Effect of a quality-improving codend on size selectivity and catch patterns of cod in the Barents Sea bottom trawl fishery

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Abstract

To address the issues related to catch quality of trawl-caught fish a new codend concept developed and tested exhibited significantly improved quality of caught cod (*Gadus morhua* L.) compared to that of the conventional codend used in the Barents Sea bottom trawl fishery. However, the design of the new quality-improving codend raised concerns about its size selectivity and the possibility that lower selectivity could negatively impact the catch pattern by increasing the proportion of undersized cod. Therefore, the goal of this study was to quantify and compare the size selectivity and catch pattern for cod of the conventional and new quality improving codend in the Barents Sea bottom trawl fishery. The new quality-improving codend had significantly lower relative size selectivity than the conventional codend, but no significant difference in the catch patterns was detected. Further, estimation of the absolute size selectivity revealed that the increased retention of small cod when using the quality-improving codend was minor. Hence, despite the reduced selectivity, the quality-improving codend can be used with low risk of retaining small cod.

Keywords: Codend, bottom trawl, cod, sequential codend, size selectivity

Introduction

The quality of trawl caught fish can vary greatly, and can be of deteriorated catch quality (Digre et al., 2010; Rotabakk et al., 2011). In the Barents Sea bottom trawl fishery, about 70% of the annual quota of Northeast Arctic cod (*Gadus morhua* L.) is caught with bottom trawls (ICES, 2015). The technical regulations are largely designed to minimize the amount of bycatch and consist mainly of minimum codend mesh size regulations and the compulsory use of a size selective sorting grid. An important factor that is believed to contribute to catch defects is the large meshes that are regulated by law. Large meshes are required to ensure the possibility of escapement of undersized fish that do not escape through the mandatory size selective sorting grid (Sistiaga et al., 2016a; Brinkhof et al., 2018a). Moreover, codends often are made from coarse materials with a large mesh size, causing high water flow, and thus they do not create a lenient and benign environment for fish.

Brinkhof et al. (2018a) recently described a new codend concept, called a dual sequential codend, that demonstrated improved quality of trawl-caught cod. They reported that the probability of catching cod without any visual quality defect was five times higher when using the sequential codend. The codend was designed so that it would maintain the size selective properties required during towing at the seabed while also providing a more quality-preserving environment for the catch during haul-back. In the dual sequential codend, the fish are retained in the anterior codend segment during towing, and this segment has the size selective attributes required by law (i.e., minimum mesh size of 130 mm). The entrance to the posterior codend segment is kept closed with a hydrostatic codend releaser during fishing, and it is opened at a pre-set depth during haul-back. This posterior quality-improving codend segment, which the catch enters during haul-back, consists entirely of small meshes made of thick twine (Brinkhof et al., 2018a). Hence, it is reasonable to assume that when the catch enters the posterior codend segment, the escapement of undersized fish is no longer possible. This could potentially alter the size selective properties of the codend compared to a conventional codend, from which fish are able to escape during haul-back. If few or no fish escape during the haul-back phase regardless of codend type, the overall selectivity of the fishing process would be unaffected by the new codend. However, if fish generally escape from the conventional codend during the haul-back phase, the new codend could potentially affect the overall size selectivity of the fishing process. This would mean that the dual sequential codend would likely retain more undersized fish compared to a conventional codend. Previous studies have documented an ongoing selection process during haul-back (Madsen et al., 2008; Grimaldo et al., 2009; Herrmann et al., 2013; Brinkhof et al., 2017), so this potential issue needed to be investigated.

Therefore, the aim of this study was to compare the size selectivity and catch pattern for cod with the conventional and dual sequential codends in the Barents Sea bottom trawl fishery. Specifically, the following research questions were addressed:

- Is there any difference in the size selectivity between the trawl equipped with the conventional codend or that with equipped with the dual sequential codend?
- Is there any effect on the length-dependent catch patterns between the two codends?
- Will the retention risk for small cod be sufficiently low when using the sequential codend?

Materials and methods

Study area, trawl rigging, and data collection

Experimental fishing trials were conducted between 27 February and 5 March 2018 onboard the R/V "Helmer Hanssen" (63.8 m, 4080 HP) along the coast of north Norway in the southern Barents Sea (N 71°21' E 23°43' – N 71°21' E 24°24'). During the first part of the cruise, two identical and commercially rigged trawls were used; one was equipped with a conventional codend and the other was equipped with the sequential codend. The trawls were used alternately, which enabled estimation of the relative size selectivity between the two trawls equipped with the two different codends. The trawls were equipped with Injector Scorpion (3100 kg, 8 m^2) otter boards with 3 m long backstraps followed by a 7 m long chain, which was linked to the 60 m long sweeps. To reduce abrasion, an Ø53 cm bobbin was inserted in the center of the sweeps. The 46.9 m long ground gear consisted of a 14 m chain (Ø19 mm) with three bobbins (Ø53 cm) on each side and an 18.9 m long rockhopper gear with Ø53 cm rubber discs. The ground gear was attached to the 19.2 m long fishing line of the trawl. The two trawls, Alfredo No. 3, were built entirely out of polyethylene with a 155 mm mesh size. The headline of the trawls was 35.6 m long and equipped with 170 floats (Ø8``). Both trawls were equipped with a flexigrid with 55 mm bar spacing, which is one of the compulsory sorting grids in this fishery (Sistiaga et al., 2016a).

The section with the flexigrid in the conventionally configured trawl was followed by an 9 m long extension piece (150 mm mesh size), which was preceded by a 11 m long two-panel codend consisting of single-braided Ø8 mm Euroline Premium (Polar Gold) netting in the under panel and double-braided Ø4 mm polyethylene in the upper panel, with a mesh size of 133 ± 5.1 mm. The second trawl was equipped with a dual sequential codend mounted directly to the flexigrid section (Brinkhof et al., 2018a) (Fig. 1). The first codend segment built in exactly the same way as the conventional codend, and had a mesh size of 139 ± 2.5 mm. The second codend segment, which was the quality-preserving section (Brinkhof et al., 2018a), was 10 m long and consisted of four panels with a nominal mesh size of 6 mm (1440 meshes in circumference, 360 meshes in each panel) (Fig. 1). The codend segment was strengthened with an outer knotless codend (Ultracross) with 112 mm nominal mesh size (90 meshes in circumference) and four lastridge ropes, which were 5% shorter than the netting in the codend segment (Fig. 1). Because this codend segment does not meet the size selective properties required due to its small mesh size, the entrance of the codend was closed during fishing at the seabed. During haul-back, the entrance of the codend segment was opened by detaching a choking rope using a hydrostatic codend release mechanism (produced by www.fosstech.no) (Fig. 1). The catch releaser was charged during descent by the ambient pressure. The accumulated pressure was used to open a release hook during the ascent, which then detached the choking rope at a pre-set depth of 120 m, thereby enabling free passage of fish from the selective codend segment into the quality-improving codend segment.

