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

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Abstract

A new codend concept developed and tested exhibited significantly improved quality of caught cod (*Gadus morhua*) 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 higher retention probability 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 when deploying respectively 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 in the trawl. Further, estimation of the total size selectivity in the trawl 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

Trawl caught fish has been associated with deteriorated 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 (Norwegian Directorate of Fisheries, 2018). 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, i.e. 18% compared to 3% for cod retained in the conventional 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 (Ø3 mm) (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 total 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), and therefore it is highly relevant to investigate if the new codend causes a reduced size selection. Hence, the aim of this study was to investigate the size selectivity and catch pattern for cod in the Barents Sea bottom trawl fishery when applying a conventional codend and the new dual sequential codend. Specifically, the following research questions were addressed:

- Will the sequential codend have a similar size selection as the conventional codend?
- Is there any effect on the length-dependent catch patterns between the trawl equipped with the conventional and dual sequential codend?

- How will the total size selectivity in the trawl be when employing the conventional and sequential codend, and 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

To address the research questions 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'). The research questions necessitated the quantification of the relative size selection between the two codends, the catch patterns that would be obtained from applying them in the Barents Sea fishery, and the total size selection in the trawl when equipped with respectively the conventional and dual sequential codend. To estimate the total selectivity in the trawl and the influence on the catch pattern if the traditional codend is replaced by the dual sequential codend it is necessary that the trawls were rigged as in the commercial fishery, which includes a size selective sorting grid and codends with a mesh size according to the legislation.

Optimally, to answer the three research objectives one would use two different trawl riggings with a cover to retain the escapees from both the grid section and codend. However, due to the length of the sequential codend (21 m), this would require using a cover of at least 45 m in length. However, a cover of 45 m in length is far longer than previously deployed on the research vessel, which was 14 m long (Grimaldo et al., 2017). Based on this there was concerns if such a cover could function and if it could be handled on the vessel. Therefore, it was decided to use a different experimental design based on deploying three different trawl riggings (design setups) during the cruise (Fig 1). The first two were identical trawls rigged as in the commercial fishery; one trawl equipped with a conventional codend and the second with the dual sequential codend. The trawls were deployed alternately without covers, enabling a paired structural catch comparison on the resulting catch data from these hauls for the estimation of the relative size selectivity between the two codends with best possible statistical power (explained in section for analysis) (Fig 1). The data obtained from alternating the trawls also enabled estimation of the catch patterns in the trawls with the two different codends. However, the total selectivity in each of the two trawls, i.e. grids and codend, could not be estimated alone from these hauls due to the lack of the retention of the escapees through the grids and codends. Therefore, during the last part of the cruise the trawl with the conventional codend was equipped with covers over the grids and codend to ensure that all cod entering the aft of the trawl (from grid to codline) was retained (Fig. 1). The series of hauls conducted with this third gear setup enabled estimation of the population size structure in the area where the two first gear setup were fished (Fig. 1). Combining the collected catch data from setup 1 (DS1) and 2 (DS2) with setup 3 (DS3) (Fig. 1) enabled estimation of the total gear size selection for both the trawl with the conventional codend and the sequential codend applying an unpaired estimation method (Sistiaga et al., 2016b). It was not possible to alternate all three setups on the vessel as this would have required handling three trawls. Therefore, for practical reasons the experimental setup described above was the best compromise. Fig. 1 presents how the three different design setups contribute both alone and in combination with each other to answer the outlined research questions.

FIG 1.

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 mean (± SD) 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. 2). The first codend segment was built the same way as the conventional codend, and had a mean (± SD) 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. 2). The two codend segments were connected as a 2-panel codend. 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. 2). 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. 2). 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. 2

As described above 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, DS3 in Fig. 1. 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.

Model and method for quantifying missing size selectivity in the sequential codend

This section develops a model and method for quantifying the size selection that during the haul-back phase will be missing in the sequential codend compared to the conventional codend. The method is based on comparing the catches obtained with the two trawl setups (DS1 and DS2), and relating the observed ratio in catches to the missing size selection (i.e. the size selectivity in the conventional codend that is lacking in the sequential codend) (Fig. 1). Because the conventional codend and sequential codend were each used every second haul in the same area, the collected catch data were treated as paired catch comparison data (Krag et al., 2015).

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 (Fig. 3):

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

whereas the total size selectivity with the sequential codend $r_s(l)$ can be modelled by (Fig. 3):

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

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. 3). 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:

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

According to Eq. 4 the calculation of the sampling factors is based on the assumption that the number of cod entering is expected to increase proportional with the fishing effort. With equal towing speed within the pairs, the fishing effort can be considered to be proportional with the towing time. Within the pairs, the haul with the longest towing time will have a sampling factor equal to 1.0, while the other tow will have a sampling factor which is scaled down with the ratio between the two towing times.

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. 3).

FIG. 3

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:

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

Based on models (1) to (5) and Fig. 3, the theoretical catch comparison rate *CC(l)* becomes:

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

Next, the following assumptions are introduced:

$$\begin{aligned} rt_c(l) &\approx rt_s(l) \\ rha_c(l) &\approx rha_s(l) \\ rhb_s(l) &= 1.0 \end{aligned} \quad (7)$$

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 (*$rhb_c(l)$*) that will be missing with the sequential codend and the catch comparison rate (*CC(l)*). Therefore, this size selectivity then can be assessed based on estimating the catch comparison rate. Based on combining equations (1) and (2) while using the assumptions (7) we arrive at that *$rhb_c(l)$* also quantifies the ratio between the size selectivity in the trawl with the conventional codend (DS1) and the trawl with the sequential codend (DS2).Therefore, the size selectivity in the trawl with the sequential codend can be expressed in terms of the selectivity in the trawl with the conventional codend multiplied by a factor that is one divided by the missing selectivity:

$$r_s(l) = \frac{1.0}{rhb_c(l)} \times r_c(l) \quad (9)$$

Therefore, if some cod first escape through the meshes in the aft of the codend during haul-back the use of the sequential codend will scale the retention probability for the total trawl process up by 1.0 divided the missing haul-back selectivity.

