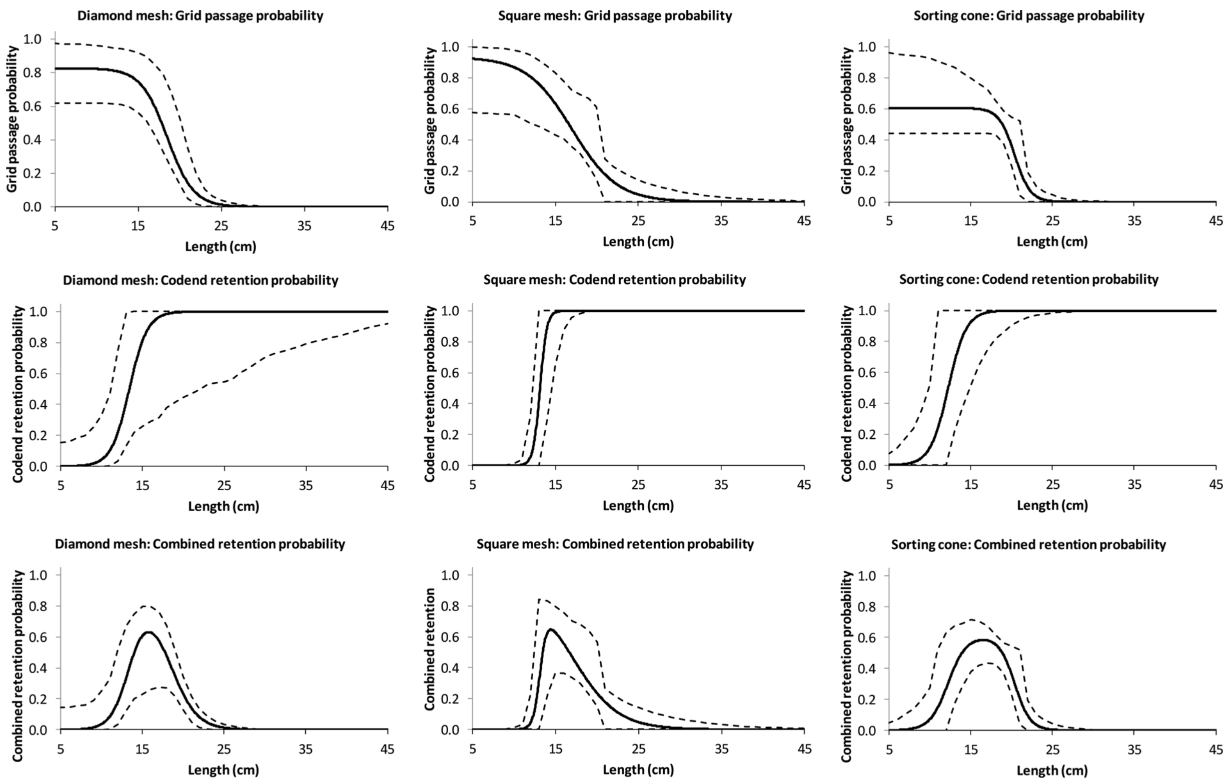

Fig. 5. Grid passage probability, codend retention probability and combined (grid + codend) retention probability for the grid and diamond mesh codend, grid and square mesh codend, and grid and sorting cone setups. Black solid line shows the selectivity curve and the stippled lines represent the 95% CIs.

3.2. Size selectivity of cod

The selectivity results obtained clearly show that the model presented by Larsen et al. (2018) represented the experimental data well (Fig. 4). This is reflected by the fit statistics, which show p-values > 0.05 and deviance values of the same order of magnitude as the DOF for all three setups tested (Table 2). For all three combinations of gear, the combined size selectivity showed the expected bell-shaped curve (Fig. 5).

The percentage of cod that contacted the grid was relatively high and was estimated to be 83% and 94% when the grid was used in combination with the diamond mesh codend or the square mesh panel codend, respectively. However, when the grid was used with the sorting cone, only 61% of the cod entering the gear was estimated to contact the grid (Table 2; Fig. 5). However, the differences in contact probability estimated with the three gears were not statistically significant.

The estimated *LRmax* and *Rmax* values were similar for the three gear setups, and the small differences among them were not statistically significant. For the diamond mesh codend and the square mesh panel codend, the maximum retention of cod was estimated to be 63% for cod of ~16 cm and 17 cm, respectively, whereas for the grid combined with the sorting cone the maximum retention of cod was estimated to be at 58% but for cod of ~18 cm.

