Catch pattern and size selectivity for a gear designed to prevent fish injuries during the capture process in a North-East Atlantic demersal trawl fishery

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ARTICLE INFO

ABSTRACT

In the North-East Atlantic demersal trawl fishery targeting cod and haddock, the interest on fishing gear designs that preserve fish quality and welfare has grown. However, the gear configurations tested so far imply practical challenges, therefore, more user-friendly designs are still sought by the industry. For a new design to be considered, it needs to have size selective properties that are at least comparable to those obtained with the standard grid and codend gear configuration used in the fishery today. In the present study, we investigated the size selectivity of a new design on three of the most important commercial species in the fishery: cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinnus*) and redfish (*Sebastes spp.*). The new design did not include a sorting grid and was composed of a large mesh segment followed by a quality preserving codend installed in the aft of the gear. The results showed that the experimental gear did not work as intended, catching significantly higher numbers of undersized fish than the standard gear for all three species included in the study. Further, based on hypothesis testing, the null hypothesis of "zero release from the experimental gear" could not be falsified, meaning that it could not be ruled out that there was no escape of fish at all from the experimental gear tested. Despite the negative results obtained, the results from this study enhance the understanding of gear selectivity in towed fishing gears.

1. Introduction

The trawl fishery targeting cod (*Gadus morhua*) is the most important demersal fishery in the North-East Atlantic (Bergstad et al., 1987; Yaragina et al., 2011) with annual quotas (i.e. total allowable catches; TAC) that in the last decade have fluctuated between 600,000 and 1,000,000 metric tons (Norwegian directorate of Fisheries, 2020). Most of the gear technology research related to this fishery in the last thirty years has focused on size selectivity, and specifically, on the development of devices that aim at releasing undersized fish (e.g. Jørgensen et al., 2006; Sistiaga et al., 2008; Grimaldo et al., 2015). However, since the introduction of the sorting grids in the early 1990's (Larsen and

Isaksen, 1993), there have not been any breakthroughs that have led to any major changes in the technical regulations. Still today, fishermen must use a sorting grid with a minimum bar spacing of 55 mm and a size selective codend with a minimum mesh size of 130 mm when targeting cod in the North-East Atlantic (Sistiaga et al., 2018). The technical gear regulations in this fishery, i.e. grid bar spacing and minimum mesh size in the codend, are intended to respect the minimum target size of cod, which is 44 cm. However, apart from cod, other regulated species like haddock (*Melanogrammus aeglefinus*) with a minimum target size of 40 cm, or redfish (*Sebastes spp.*) with a minimum target size of 30 cm, are also caught frequently in relatively large numbers. Therefore, these species are often considered in size selectivity and gear related studies conducted in the region (e.g. Herrmann et al., 2013, 2019; Larsen et al., 2016; Grimaldo et al., 2018).

Apart from the continuous focus on size selectivity research, issues related to fish quality and welfare have received more attention in this fishery in the last years. Quotas for the trawl

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fleets are limited, thus the next most obvious way for fishermen to increase their revenue is by increasing the quality of their product. In addition, the authorities, the society in general and fishermen themselves are increasingly aware of the importance of fish welfare which is often linked to fish quality, as fish that are treated gently in the gear are more likely to be damaged less and thus exhibit a higher quality (Veldhuizen et al., 2018; Brinkhof et al., 2018). Some studies have recently evaluated the external damages on cod captured with gears that were comprised of modifications from the compulsory grid and codend gear used in the North-East Atlantic demersal trawl fishery. Tveit et al. (2019) investigated whether using codends constructed with 4-panels and knotless netting could lead to reduced external damages on cod compared to codends constructed with 2-panels and knotted netting. The results showed that neither changing the construction nor the construction and material leads to any significant reduction in the external damages generated on cod. A slightly earlier study tested a gear configuration composed of a sorting grid and a sequential codend, which according to the results obtained, significantly improved the catch quality of cod (Brinkhof et al., 2018) without compromising size selectivity (Brinkhof et al., 2019). The sequential codend was composed of two segments, a size selective diamond mesh codend, and a subsequent quality preserving segment. While towing, the entrance of the quality preserving segment was kept closed by a hydrostatic catch releaser, and the size selective diamond mesh segment functioned like the codends typically used in the fishery. Only once the codend reached a certain depth during the haul-back process, the passage between the two segments opened and the fish moved back to the quality preserving segment, where they remained for the rest of the haul-back operation. Despite the quality-related benefits of using such a sequential codend, the practical inconveniences of having to deal with a codend that doubles the length of an ordinary codend, and having to rely on the hydrostatic releaser every haul, have meant that this gear configuration has not yet been implemented in the commercial fishery.