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 $rhb_c(l)$:

$$-\sum_l\left\{\sum_{i=1}^{a}\left\{\frac{nc_{li}}{qc_i} \times \ln\left(CC(l)\right)\right\} + \sum_{i=1}^{a}\left\{\frac{ns_{li}}{qs_i} \times \ln\left(1 - CC(l)\right)\right\}\right\} \quad (10)$$

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

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

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 (11) 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:

$$r_{Clogit}(l, C, l_{50}, SR) = 1 - C + C \times r_{logit}(l, l_{50}, SR) = 1 - \frac{C}{1 + exp\left(\frac{\ln(9)}{SR} \times (l_{50} - l)\right)} \quad (12)$$

However, without assuming any specific model for the missing size selectivity ($rhb_c(l)$), such as equations (11) or (12), 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 (10) 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 (11), (12), and (6). This process included testing whether using models (11) and (12) 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 (10). The parameters *SP*, *L50*, and *SR* were estimated with equation (11), while the estimation in equation (12) included the additional parameter *C*. If both equations (11) and (12) 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 (Lomeli et al., 2018). We performed 1000 bootstrap replicates.

In addition to modelling the experimental catch comparison rate in (10) based on (8) using (11) or (12), 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):

$$CC(l,\boldsymbol{v}) = \frac{\exp\left(f(l,\boldsymbol{v})\right)}{1.0 + \exp\left(f(l,\boldsymbol{v})\right)} \qquad (13)$$

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 (Fig 1). The length-dependent population frequencies retained in the codends were calculated as follows:

$$fc_l = \frac{\sum_{i=1}^{a} nc_{li}}{\sum_l \sum_{i=1}^{a} nc_{li}} \qquad fs_l = \frac{\sum_{i=1}^{a} ns_{li}}{\sum_l \sum_{i=1}^{a} ns_{li}} \qquad (14)$$

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:

$$\Delta f_l = fs_l - fc_l \qquad (15)$$

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:

$$\Delta f_{li} = fs_{li} - fc_{li} \quad i \in [1 \ldots 1000] \qquad (16)$$

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 (16) using the two independently generated bootstrap files (Larsen et al., 2018).

Estimation of the total size selectivity in the two trawls

The total 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 conventional codend (DS1) with the catch data nf_{lj} for the *b* covered control hauls (DS3) with full trawl retention by minimizing (16) following the procedure described in Sistiaga et al. (2016b) for estimating the selectivity of unpaired trawl data (Fig. 1):

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

Similarly, the total 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:

$$-\sum_l \left\{ \sum_{i=1}^{a} \left\{ \frac{ns_{li}}{qs_i} \times \ln \left(\frac{SP \times r_s(l)}{SP \times r_s(l) + 1 - SP} \right) \right\} + \sum_{j=1}^{b} \left\{ \frac{nf_{lj}}{qf_j} \times \ln \left(\frac{1 - SP}{SP \times r_s(l) + 1 - SP} \right) \right\} \right\} \qquad (18)$$

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).

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, DS1 and DS2 in Fig. 1). Four additional control hauls were conducted with covers over the flexigrid and codend (DS3 in Fig. 1) 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. 4). 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

FIG. 4

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 2). 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 2). 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., lowest AIC value) (Table 2). The catch comparison curve from the Logit model based on equations (8) and (11) 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. (2016), 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 2). Based on these results, the Logit model was chosen to describe the difference in size selectivity between the conventional and dual sequential codends.

TABLE 2

FIG. 5

The catch comparison curve demonstrates a difference in size selectivity between the conventional and dual sequential codends (Fig. 5c). The size selectivity curve in Fig. 6 quantifies the missing size selectivity in the dual sequential codend after the opening of the catch releaser during haul-back. The area above 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). Specifically, considering the most conservative estimate, cod measuring 20 cm had 63% escape probability when located in the conventional codend during haul-back compared to none in the dual sequential codend (Fig. 6, Table 3). Furthermore, for cod measuring 40 cm the release possibility that would be missing during haul-back with the sequential codend was estimated to affect 51% of the cod that had not escaped prior but would during haul-back with the conventional codend (Fig. 6, Table 3). For cod measuring 44 cm, which is the minimum target size, the escape probability during haul-back was 18% in the conventional codend (Fig. 6, Table 3).

Applying the upper CI's for the missing haul-back selection curve (Fig. 6) in Eq. 9, enables estimation of the minimum scaling factor which quantifies the minimum relative size selection between the two codends, i.e. the increase in the retention probability in the sequential codend compared to the conventional codend. Cod measuring 20 cm had an increased retention probability in the trawl with the sequential codend by a factor of minimum 2.71 (Table 3).

Furthermore, for cod measuring 40 cm and 44 cm the scaling factor was 2.06 and 1.15, respectively (Table 3).