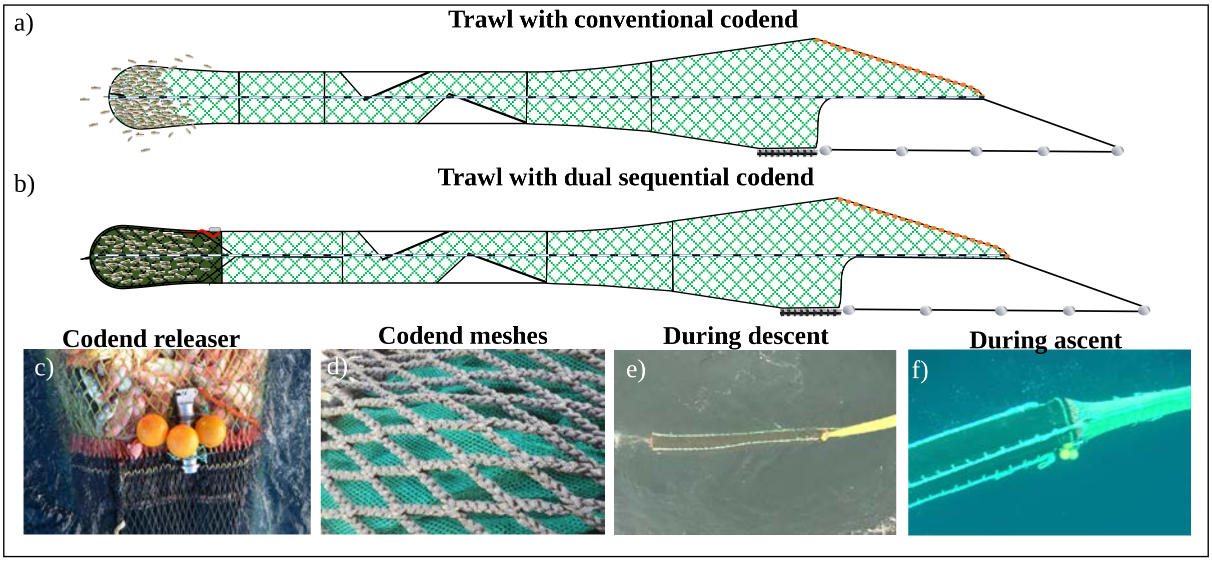

Fig. 1. Setup of the trawl with the (a) conventional codend and (b) dual sequential codend; (c) Dual sequential codend releaser mounted on the codend segment transition with the rope detached; (d) codend meshes; (e) and (f) show the dual sequential codend during descent and ascent, respectively.

During the second part of the cruise, a group of hauls were conducted with the trawl with the conventional codend, but all escape outlets were covered with covers to retain all escaping fish that entered the trawl. These hauls were used to document the abundance of all length groups of cod present in the experimental area that entered the trawl, and these data were enabled the estimation of the absolute selectivity of the trawl with the conventional codend and the sequential codend. The small meshed cover placed over the flexigrid was similar to that used by Sistiaga et al. (2016a), whereas the cover placed over the codend was the same as that used by Grimaldo et al. (2017). The total length of all cod retained in the trawls was measured to the nearest lower centimeter; no subsampling was conducted.

Experimental methods

Because the conventional codend and quality-improving codend each were used every second haul in the same area during the first part of the cruise, the collected catch data were treated as paired catch comparison data (Krag et al., 2015) obtained by an alternate haul method.

Model for quantifying missing size selectivity in the sequential codend

Based on the approach described by Brinkhof et al., (2017b), the size selectivity process during trawling with both the conventional and sequential codends can be regarded as a temporal sequential process consisting of a towing phase (*t*) followed by a haul-back phase (*h*). The haul-back selectivity phase can be viewed as a spatial sequential process, first with selectivity in the gear before the catch build up zone in the codend (*a*) followed by a selectivity process in the codend catch build up zone (*b*). Based on these considerations, the total selectivity process with the conventional codend $r_c(l)$ can be modelled by:

$$r_c\,(l) = rt_c(l) \times\; rha_c(l)\; \times\; rhb_c(l) \qquad (1)$$

whereas the total size selectivity with the sequential codend $r_s(l)$ can be modelled by:

$$r_s\,(l) = rt_s(l) \times\; rha_s(l)\; \times\; rhb_s(l) \qquad (2)$$

where *rt* denotes size selectivity during towing; *rha* denotes size selection in the anterior and codend sections in front of the catch build up zone during haul-back, which includes the sorting grid and extension piece; and *rhb* denotes size selectivity in the catch build up zone of the codend during haul-back (Fig. 2). Let nc_{li} and ns_{li} be the numbers of fish in length class *l* caught in haul pair *i* in the conventional codend and the sequential codend, respectively. Based on the group of *a* paired hauls, we can quantify the experimental average catch comparison rate CC_l (Herrmann et al., 2017) as follows:

$$CC_l = \frac{\sum_{i=1}^{a}\frac{nc_{li}}{qc_i}}{\sum_{i=1}^{a}\frac{nc_{li}}{qc_i}+\sum_{i=1}^{a}\frac{ns_{li}}{qs_i}} \qquad (3)$$

where qc_i and qs_i are sampling factors introduced to account for unequal towing time between the conventional (tc_i) and sequential (ts_i) codend within each pair *i* fished. Specifically, qc_i and qs_i were set at:

$$qc_i = \frac{tc_i}{max(tc_i,ts_i)} \qquad qs_i = \frac{ts_i}{max(tc_i,ts_i)} \qquad (4)$$

The next step is to express the relationship between the catch comparison rate $CC(l)$ and the size selection process for the conventional codend $r_c(l)$ and the sequential codend $r_s(l)$. In this process, assume that the total amount of fish n_l in length class l enters the trawl with the conventional or sequential codend (Fig. 2).

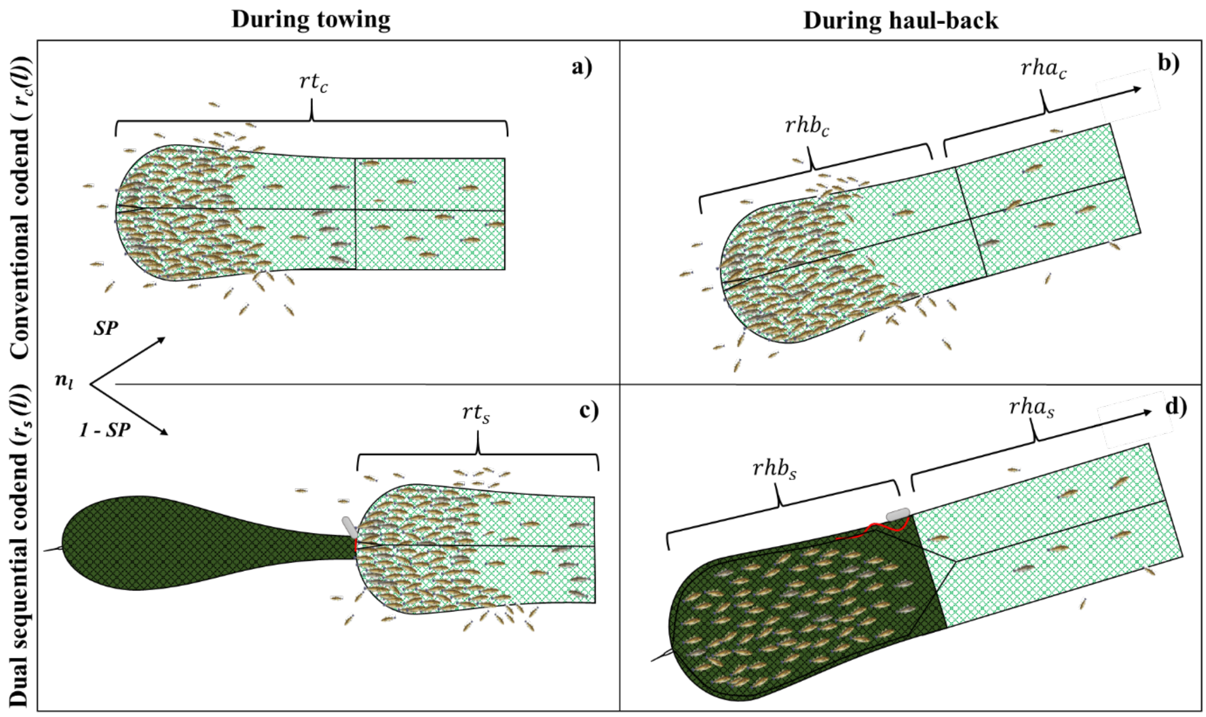

Fig. 2. Schematics showing the size selectivity that occurs with the conventional codend ($r_c(l)$) during (a) towing and (b) haul-back. (c) Size selection in the anterior codend segment of the dual sequential codend during towing, which, due to the codend design, (d) should cease during haul-back when the fish enter the posterior quality-improving codend segment.