In the present study, a new gear configuration was tested. It was composed of a large mesh segment, a subsequent quality/welfare preserving segment identical to the one used by Brinkhof et al. (2018), and it did not depend on any acoustic releaser (Fig. 1). Because no sorting grid was used, the size selectivity of this gear configuration relied completely on the sorting characteristics of the large mesh segment. The motivation for testing this new configuration was a perception that a quality/welfare preserving segment made out of high solidity netting could cause a partial flow blockage and deflect a significant portion of the water flow out through the large meshes in front of the high solidity segment. The hypothesis was that most fish would be guided by the water flow towards the large meshes and size selected by them, thereby preventing capture of undersized fish (Fig. 1b). Further, recent research have demonstrated that fishing with this design significantly increases the probability for cod and haddock without any outer damages in the catch as well as significantly reducing the severeness of the damages to the fish compared to fishing with the grid and codend configuration used in the fishery today (Brinkhof et al., 2019; Sistiaga et al., 2020). Thus, if it worked as intended regarding size selectivity, this gear configuration would not only improve catch quality with respect to the grid and codend configuration used in the fishery today, it would also represent an alternative size selective configuration that does not require a sorting grid.

Thus, the aim of the present study was to investigate the size selection properties and catch patterns obtained by a gear composed of a large mesh segment and a subsequent quality preserving codend, and compare them to the properties of the grid and codend configuration used in the fishery today.

2. Materials and methods

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

Sea trials were carried out onboard the R/V "Helmer Hanssen" (63.8 m length overall and 4080 HP engine) from 01–05 March 2019. The fishing area was off the North coast of Norway between 71°31.33–71°54.76 N and 24°40.65–25°57.53 E, with depths ranging between 263 and 291 m.

During the fishing trials two identically rigged two-panel Alfredo 3 trawls built entirely of 150-mm polyethylene (PE) meshes were used. The trawls were kept open by a set of Injector Scorpion otter boards (each weighing 3100 kg and measuring 8 m^2) that were linked to 60 m sweeps by 7 m long chains. The sweeps were equipped with a Ø 53 cm steel bobbin at the center, to protect them from excessive abrasion. The ground gears were 46.9 m in length and consisted of 18.9 m long rockhopper gears with Ø 53 cm discs in the center and 14 m chains (Ø 19 mm) on each side equipped with three steel bobbins (Ø 53 cm).

In one of the trawls, a standard gear composed of a 2-panel Sort-V grid section (Herrmann et al., 2013); Fig. 2, a 2- to 4-panel transition section and a 4-panel diamond mesh codend was installed. The grid (1234 mm wide and 1750 mm long) was made of steel and installed so that it maintained an angle of approximately 25–26° while fishing, which is considered optimal for selectivity. The bar spacing in the grid was 55.88 ± 2.38 mm (mean ± SD). The 2- to 4-panel transition section between the grid section and the codend was 5.9 m long and constructed with 130 mm meshes (8 mm PE Euroline Premium twine). The 4-panel codend was 11 m long, 64 meshes in circumference, and was made of 8 mm PE Euroline Premium twine. The meshes were 131.1 ± 2.73 mm (mean ± SD) in size. Measurements were made according to the protocol described in Wileman (1996) (Fig. 2a).

In the aft of the other trawl, an experimental gear composed of a large mesh segment with shortened lastridges and a subsequent quality/welfare preserving segment identical to the one used by Brinkhof et al. (2018) was installed. The large mesh segment, which was comprised of 4-panels, was built of 150.2 ± 3.4 mm (mean ± SD) mesh size knotless Ultra Cross netting with 9 mm PE twine. This segment was 49 meshes long and had a circumference of 60 open meshes. The lastridge ropes were 30% shorter than the stretched meshes, with the purpose of keeping the meshes constantly open. A 2- to 4-panel transition section identical to the one described for the first trawl was installed between the trawl and the Ultra Cross selective section (Fig. 2b). The quality preserving segment installed subsequent to the large mesh segment was 10 m long and comprised four panels. It was built with a 6 mm nominal mesh size (2 mm twine thickness) and had a circumference of 1440 meshes (360-meshes wide in each panel). To strengthen the codend, the small mesh netting was reinforced with an outer codend of knotless Ultra Cross with a nominal mesh size of 112 mm (90 meshes in circumference), and four 36 mm lastridge ropes (5% shorter than the codend netting).

The use of the standard grid and codend configuration and the new experimental configuration was alternated so that the hauls carried out with the different gears could be later paired for the data analysis. Both trawls were monitored by Scanmar acoustic sensors measuring the door spread, trawl height and catch volume. A grid sensor was installed at the grid for a couple of hauls before and after the trials to ensure that the grid angle was approximately 25°.