FIG. 6

TABLE 3

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

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

The four control hauls (DS3 in Fig. 1) 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 (DS1 in Fig. 1) and sequential codend (DS2 in Fig. 1), 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 total size selectivity in the trawl with the conventional codend and sequential codend (Fig. 8c, d, Table 4). The fit statistics 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 ($\frac{\sum_{i=1}^{a}\frac{nc_{li}}{qc_i}}{\sum_{i=1}^{a}\frac{nc_{li}}{qc_i}+\sum_{j=1}^{b}\frac{nf_{lj}}{qf_j}}$ and $\frac{\sum_{i=1}^{a}\frac{ns_{li}}{qs_i}}{\sum_{i=1}^{a}\frac{ns_{li}}{qs_i}+\sum_{j=1}^{b}\frac{nf_{lj}}{qf_j}}$) 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 target size in the trawl equipped with the sequential codend. However, based on the total selectivity estimate using the unpaired method (Sistiaga et al., 2016b), no significant difference was detected. Furthermore, the estimated L_{50} of 64.33 cm (CI: 56.87–69.81) for the trawl with the conventional codend and 62.90 cm (CI: 57.69–69.68) for the trawl with the sequential codend do not differ significantly (Table 4), and these values lie far above the minimum target size, which in the Barents Sea cod fishery is 44 cm. The L_{50} values, even when considering the lower CI's, are high compared to previous studies using a flexigrid in combination with a conventional diamond mesh codend (Sistiaga et al., 2009).

FIG. 8

TABLE 4

Discussion

Brinkhof et al. (2018a) described a dual sequential codend concept that significantly improved the quality of trawl-caught cod compared to a conventional codend. The goal of this study was to address concerns about the potential negative effect on the size selectivity in the trawl if this codend was applied in the fishery. The conventional and anterior segment of the sequential codend were designed similarly, and the water flow in the codends was believed to be similar. The two codends applied were thus assumed to have similar size selective properties until the catch was released into the posterior codend segment in the dual sequential codend during haul-back. However, there was a difference of approximately 6 mm in the mesh size between the anterior segment of the sequential codend and the conventional codend. Since it was the conventional that had the largest mesh size, the results presented in this study are conservative estimates. Therefore, it was reasonable to assume that any difference in the size selectivity in the codends can be attributed the dual sequential codend during haul-back.

During haul-back, the dual sequential codend exhibited a relative increase in the probability of retaining cod up to 47 cm long compared to the conventional codend (Fig. 6). 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 or codend during towing.

A study has 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 (DS3 in Fig. 1) 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 total size selectivity (grid and codend) 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 (Brinkhof et al., 2018a) 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 catch comparison model (Eq. 8, 11) applied in this study agreed well with results of the empirical model (Eq. 13). 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 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).

The experimental design with the three different trawl design setups described in Fig. 1 enabled both the estimation of the missing size selectivity in the sequential codend during haul-back, as well as the catch patterns and total size selectivity in the two trawls. Alternating DS1 and DS2 (Fig. 1) enabled estimation of the missing size selection using the paired structural catch comparison model. This model has high statistical power because the catch comparison rate is explicit related to the missing size selection (Eq. 8) without having first to estimate the size selectivity for the two designs. However, the estimation of the total selectivity (Fig. 1) required unpaired analysis, subsequently entailing lower statistical power with wider CI's. Further, the unpaired method relies on the assumption that the size structure of cod entering during the group of test hauls (DS1 and DS2) is on average the same for the group of control hauls (DS3). If this assumption is violated, the estimated size selectivity for the test trawls can be biased. Such risk could be particular high under the logistic constrains the sea trials were conducted, i.e. all control hauls were being taken after the all the test hauls instead of as recommendable distributed between them. Such bias in size selection assessment might explain the unusual high L_{50} values obtained for the total size selection, thus, we need to have some caution with these results. The risk for bias in the catch structure sampling and thereby in the estimation of size selectivity could be avoided by using a twin trawl setup, however, to answer the objectives highlighted in Fig. 1, this would have required six different trawl setups: i) DS1 and DS2, ii) DS1 and DS3, and iii) DS2 and DS3). Compared to the three trawl setups applied in this study which maximizes the utilization each length measurement, a twin setup would have required an increased number of fish measurements. Therefore, it is unsure which design setup would require the lowest number of cod caught and length measured to obtain a specific statistical power for addressing the research objectives. But the twin setup eliminates the risk for bias in the assessment of the size selectivity. The research vessel for our disposal could not handle a twin trawl setup. However, it could be advisable to follow up with a twin setup experiment on another vessel. Preferable, such a follow up experiment should be conducted on a commercial fishing vessel enabling commercial catch sizes with a twin trawl setup as commercial catches affect results (Richards and Hendrickson 2006).

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. This means that although estimation of the relative selectivity demonstrated that there is possibility of increased retention rate of small cod in the sequential codend this requires that they are present in the fishing area and that they do not manage to escape prior being retained in the codend. However, the estimation of the total selectivity demonstrated that, in this case, although the catch patterns revealed the presence of small cod, they likely managed to escape prior being retained in the codend. Thus, despite the missing selectivity, the total 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. Further studies should investigate if the sequential codend improves catch quality of other species besides from cod, such as haddock (*Melanogrammus aeglefinus*) and saithe (*Polachius virens*), without compromising size selectivity significantly. Additionally, it would be of interest to investigate the applicability of the codend in other fishing gears, such as demersal seine, as well other similar fisheries.

Acknowledgments

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Fig. 1. Schematic showing how the three different trawl designs contribute to the objectives. DS1 represents the trawl with the conventional codend, DS2 the trawl with the dual sequential codend, and DS3 the trawl with covers for the collection of the escapees.

Fig. 2. 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.

Fig. 3. 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. (The section are not scaled according to each other).