SP is the proportion of fish entering the aft part of the trawl with the conventional codend compared to the sequential codend. SP is assumed to be length independent. Therefore, the expected values for $\sum_{i=1}^{a}\frac{nc_{li}}{qc_i}$ and $\sum_{i=1}^{a}\frac{ns_{li}}{qs_i}$, respectively, are:

$$\sum_{i=1}^{a}\frac{nc_{li}}{qc_i} = n_l \times SP \times r_c(l)$$
$$\sum_{i=1}^{a}\frac{ns_{li}}{qs_i} = n_l \times (1 - SP) \times r_s(l) \qquad (5)$$

Based on models (1) to (5) and Fig. 2, the theoretical catch comparison rate $CC(l)$ becomes:

$$CC(l) = \frac{n_l \times SP \times rt_c(l) \times rha_c(l) \times rhb_c(l)}{n_l \times SP \times rt_c(l) \times rha_c(l) \times rhb_c(l) + n_l \times (1-SP) \times rt_s(l) \times rha_s(l) \times rhb_s(l)} \qquad (6)$$

Next, the following assumptions are introduced:

$$rt_c(l) \approx rt_s(l)$$
$$rha_c(l) \approx rha_s(l) \qquad (7)$$
$$rhb_s(l) = 1.0$$

The first condition assumes that the size selection between the two trawls is approximately equal during the towing phase because the grid systems are identical and the active codends during towing are designed to have equal size selectivity. The second condition assumes that the size selectivity in front of the codends during haul-back is approximately equal based on the use of the same grid systems and mesh size in the netting. The last condition assumes that the active codend in the quality-improving codend during haul-back will retain all sizes of cod due to the small mesh size.

Based on the three assumptions equation (6) can be simplified to:

$$CC(l) = \frac{SP \times rhb_C(l)}{SP \times rhb_C(l) + 1 - SP} \quad (8)$$

With (8) we have obtained a direct relationship between the size selection process that will be missing with the sequential codend and the catch comparison rate. Therefore, this size selectivity then can be assessed based on estimating the catch comparison rate.

We estimated the average missing size selectivity with the sequential codend using maximum likelihood methods by minimizing the following equation with respect to the parameters describing *CC(l)*, which in addition to *SP*, include the parameters in the model that we apply for $rhb_C(l)$:

$$-\sum_l \left\{ \sum_{i=1}^{a} \left\{ \frac{nc_{li}}{qc_i} \times \ln(CC(l)) \right\} + \sum_{i=1}^{a} \left\{ \frac{ns_{li}}{qs_i} \times \ln(1 - CC(l) \right\} \right\} \quad (9)$$

Often, the size selection for diamond mesh codends is described using a Logit size selectivity model (Wileman et al., 1996):

$$r_{logit}(l, l_{50}, SR) = \frac{\exp\left(\frac{\ln(9)}{SR} \times (l - l_{50})\right)}{1 + \exp\left(\frac{\ln(9)}{SR} \times (l - l_{50})\right)}, \quad (10)$$

where *L50* is the length of fish with a 50% probability of being retained during the selection process and *SR* is *L75–L25*. Thus, we used model (10) as a starting point. However, we also must consider the potential situation where only a fraction of the fish in the codend is capable of attempting to escape, which is obtained by considering the assumed length-independent contact parameter *C* (Herrmann et al., 2013) as follows:

$$r_{Clogit}(l, C, l_{50}, SR) = 1 - C + C \times r_{logit}(l, l_{50}, SR) = 1 - \frac{C}{1 + exp\left(\frac{\ln(9)}{SR} \times (l_{50} - l)\right)} \quad (11)$$

However, without assuming any specific model for the missing size selectivity ($rhb_c(l)$), such as equations (10) or (11), we also could formally determine whether there is evidence of missing size selectivity with the sequential codend by analyzing the catch comparison data. The null hypothesis was that the size selectivity of the two codend types was equal, which implies that $rhb_c(l) = 1.0$ for all l. Thus, based on equation (8), $CC(l) = SP$. We first tested whether this hypothesis could be rejected based on the collected data by estimating the value of SP under this hypothesis based on equation (9) and then calculating the *p*-value to obtain at least as big discrepancy as observed between the experimental catch comparison data and the model by chance. If this *p*-value was below 0.05, we could reject the null hypothesis unless the data appeared to exhibit over-dispersion, which would be indicated by lack of any fish length-dependent pattern in the deviation between the modeled catch comparison rate and the experimental data points. In case the null hypothesis is rejected, thereby providing evidence for missing size selectivity, we then quantified this selectivity using models (10), (11), and (6). This process included testing whether using models (10) and (11) in (6) could describe the observed catch comparison data sufficiently well (*p*-value > 0.05), and we employed these models to estimate the parameters with equation (9). The parameters *SP*, *L50*, and *SR* were estimated with equation (10), while the estimation in equation (11) included the additional parameter *C*. If both equations (10) and (11) could describe the experimental data, then the one with the lowest Akaike's information criterion (AIC) value (Akaike, 1974) would be selected for modeling the missing size selectivity. We estimated 95% confidence intervals (CIs) for the catch comparison curve and the resulting sequential codend size selection curve using double bootstrapping for paired catch comparison data (Sistiaga et al., 2016a). We performed 1000 bootstrap replicates.

In addition to modelling the experimental catch comparison rate in (9) based on (8) using (10) or (11), we also tested the empirical modelling approach that often is used in catch comparison studies (Krag et al. 2014, 2015; Herrmann et al. 2017, 2018):

$$CC(l,\boldsymbol{v}) = \frac{\exp(f(l,\boldsymbol{v}))}{1.0+\exp(f(l,\boldsymbol{v}))} \qquad (12)$$

where f is a polynomial of order 4 with coefficients $v_0,\ldots,v_4$ so $\boldsymbol{v} = (v_0,\ldots,v_4)$. Leaving out one or more of parameters $v_0\ldots v_4$, we obtained 31 additional models that were considered as potential models to describe $CC(l,\boldsymbol{v})$. Based on these models, model averaging was applied to describe $CC(l,\boldsymbol{v})$ according to how likely the individual models were compared to each other (Burnham and Anderson, 2002). The models were ranked in order of AIC value following the procedure described by Katsanevakis (2006) and Herrmann et al. (2017), and those within +10 of the value of the model with the lowest AIC value were included in the combined model (Akaike, 1974; Burnham and Anderson, 2002).

Estimation of difference in size-dependent catch pattern between the two codends

The actual difference in catch pattern between the two codend types was assessed by calculating the difference in the population structure of the catch for the two codends. The length-dependent population frequencies retained in the codends were calculated as follows:

$$fc_l = \frac{\sum_{i=1}^{a} nc_{li}}{\sum_l \sum_{i=1}^{a} nc_{li}} \qquad fs_l = \frac{\sum_{i=1}^{a} ns_{li}}{\sum_l \sum_{i=1}^{a} ns_{li}} \qquad (13)$$

where fc_l and fs_l are the frequencies of fish at length *l* (in length class with middle point *l*) retained in the conventional codend and the sequential codend, respectively. The 95% confidence interval (CI) was obtained using the double bootstrapping technique described above.