RA_{05}, which quantifies the area of the retention bell-shaped curve when the probability of fish retention is ≥ 5%, is a good indicator of how many juvenile cod of different sizes are really retained by the gear. The results obtained indicated that the grid and sorting cone combination retained slightly more juvenile cod than the other two gear combinations. However, these differences were small and not statistically significant (Table 2).

3.3. Differences in size selection among the different codends

Substituting the diamond mesh codend used by the fleet today with the square mesh panel codend or the sorting cone did not result in additional release of cod from the shrimp trawl. The results were similar when the codend data were analyzed in combination with the grid, and no significant differences among the different codends in combination with the grid were detected for any of the length classes (Fig. 6).

4. Discussion

Among several input controls, the technical regulations for the bottom trawl fisheries have contributed to the recovery and positive development of many fish stocks in the Northeast Atlantic (Zimmerman and Werner, 2019). In the present study, we investigated the size selectivity of cod in the Northeast Atlantic shrimp trawl fishery using a 19 mm Nordmøre grid followed by a 35 mm diamond mesh codend, which is the compulsory gear in the area. In addition, we tested two alternative designs in which the diamond mesh codend was replaced by a codend with 35 mm square mesh panels or a square mesh sorting cone.

The selectivity data obtained during the sea trials showed that the selectivity of cod in a shrimp trawl equipped with a Nordmøre grid and a diamond mesh codend followed the expected bell-shaped curve. This finding agrees with the results obtained in an earlier study of other fish species caught with the same type of selectivity gear and in the same fishery (Larsen et al., 2018). The top of the bell-shaped selectivity curve was estimated to be at a retention rate of 63% for cod of ~16 cm, meaning that 63% of the cod at this length entering the shrimp trawl would be retained by the gear. Considering the regulations and that the authorities close fishing areas where the catch contains more than eight cod juveniles per 10 kg of catch, it is clear that the 19 mm grid and 35 mm diamond mesh codend gear used in the fishery today would not perform satisfactorily in shrimp fishing grounds where juvenile cod were relatively abundant.