Fig. 4. 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).

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).

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.

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.

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.

FIG. 1.

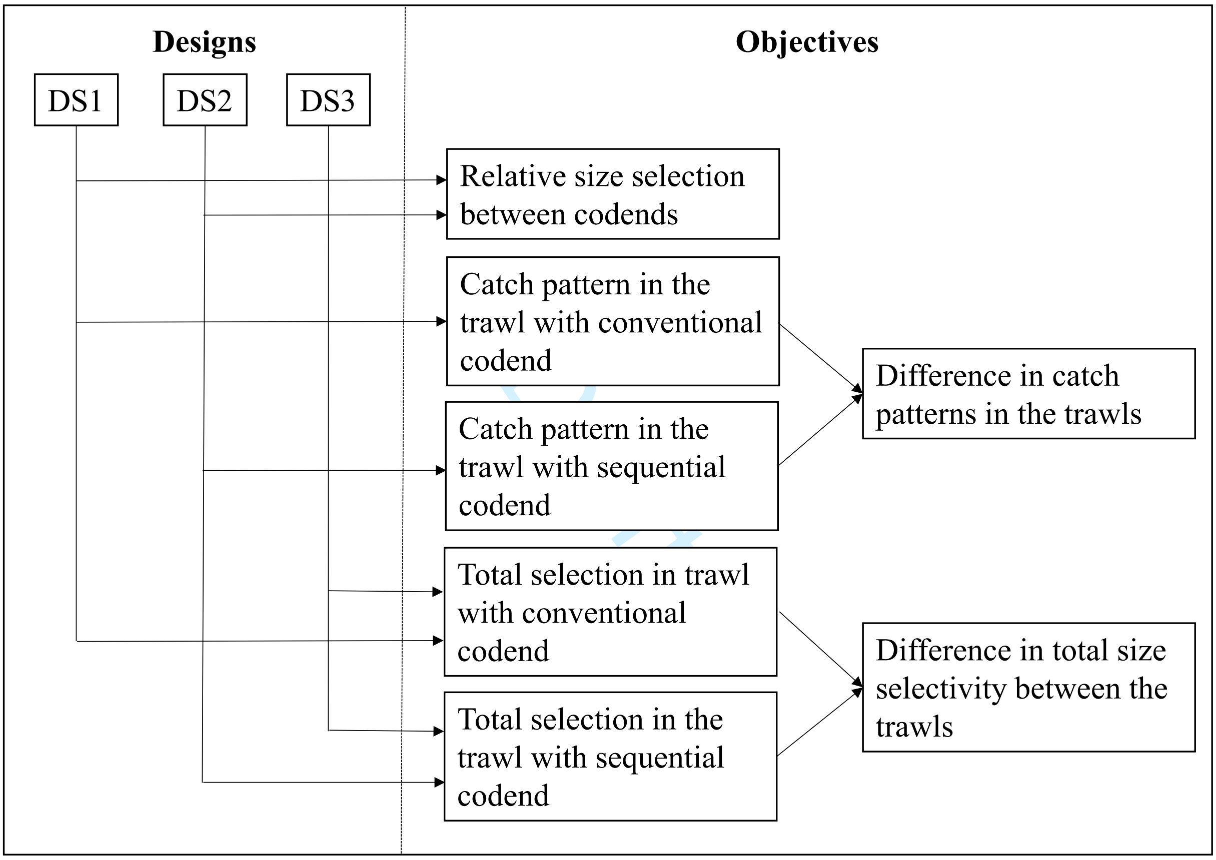


FIG. 2

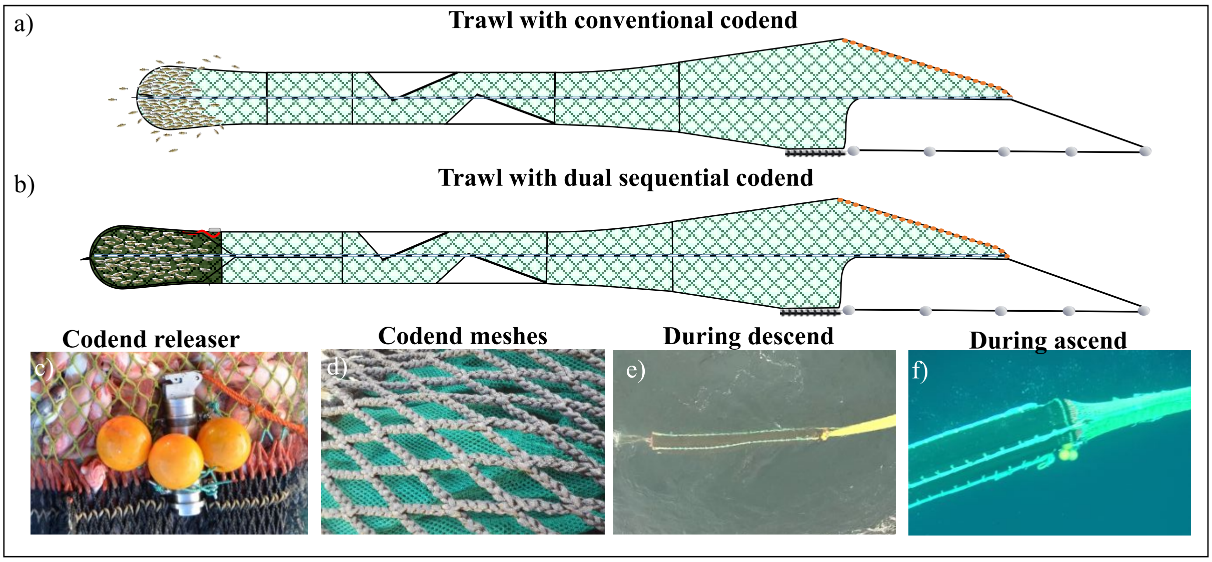

a)
Trawl with conventional codend
b)
Trawl with dual sequential codend
Codend releaser
Codend meshes
During descend
During ascend
c)
d)
e)
f)