To infer the effect of changing from the conventional to the sequential codend on population size structures, the change in the length-dependent frequency Δf_l was estimated as:

$$\Delta f_l = fs_l - fc_l \qquad (14)$$

Efron 95% percentile confidence limits (Efron, 1982) for Δf_l were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) for both fs_l and fc_l. As they are obtained independently, a new bootstrap population of results was created for Δf_l as follows:

$$\Delta f_{li} = fs_{li} - fc_{li} \;\; i \in \; [1 \ldots 1000] \qquad (15)$$

where *i* denotes the bootstrap repetition index. Because 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 (15) using the two independently generated bootstrap files (Larsen et al., 2018).

Estimation of the absolute size selectivity in the two trawls

The absolute size selectivity $r_c(l)$ for the trawl equipped with the traditional codend was estimated by combining the catch data nc_{li} for the *a* uncovered hauls conducted using the traditional codend with the catch data nf_{lj} for the *b* covered control hauls with full trawl retention by minimizing (16) following the procedure described in Sistiaga et al. (2016b) for estimating the selectivity of unpaired trawl data:

$$-\sum_{l}\left\{\sum_{i=1}^{a}\left\{nc_{li}\times\ \ln\left(\frac{SP\times r_c(l)}{SP\times r_c(l)+1-SP}\right)\right\}+\sum_{j=1}^{b}\left\{nf_{lj}\times\ \ln\left(\frac{1-SP}{SP\times r_c(l)+1-SP}\right)\right\}\right\} \qquad (16)$$

Similarly, the absolute size selectivity $r_s(l)$ for the trawl equipped with the quality-improving codend was estimated by combining the catch data ns_{li} for the a uncovered hauls conducted using the quality-improving codend with the catch data for the b covered control hauls by minimizing the following:

$$-\sum_{l}\left\{\sum_{i=1}^{a}\left\{ns_{li}\times\ \ln\left(\frac{SP\times r_s(l)}{SP\times r_s(l)+1-SP}\right)\right\}+\sum_{j=1}^{b}\left\{nf_{lj}\times\ \ln\left(\frac{1-SP}{SP\times r_s(l)+1-SP}\right)\right\}\right\} \qquad (17)$$

For both $r_c(l)$ and $r_s(l)$ we considered both the Logit (10) and Clogit (11) size selection models and used the one with the lowest AIC value. Only in case of poor fit statistics (p-value < 0.05) would we consider other size selection models.

All estimates were obtained using the software tool SELNET, which was developed for estimating size selectivity and catch comparisons for fishing gears (Herrmann et al., 2013). The estimates were then exported and graphically represented using R (R Core Team, 2013).

Fall-through experiments

Fall-through experiments were conducted to further assess the potential size selectivity in the codends. The lengths of sample fish within the size selective range were measured. To determine if the fish could pass through the meshes of the codend, each fish was tested under the influence of gravity in a vertical direction (see Herrmann et al., 2009). A factor influencing the size selective potential of codend is the openness of the meshes, which varies during fishing according to the state of the meshes (Herrmann et al., 2016). Hence, the fall-through experiments were conducted for two different mesh configurations (slack and stiff). Because the lower and upper panels of the codends consisted of two different materials, this experiment was conducted using both codend materials.

Results

During the cruise a total of 20 valid trawls were conducted. Sixteen hauls were conducted alternately using the two different codends (8 haul pairs) in order to estimate the potential missing size selectivity of the sequential codend (Table 1). Four additional control hauls were conducted with covers over the flexigrid and codend to obtain a length-based abundancy measure of the fish entering the trawl during the experimental fishing. To ensure that the fish were caught from the same population and to minimize the between-haul variance, towing area and depth were kept as constant as possible, as was the number of days spent collecting the data (Table 1, Fig. 3). In total, 6889 cod were caught, 2439 of which were retained in the conventional codend and 3068 of which were retained in the dual sequential codend. The remaining 1382 cod were caught in the four control hauls.

Table 1. Details for each haul and haul pair showing codend type, depth, date, towing start time, towing time, number of cod caught, and the sub-sampling factor that compensates for the difference in towing time

Haul No.	Codend type	Depth (m)	Date	Start time (UTC)	Towing time (min.)	Number of cod	Sub-sampling factor
1	Conventional	368	01.03.2018	08:44	62	104	1.00
2	Dual sequential	362	01.03.2018	10:47	62	282	1.00
3	Dual sequential	376	01.03.2018	12:35	60	443	0.83
4	Conventional	349	01.03.2018	15:46	75	172	1.00
5	Dual sequential	310	02.03.2018	14:59	45	213	0.75
6	Conventional	338	02.03.2018	16:30	60	116	1.00
7	Conventional	351	02.03.2018	18:13	90	166	1.00
8	Dual sequential	372	02.03.2018	20:40	90	196	1.00
9	Dual sequential	329	03.03.2018	00:59	90	998	1.00
10	Conventional	318	03.03.2018	09:12	75	137	0.83
11	Conventional	320	03.03.2018	11:24	75	154	0.83
12	Dual sequential	326	03.03.2018	13:25	90	336	1.00
13	Dual sequential	297	03.03.2018	18:58	72	452	1.00
14	Conventional	295	03.03.2018	22:39	36	337	0.50
15	Conventional	303	04.03.2018	02:55	25	525	0.83
16	Dual sequential	322	04.03.2018	18:45	30	95	1.00
17	Control	301	05.03.2018	10:06	61	151	1.00
18	Control	296	05.03.2018	12:49	30	740	1.00
19	Control	299	05.03.2018	18:14	20	180	1.00
20	Control	299	05.03.2018	20:15	20	311	1.00