In a series of experiments carried out in the Icelandic shrimp trawl

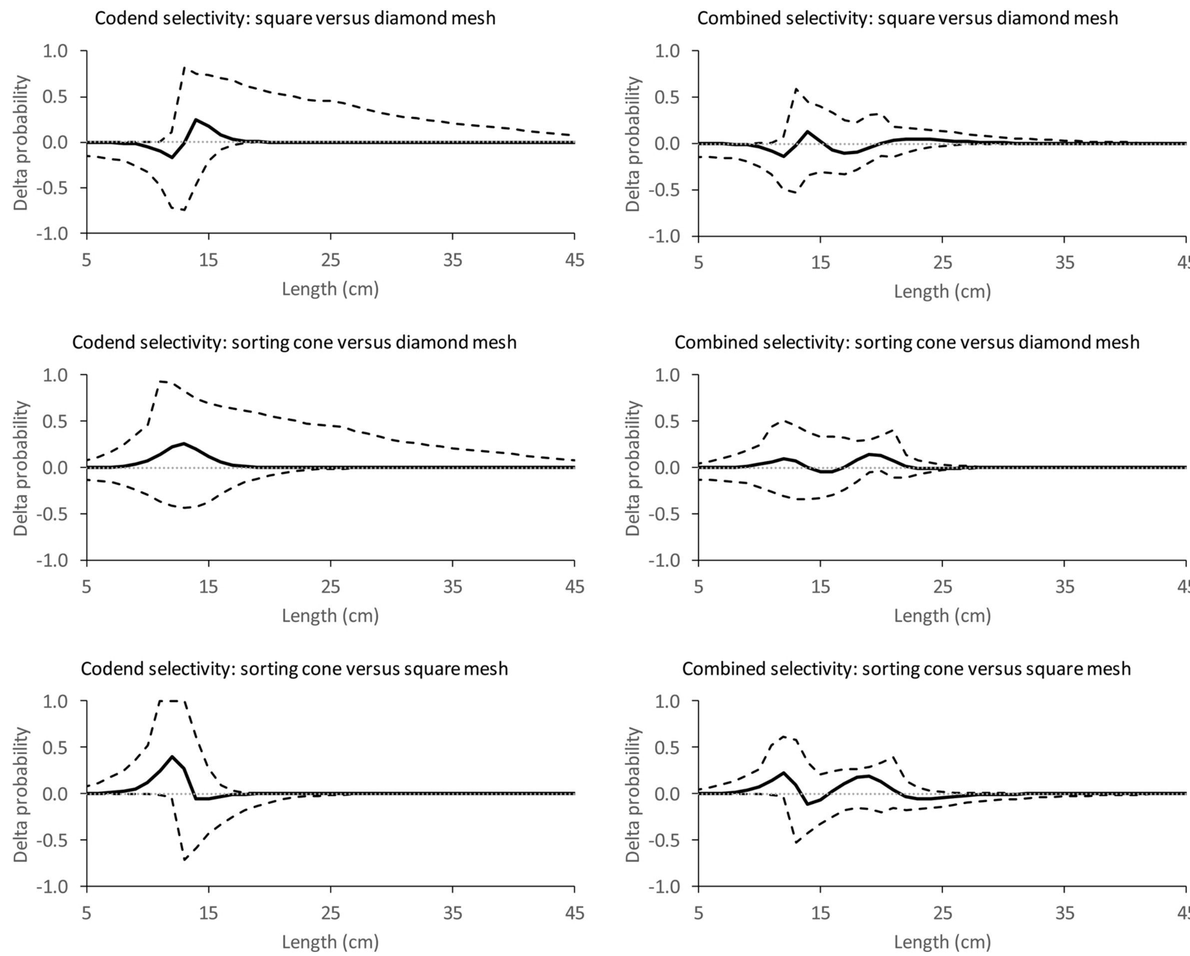

Fig. 6. Differences in the selection properties between the three gears tested expressed as delta retention probability. The black solid curve represents the difference in selectivity for each of the comparisons, while the stippled curves represent the 95% CIs for this difference.

fishery, Thorsteinsson (1992) studied the effect of changing from a diamond mesh codend to a square mesh codend on the size selectivity of several juvenile fish species. The results of the study showed in general a dramatic decrease for all juvenile species with the change in the codend design. Studies with square mesh codends carried out in different shrimp fisheries have also reported reductions of juvenile fish bycatch (Karlsen and Larsen, 1989; Broadhurst and Kennelly, 1996; Silva et al., 2012).

We tested codends with square mesh panels or a square mesh sorting cone to investigate whether they could improve the selectivity of cod relative to the diamond mesh codend. Neither codend provided any significant improvement in cod selectivity with respect to the diamond mesh codend. The results for the square mesh panel codend contrast some results reported in the literature (Karlsen and Larsen, 1989; Thorsteinsson, 1992; Broadhurst and Kennelly, 1996; Silva et al., 2012), although there are studies that also failed to demonstrate any significant improvement in fish juvenile selectivity with the application of square mesh codends (Lehmann et al., 1993). One reason for not finding any significant differences between the diamond mesh codend and the square mesh panel codend could be related to the design we used. We tested a conventional diamond mesh codend with square mesh sections installed in the aft and side panels of the codend. The positioning of the panels could have been suboptimal for the escape of juvenile cod from the codend, although Melli et al. (2018) showed that small cod prefer to stay close to the lower panel of the gear, and one would therefore expect the design used here to be adequate. Regarding the sorting cone, one would expect that a narrowing passage with square meshes would facilitate the escape of cod that has passed through the grid, but the results show that this was not the case. This type of sorting cone was tested in Norway in in the late 1980s and seemed to be relatively successful at sorting juveniles of different species, but the design we tested did not work for cod (Valdermarsen, 1986).

In conclusion, the results of this study show that the gear consisting of the 19 mm grid and 35 mm diamond mesh codend used by the shrimp trawler fleet in the Northeast Atlantic today does not reduce the capture of all juvenile cod efficiently. Furthermore, inserting square mesh panels in the lower and side panels of the codend or replacing the diamond mesh codend with a sorting cone did not provide any significant improvement in the selectivity of juvenile cod in the Northeast Atlantic shrimp trawl fishery.

Acknowledgements

We would like to thank the crew of RV “Helmer Hanssen” and Ivan Tatone, Lise Langård, Ingeborg Sætra, Hermann Pettersen, Tomas Araya, and Andre Frainer for their valuable help during the sea trials. We are grateful to the Arctic University of Norway UIT in Tromsø, the Norwegian Seafood Research Fund (Grant number 901303), and the Directorate of Fisheries of Norway for their financial support.

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