FIG. 3

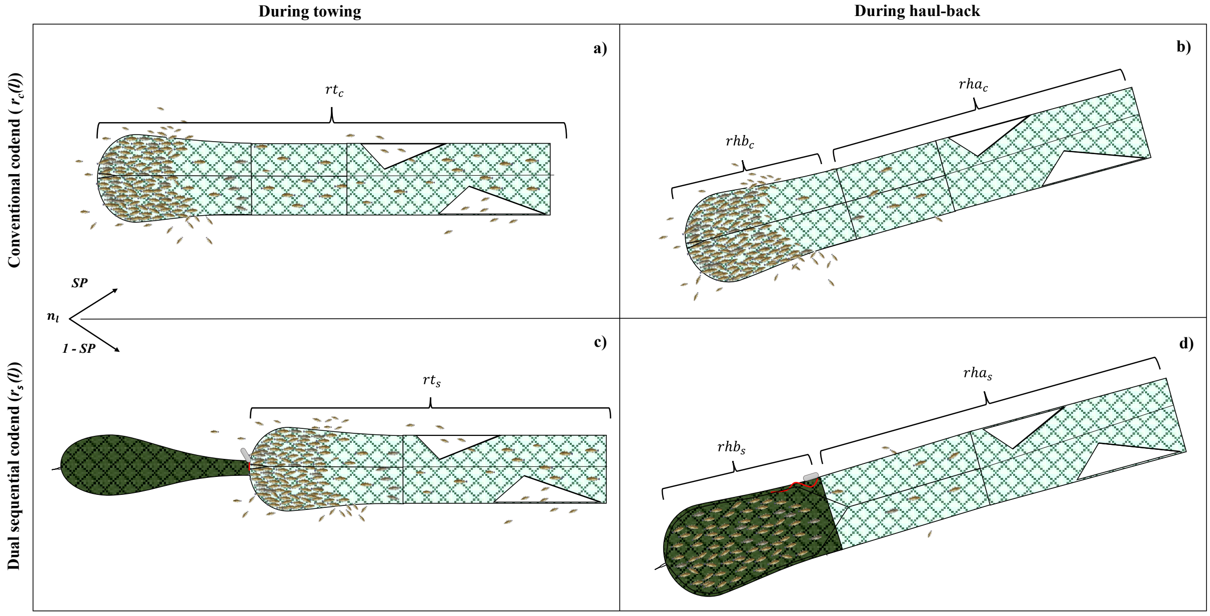

During towing
During haul-back
a)
b)
c)
d)
rt_c
rhb_c
rha_c
Conventional codend ($r_c(l)$)
Dual sequential codend ($r_s(l)$)
SP
n_l
1 - SP
rt_s
rhb_s
rha_s

FIG. 4

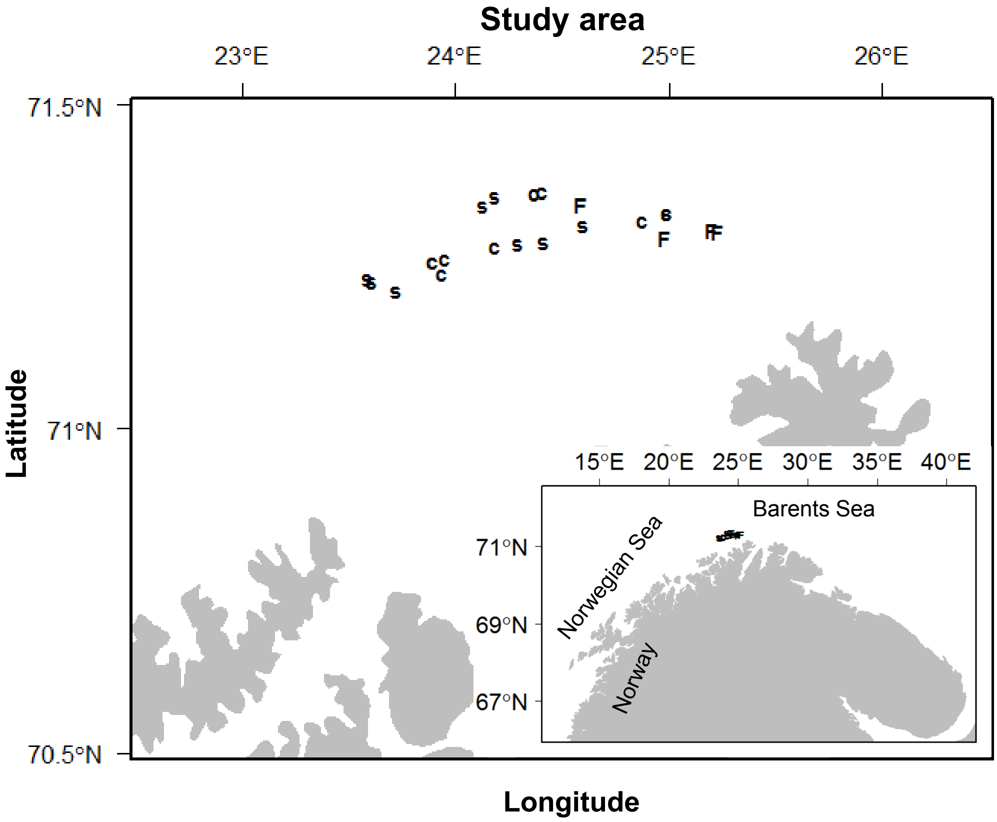

Study area
23°E
24°E
25°E
26°E
71.5°N
71°N
70.5°N
Latitude
Longitude
15°E
20°E
25°E
30°E
35°E
40°E
71°N
69°N
67°N
Barents Sea
Norwegian Sea
Norway