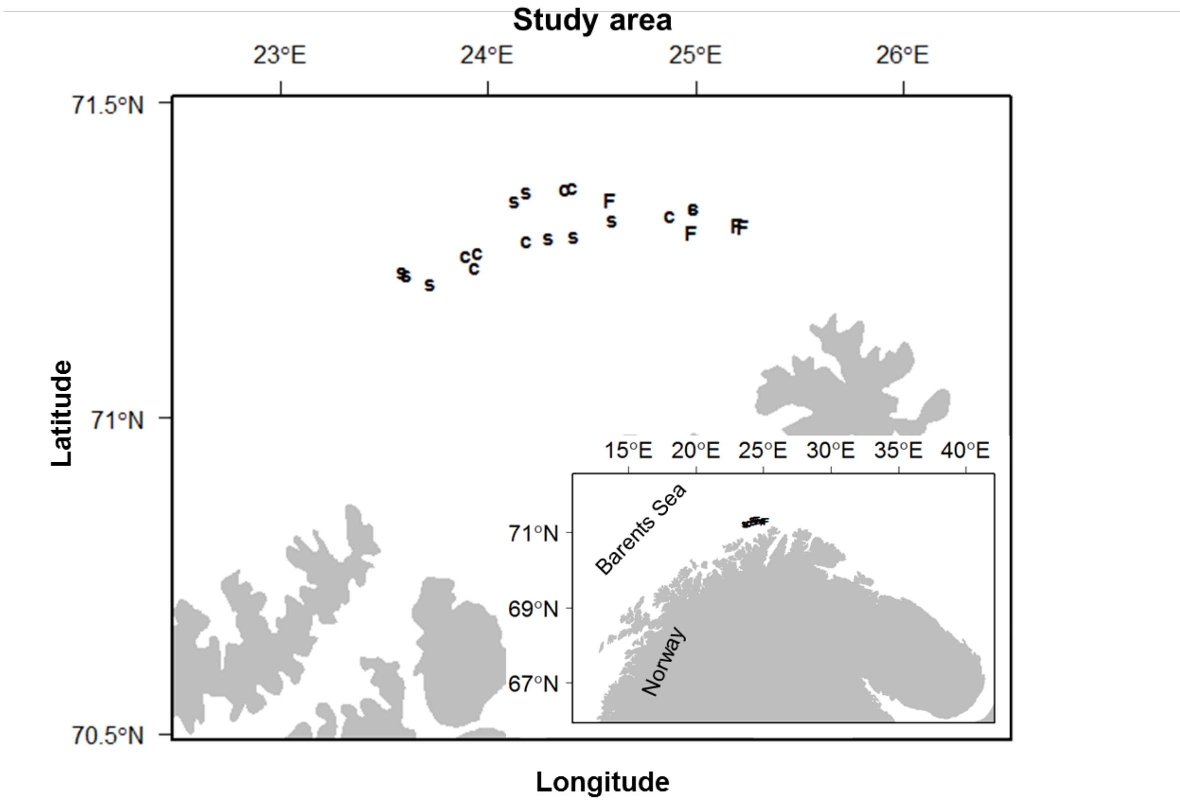

Fig. 3. Map of the area showing where the trawl hauls were conducted. ‘c’ and ‘s’ denote the towing start position for the haul conducted with the conventional codend and with the sequential codend, respectively, and ‘F’ indicates the hauls with covers (i.e., with full retention of all fish).

Fall-through experiments

Fall-through experiments were conducted using 50 cod randomly sampled from the codend during the cruise. These cod ranged between 35 and 80 cm in length. The same codends used during the fishing trials were used for the fall-through experiments, and tests were conducted for two different mesh configurations (i.e., slack and stiff meshes). In addition, the experiments were conducted for the two mesh configurations on both the upper and lower panels. The size selectivity curves from the fall-through experiments provide an upper limit for possible selection in each codend (Fig. 4). Specifically, the results from the fall-through experiments demonstrated that the slack meshes in the lower panel provided the lowest retention probability, with a L_{05} of 47.5 cm (Table 2). The highest retention probability, with a L_{95} of 65.51 cm, was achieved with slack meshes in the upper panel (Table 2).

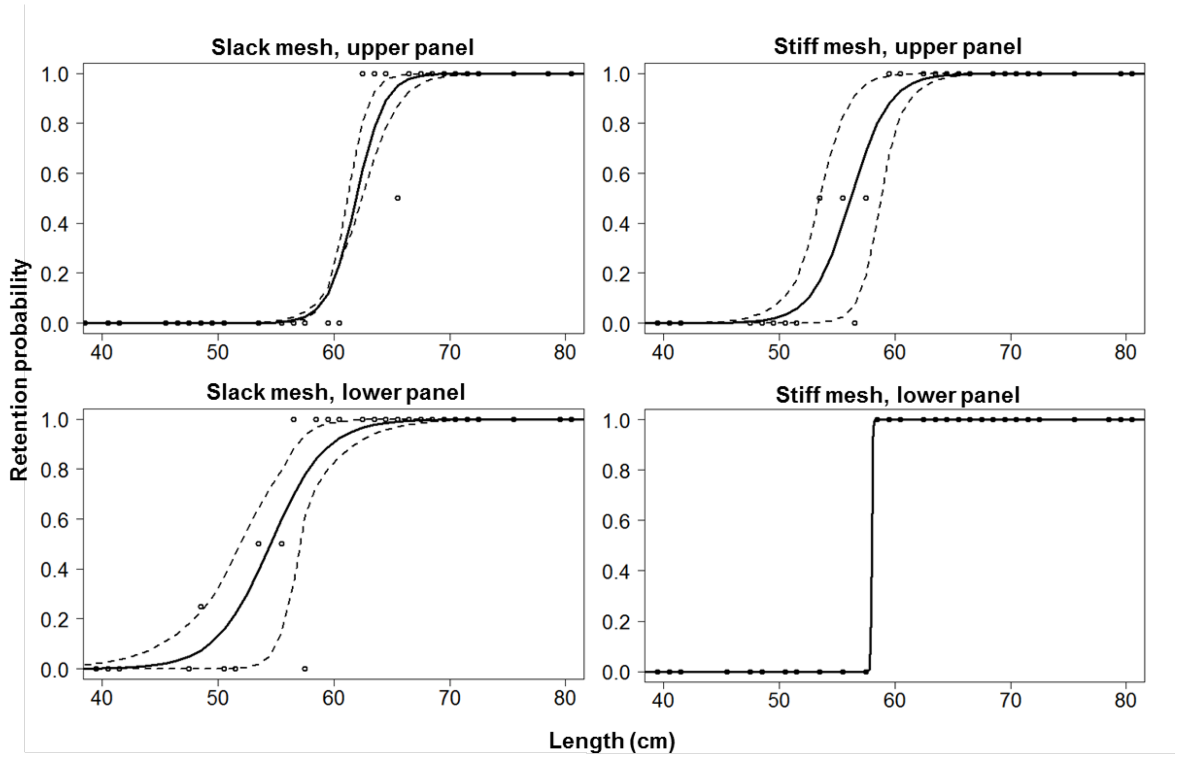

Fig. 4. Fall through selectivity curves for slack and stiff meshes for both lower and upper panels

Table 2. L_{05} and L_{95} with 95% CI in parenthesis for the fall-through experiments for both slack and stiff meshes from both codend panels

Mesh	L_{05} (95% CI)	L_{95} (95% CI)
Slack, upper panel	58.36 (57.71-61.37)	65.51 (61.49-69.52)
Stiff, upper panel	51.23 (48.94-58.38)	61.11 (57.77-64.44)
Slack, lower panel	47.50 (42.54-54.95)	61.56 (58.37-64.74)
Stiff, lower panel	57.87 (57.87-57.87)	58.13 (58.13-58.13)

Estimation of the missing size selectivity

Figure 5a shows the length distribution of all cod caught in the conventional codend and the dual sequential codend. Cod in the size range between 40 and 119 cm were retained during the fishing trials. The p-value for the null hypothesis model (H_0) was 0.0033, which means we could reject this model (i.e., no difference in the size selection between the conventional and dual sequential codends) (Table 3). A difference in size selectivity between the two codends was supported by the discrepancy between catch comparison curves for the H_0 model and the length-dependent pattern in the experimental data (Fig. 5b). Being a length-independent catch comparison rate, the H_0 model curve is equal to that of the SP (i.e., 0.4625). The empirical model provided good fit statistics and fitted the experimental data points nicely (Fig. 5c, Table

3). However, empirical models cannot provide selection parameters. Therefore, two structural models were investigated. Although the Clogit model provided a significantly improved model fit compared to the H_0 model, the Logit model provided the best model fit (i.e., highest p-value and lowest AIC value) (Table 3). The catch comparison curve from the Logit model based on equations (8) and (10) also followed the experimental data points well (Fig. 5c). A comparison of the catch comparison curve from the Logit model with that from the empirical model showed nearly identical curves in the length-span were the experimental data have power (Fig. 5), which provides good support for the more informative structural Logit model. Applying equation (2) in Herrmann et al. (2106), the H_0 model and the Clogit model demonstrated a relative model likelihood of 6.57×10^{-5}% and 36.97%, respectively, compared to the Logit model (Table 3). Based on these results, the Logit model was chosen to describe the difference in size selectivity between the conventional and dual sequential codends.

Table 3. Fit statistics (p-value, deviance, degrees of freedom (DOF)), AIC values, and the relative model likelihood in percentage for the three models evaluated

Model	**p-value**	**Deviance**	**DOF**	**AIC value**	**Relative likelihood (%)**
H0	0.0033	115.02	77	7564.32	6.57×10^{-5}
Empirical	0.217	82.15	73	7532.99	417.87
Clogit	0.1646	85.79	74	7537.84	36.97
Logit	0.1852	85.79	75	7535.85	100

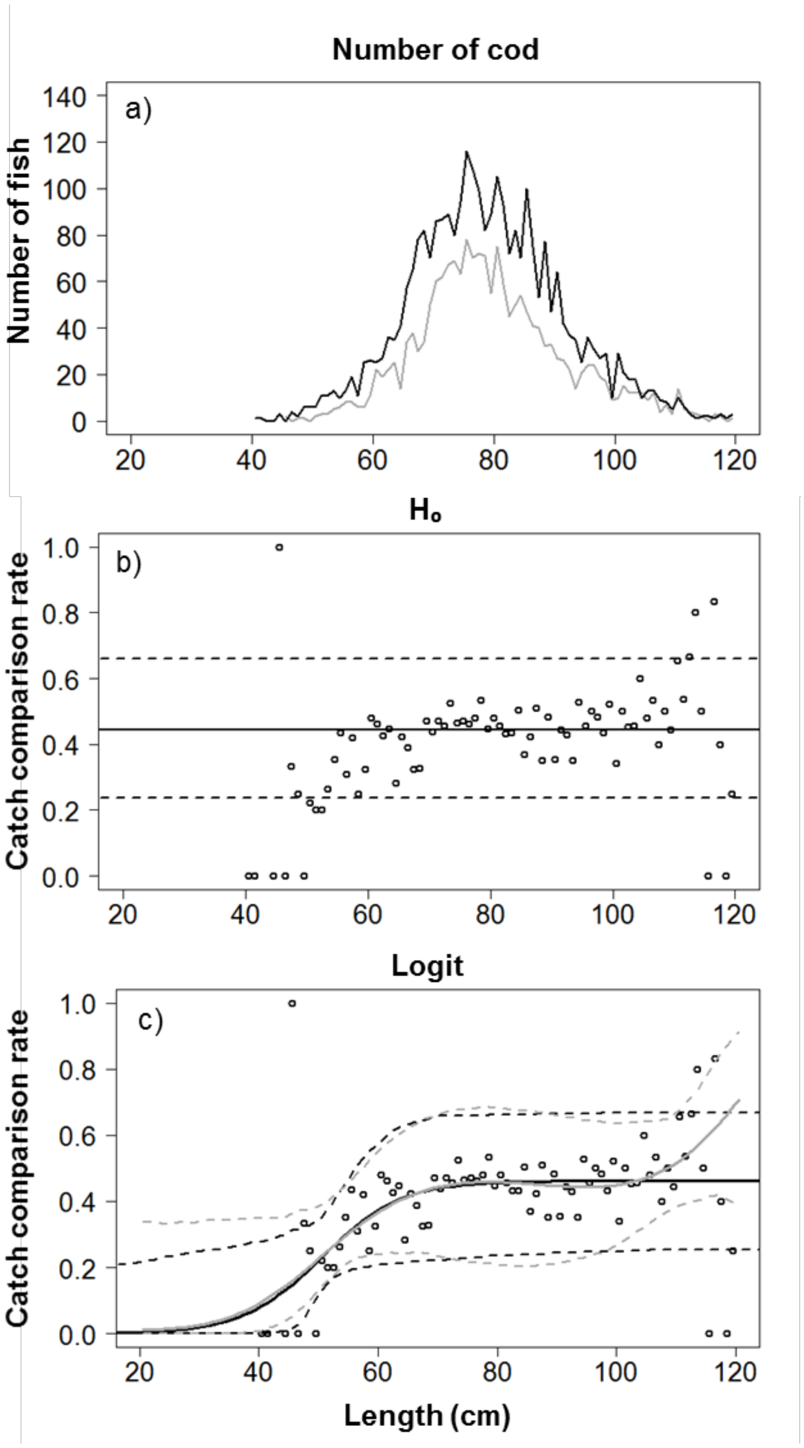

Fig. 5. (a) Size distribution of the cod retained in the conventional codend (grey) and the dual sequential codend (black). (b) Experimental catch comparison rates (dots) and the H_0 model (black solid line) with 95% CI (black stippled curves). (c) Modeled structural catch comparison rate (black solid curve) with 95% CI (stippled curves) and the experimental catch comparison rates (dots). The grey curve represents the catch comparison rate from the empirical model with 95% CI (grey stippled curves).

The results from the fall-through experiments provide an upper and lower limit for any possible missing size selection in the anterior codend segment compared to that of the conventional codend. Specifically, the grey vertical line to the left in Figure 6 represents the upper limit (L_{95}) for possible size selection and thus the limit where 95% of the cod is retained. The highest upper limit was achieved for slack meshes in the upper panel, which provided an L_{95} for cod of length 65.51 cm (Fig. 6, Table 2). The lowest limit (i.e., where there is only 5% probability of retention (L_{05})) is represented by the vertical line on the left side in Figure 6. The lowest retention probability was achieved for slack meshes in the lower panel, which provided an L_{05} for cod of length 47.5 cm (Fig. 6, Table 2). The catch comparison curve demonstrates a difference in size selectivity between the conventional and dual sequential codends (Fig. 5c). The size selectivity curve in Figure 6 quantifies the missing size selectivity in the dual sequential codend after the opening of the catch releaser during haul-back. The upper CI in the size selectivity curve provides evidence for the reduced size selectivity in the sequential codend compared to the conventional codend for cod up to 47 cm (Fig. 6). This is just 0.5 cm below the L_{05} limit identified in the fall-through experiments. The size selection curve also indicates increased probability of retaining fish above 47 cm in the dual sequential codend compared to the conventional codend, although this is not provable because the upper CI is equal to 1 (Fig. 6). Specifically, considering the most conservative estimates, cod measuring 20 cm had a 63% higher escape probability when located in the conventional codend during haul-back compared to the dual sequential codend, meaning that the latter codend had an increased probability of retaining cod measuring 20 cm of 37% (Fig. 6, Table 4). Furthermore, for cod measuring 40 cm the reduced size selectivity in the sequential codend was estimated to be 51% (i.e., increased retention probability of 49%) (Fig. 6, Table 4). For cod measuring 44 cm, which is the minimum landing size, the escape probability during haul-back was 18% higher in the conventional codend compared to the sequential codend (Fig. 6, Table 4).