FIG. 5

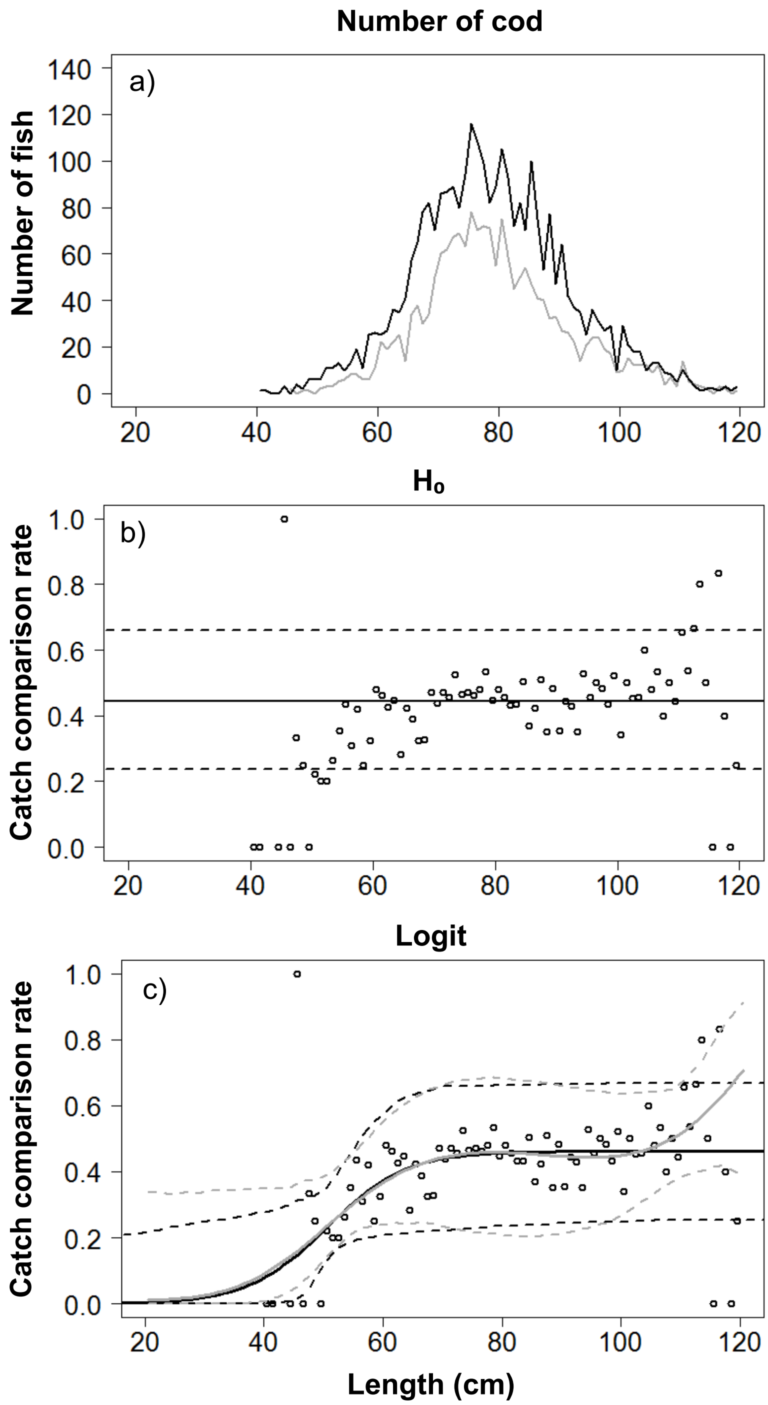

Number of cod
a)
Number of fish
140
120
100
80
60
40
20
0
20
40
60
80
100
120
H_0
b)
Catch comparison rate
1.0
0.8
0.6
0.4
0.2
0.0
Logit
c)
Length (cm)