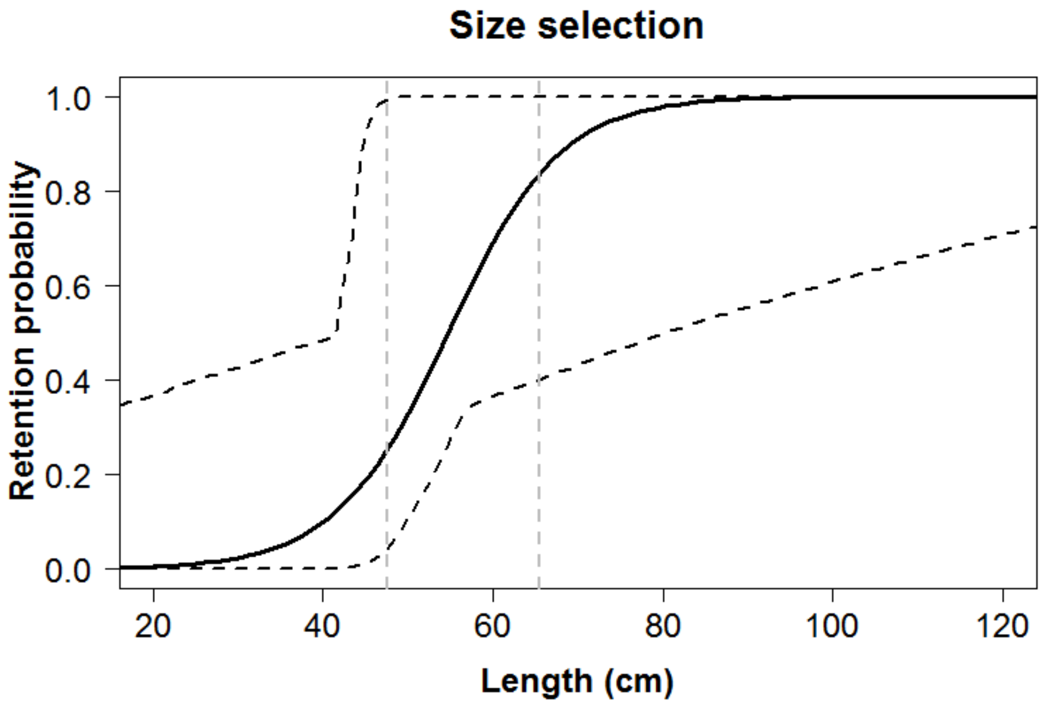

Fig. 6. Size selection curve (black solid curve) with 95% CI (stippled curves) showing the missing size selectivity when using the dual sequential codend. The grey stippled lines represent L_{05} (left line) for the slack meshes in the lower panel and L_{95} for the slack meshes in the upper panel.

Table 4. Reduced escape probability for cod with 5 cm length intervals with 95% CIs for the cod retained in the dual sequential codend compared to the conventional codend

Length (cm)	Escape probability	CI 95%, lower	CI 95%, upper
20	0.99	0.63	1.00
25	0.99	0.60	1.00
30	0.97	0.57	1.00
35	0.95	0.54	1.00
40	0.89	0.51	1.00
44	0.82	0.13	0.99
50	0.65	0.00	0.88
55	0.47	0.00	0.71
60	0.29	0.00	0.63
65	0.16	0.00	0.60
70	0.09	0.00	0.56
75	0.04	0.00	0.53
80	0.02	0.00	0.50
85	0.01	0.00	0.47

Although these results demonstrate reduced size selectivity in the sequential codend compared to the conventional codend, this would be a problem only if undersized fish are present in the fishing area, are caught, and fail to escape through the size selective grid or codend meshes before haul-back. When we investigated the population structure retained in the two codends (Fig. 7a, b), we found no significant difference (Fig. 7c). However, it is important to emphasize that these results are case specific and could be due to the lack of undersized fish in the area during the data collection period or to efficient release of undersized fish in the sections anterior to the codend (i.e., size sorting grid and extension piece), as well as during towing.

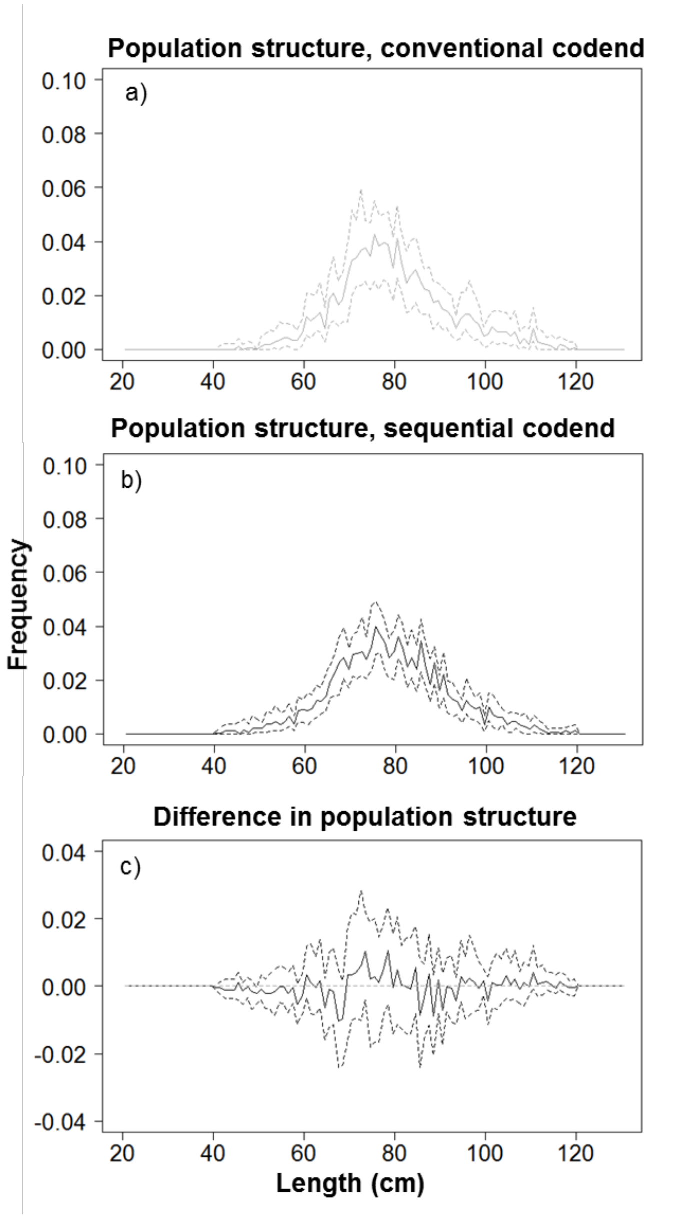

Fig. 7. Population structure in the (a) conventional codend and (b) sequential codend; (c) shows the difference in population structure between the two codends. Stippled lines represent 95% CIs.

Absolute size selectivity in the trawl with the conventional codend and the sequential codend

The four control hauls that were equipped with covers to retain all escapees provided a length-based abundance measure for the cod entering the trawl. The length distribution of the cod retained in the four control hauls (grey line in Fig. 8a, b) differs from the black distribution curves in the figures showing the length distribution of cod retained in the conventional and sequential codend, respectively. This demonstrates that small cod were present in the area when experimental fishing was conducted. Thus, the four control hauls enabled estimation of the absolute size selectivity in the trawl with the conventional codend and sequential codend (Fig. 8c, d, Table 5). The fit statistic presented in Table 5 demonstrate a good fit of the model (i.e., the p-value is well above 0.05, making it highly likely that the observed discrepancy between the experimental catch sharing rates ($\frac{\sum_{i=1}^{a} nc_{li}}{\sum_{j=1}^{b} nf_{lj}}$ and $\frac{\sum_{i=1}^{a} ns_{li}}{\sum_{j=1}^{b} nf_{lj}}$) and the fitted model is a coincidence). For both codend types, the Logit model provided the lowest AIC value. Comparing the size selection curves in Figure 8c indicates a minor increase in the retention of fish below the minimum landing size in the trawl equipped with the sequential codend. However, based on the absolute selectivity estimate using the unpaired method (Sistiaga et al., 2016b), no significant difference was detected. Furthermore, the estimated L_{50} of 64.33 cm for the trawl with the conventional codend and 62.90 cm for the trawl with the sequential codend do not differ significantly (Table 5), and these values lie far above the minimum landing size, which in the Barents Sea cod fishery is 44 cm.

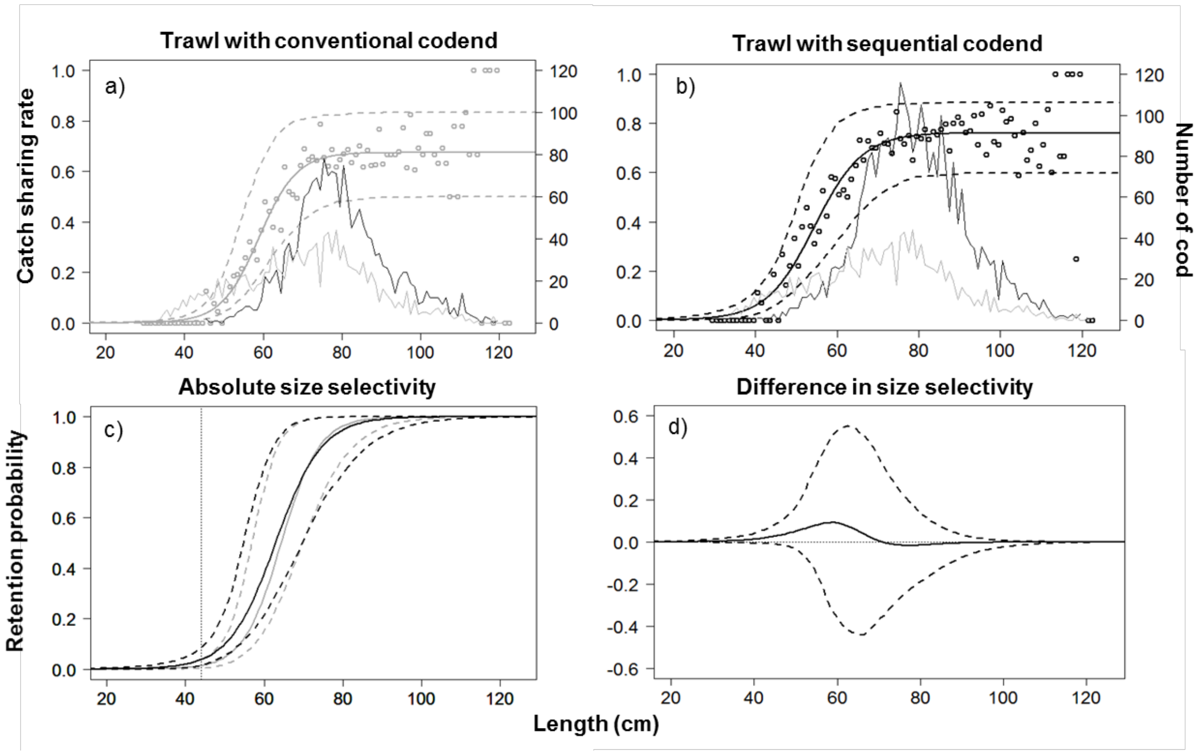

Fig. 8. Catch sharing rate for the trawl with the (a) conventional codend and (b) sequential codend. Dots represent the experimental data points, and dashed curves represent CIs. The distribution curve in black represents the number of cod retained in the codend, whereas the distribution curve in grey represents the cod caught in the four control hauls that retained all fish entering the trawl, including escapees. (c) Absolute size selectivity in the trawl with the conventional codend (grey) and sequential codend (black) (grey stippled line represents the minimum target size of 44 cm). (d) Difference in size selectivity between the two codends.

Table 5. Size selectivity parameters and fit statistics for the absolute size selectivity in the trawl with the conventional codend and the sequential codend

	Total selectivity	
Parameter	**Trawl with conventional codend**	**Trawl with sequential codend**
L_{50}	64.33 (56.87–69.81)	62.90 (57.69–69.68)
SR	10.54 (6.26–14.91)	12.89 (7.49–18.50)
SP	0.67 (0.48–0.84)	0.76 (0.61–0.89)
p-value	0.928	0.5693
Deviance	71.21	87.02
DOF	90	90

Discussion

Brinkhof et al. (2018a) described a dual sequential codend concept that significantly improved the quality of trawl-caught cod. The goal of this study was to address concerns about the potential negative effect of this design on the size selectivity of the codend. Data were collected using two identically rigged trawls that differed only in the codend used. These codends were assumed to have equal size selective properties until the catch was released into the posterior codend segment in the dual sequential codend during haul-back. Therefore, it was reasonable to assume that any difference in the size selectivity can be attributed the dual sequential codend.

During haul-back, the dual sequential codend exhibited an increased probability of retaining cod up to 47 cm long compared to the conventional codend. The upper limits from the fall-through experiments and the size selectivity curve, which demonstrated missing selectivity in the sequential codend compared to the conventional codend, also indicated that the sequential codend had increased retention probability for cod above 47 cm long (Fig. 6). However, this latter premise is not provable due to the wide CIs. Although this study demonstrates that the sequential codend had significantly lower size selectivity during haul-back compared to the conventional codend, no difference in the population structure retained in the two codends was detected. This means that the catch pattern between the two codends was not significantly different based on the present data. However, it is important to emphasize that this result is case specific, and may have been caused by lack of undersized fish in the fishing area during data collection or by efficient release through the grid.

Studies have demonstrated that the flexigrid, which is the most used sorting grid in the Barents Sea, can be insufficient at releasing undersized fish (Sistiaga et al., 2016a). However, the four control hauls conducted in this study, which retained all cod that entered the trawl, demonstrated that although some undersized fish entered the trawl, most of them managed to escape, either through the grid or through the codend meshes during towing. Estimation of the absolute size selectivity indicated that there was only a minor increase in the retention rate for undersized cod with the sequential codend compared to with the conventional codend. The high L_{50} values obtained with both trawl codends in this study demonstrate low retention of fish below the minimum target size. Even if the sequential codend had led to a significantly lower L_{50} than the conventional codend, which was not the case, a lower L_{50} would still be in accordance with the fishery management regulations. The increased catch quality provided by the sequential codend can be considered to be of greater importance than the minor increase in the retention of small cod. Low catch quality can increase the risk of illegal discarding and high-grading (Batsleer et al., 2015). Furthermore, as argued in Madsen et al. (2008) and Brinkhof et al. (2017), fish escaping during haul-back is likely to affect their survivability negatively due to stress-, catch-, or barotrauma-related injuries.

Results of the structural Logit model applied in this study agreed extremely well with results of the empirical model. The catch comparison curves from the structural and empirical model were nearly identical in the length span in which the experimental data occurred. The discrepancy between the two modeled curves, which occurred above L_{95} and thus outside the area where any size selection can occur, was likely caused by the difference in the fish entry rates, and it was not significant considering the wide CIs. Because structural models enable estimation of selectivity parameters, the structural model with the best fit was chosen. Structural models are also beneficial due to their robustness for extrapolations outside the range of available length groups that were measured (Santos et al., 2016). Regarding the assumptions about equal selectivity in the two trawls, as stated in equation (7), it might be possible that the water flow inside the anterior part of the sequential codend changes when the catch releaser opens the posterior quality-improving codend segment. This might have a minor influence on the size selectivity for cod that have not yet have entered the codend.

Because the data were collected by alternating between the trawls with the two different codends, a paired analysis was possible. However, the four control hauls, which were collected to enable calculation of the absolute selectivity and to provide a measure of the abundancy of all length groups of cod available during the experimental fishing, were collected unpaired, thus the absolute selectivity analysis was conducted unpaired. Unpaired data possess more uncertainty, resulting in wider CIs. However, combining those 4 control hauls with the data from the 16 alternating hauls with the two codends trawls allowed estimation of the absolute selectivity of the codends.

It is important to distinguish between potential size selectivity, which in this case demonstrated significant missing size selectivity in the sequential codend compared to the conventional codend, and the actual size selectivity in the trawl (i.e., actual catch pattern), which in this case did not exhibit any significant difference between codends. Furthermore, estimation of the absolute size selectivity indicated that there was a minor increase in the retention of small fish in the dual sequential codend, but it was negligible. Despite the missing selectivity, the absolute selectivity obtained for the trawl equipped with the quality-improving codend revealed a low retention risk for cod below the minimum target size. Hence, this study demonstrates that compared to the conventional codend, the sequential codend has a minor effect on the overall trawl size selectivity.

Acknowledgments

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