FIG. 6

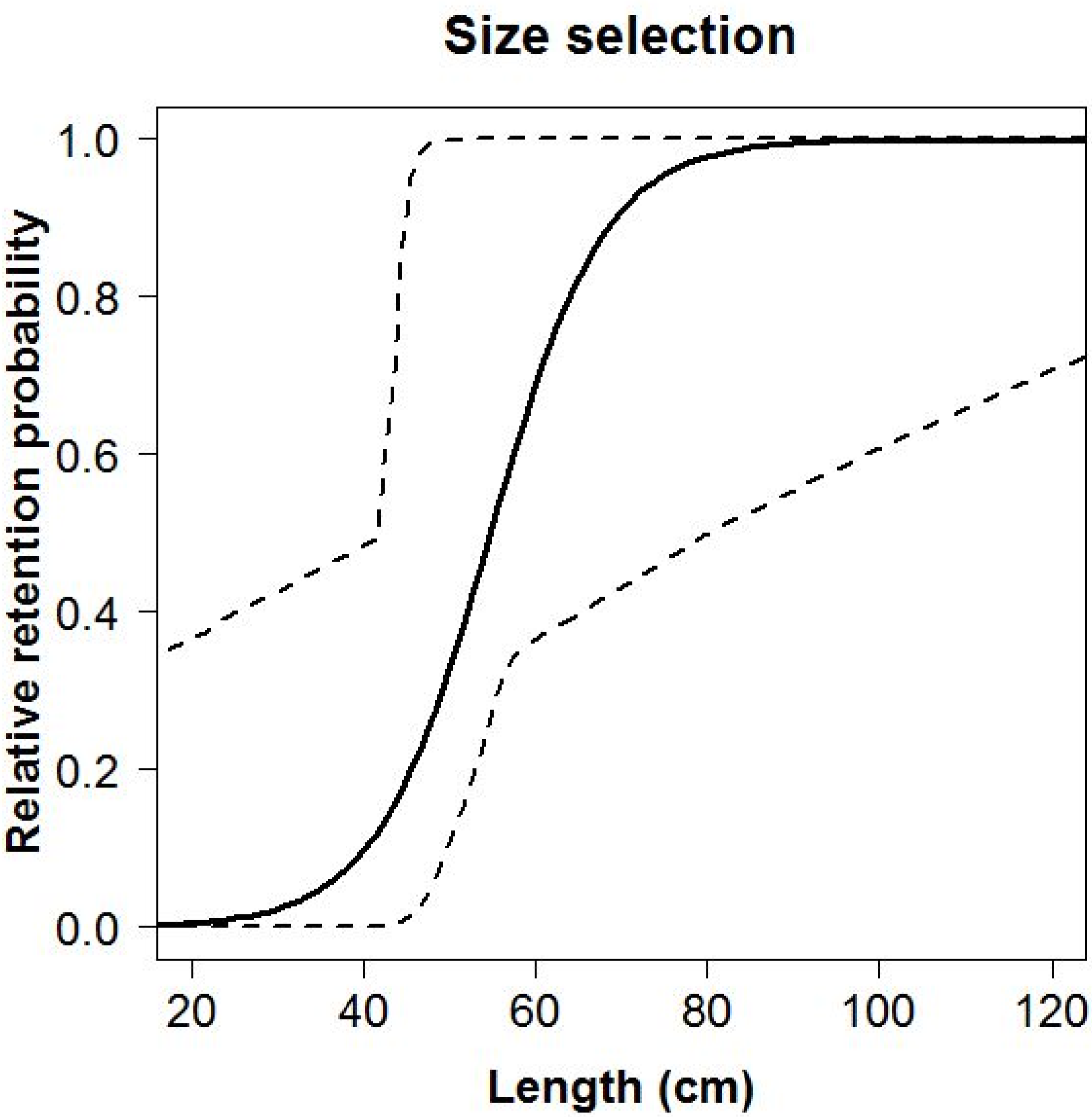

Size selection
Relative retention probability
0.0
0.2
0.4
0.6
0.8
1.0
20
40
60
80
100
120
Length (cm)

FIG. 7

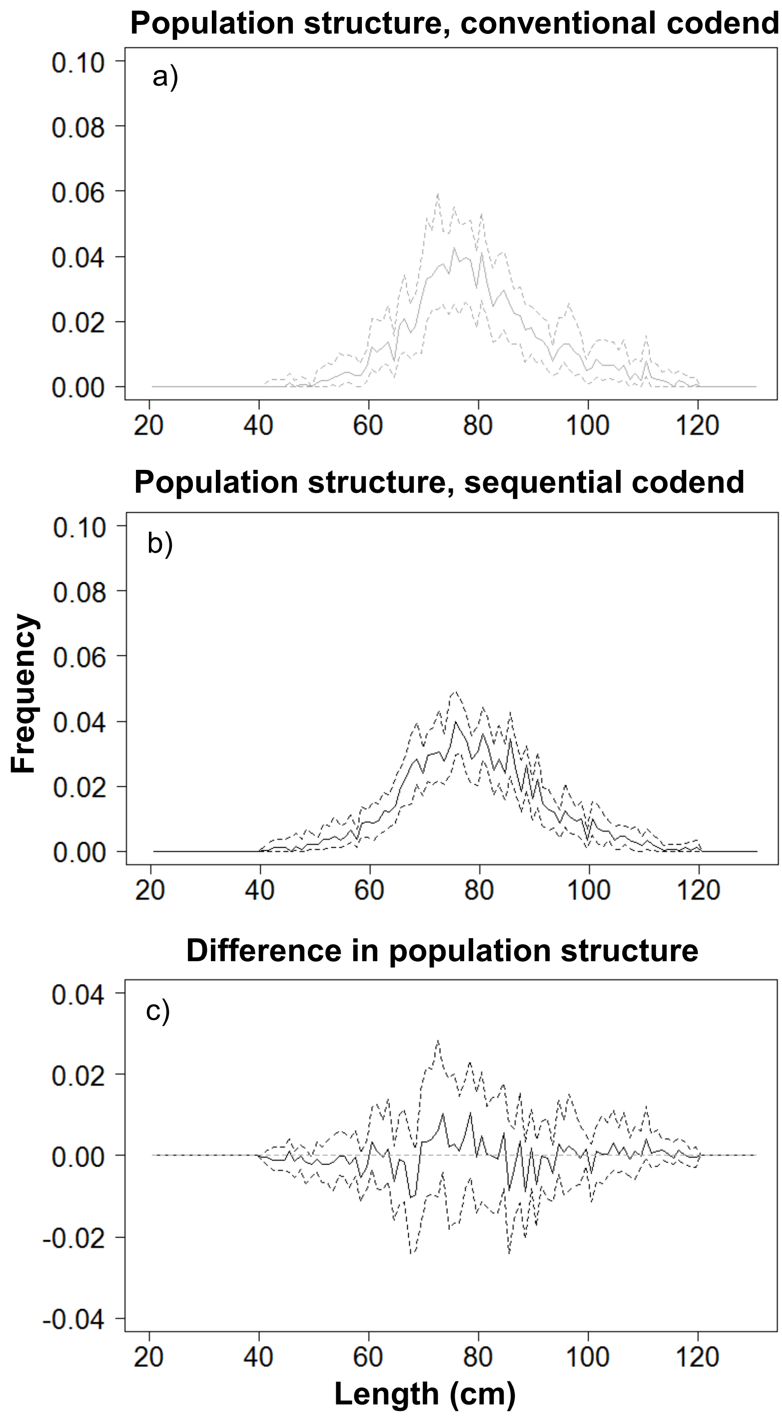
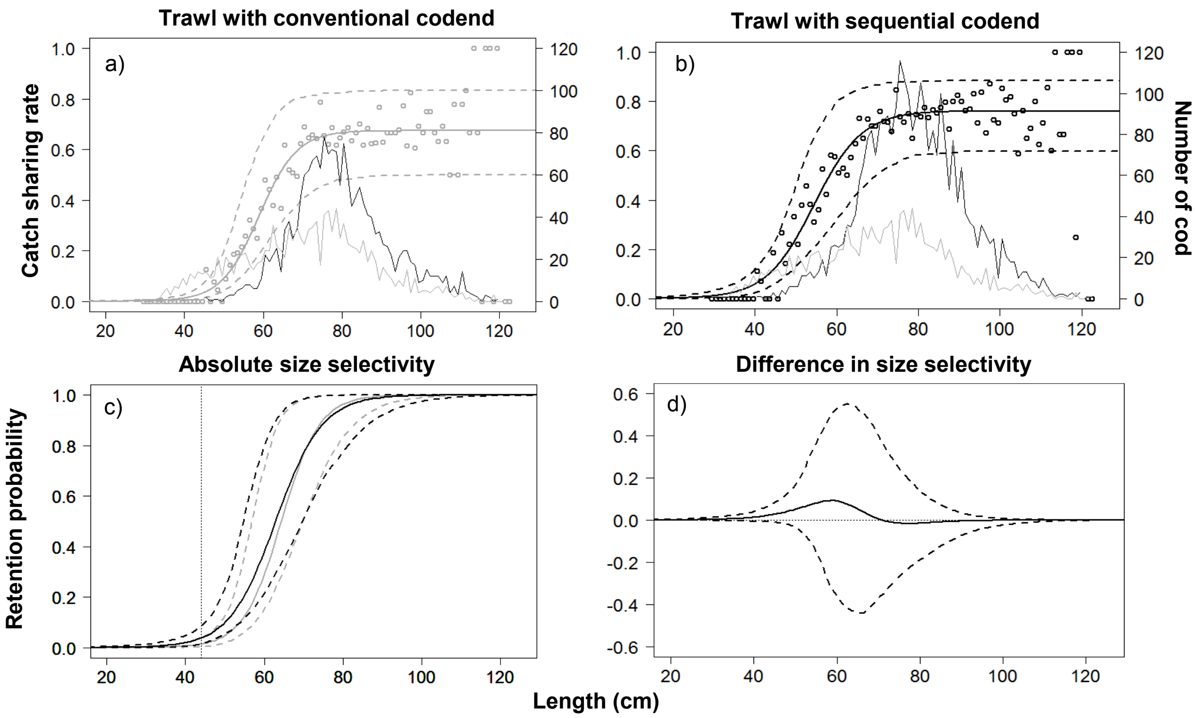

Population structure, conventional codend
a)
Population structure, sequential codend
b)
Frequency
Difference in population structure
c)
Length (cm)
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
20
40
60
80
100
120

FIG. 8


Trawl with conventional codend
Trawl with sequential codend
a)
b)
Catch sharing rate
Number of cod
Absolute size selectivity
Difference in size selectivity
c)
d)
Retention probability
Length (cm)

125

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

Table 2. Fit statistics (p-value, deviance, degrees of freedom (DOF)), AIC values, and the relative model likelihood in percentage for the three models evaluated

Table 3. Reduced escape probability, and increased retention probability including the lower limit of the scaling factor for cod with 5 cm length intervals with 95% CIs for the cod retained in the dual sequential codend compared to the conventional codend

Table 4. Size selectivity parameters and fit statistics for the absolute size selectivity in the trawl with the conventional codend and the sequential codend

TABLE 1

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

TABLE 2

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

TABLE 3

Length (cm)	Escape probability (95% CI)	Scaling factor ($\frac{1.0}{rhb_c(l)}$)
20	0.99 (0.63-1.00)	2.71
25	0.99 (0.60-1.00)	2.48
30	0.97 (0.57-1.00)	2.33
35	0.95 (0.54-1.00)	2.18
40	0.89 (0.51-1.00)	2.06
44	0.82 (0.13-0.99)	1.15
50	0.65 (0.00-0.88)	1.00
55	0.47 (0.00-0.71)	1.00
60	0.29 (0.00-0.63)	1.00
65	0.16 (0.00-0.60)	1.00
70	0.09 (0.00-0.56)	1.00
75	0.04 (0.00-0.53)	1.00
80	0.02 (0.00-0.50)	1.00
85	0.01 (0.00-0.47)	1.00

TABLE 4

	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

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