Once the catch was taken onboard, the total length of all cod, haddock and redfish were measured to the nearest cm below.
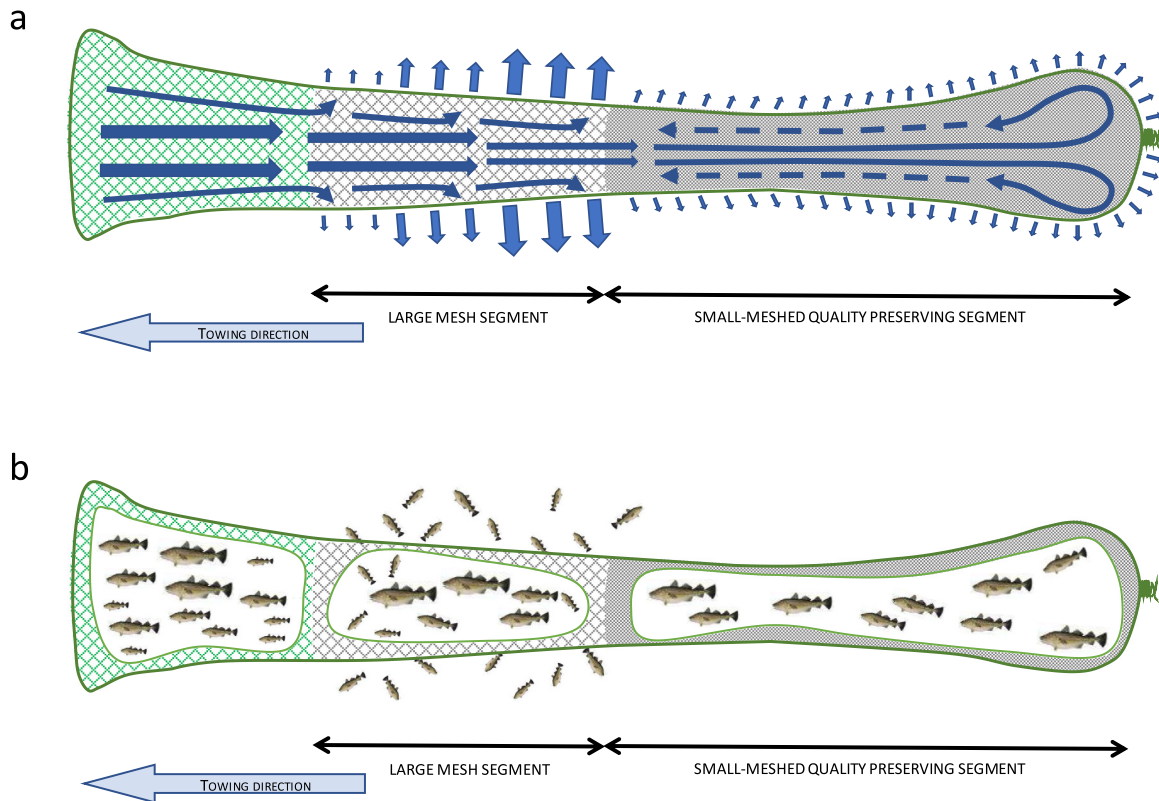
Fig. 1. Illustration of the intended working principle of the new selectivity system tested in the present study. The expected waterflow (a) and size selectivity (b).
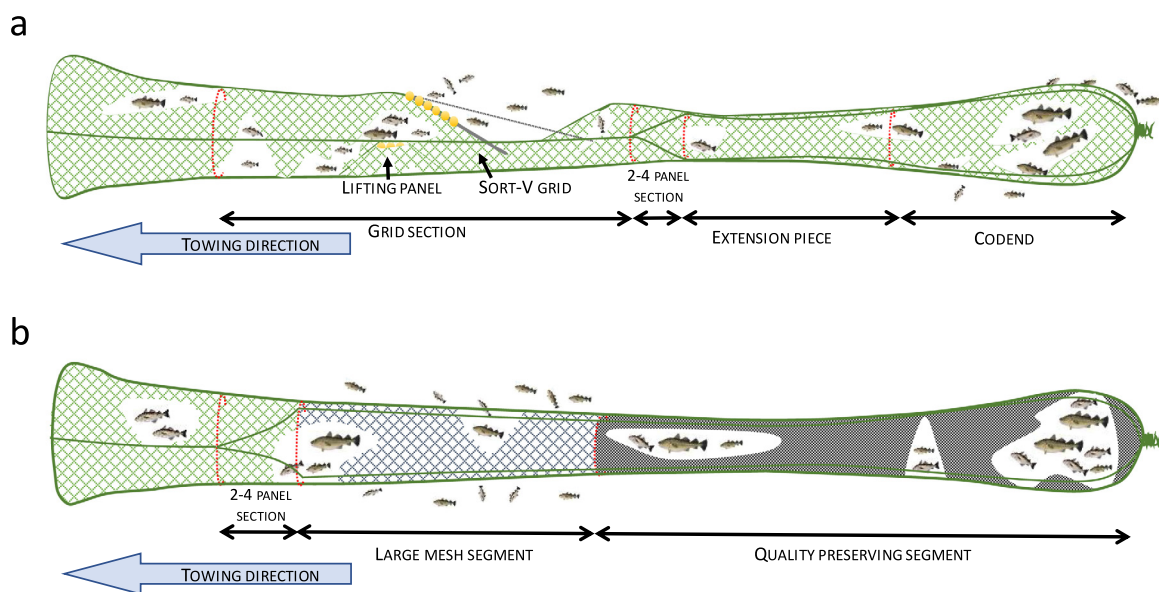

Fig. 2. Standard grid and codend configuration (a) and the experimental gear (b) used during the sea trials.

2.2. Catch pattern analysis

Size frequency distribution and cumulative size frequency distribution analyses were used to compare length distributions of the main fish species caught during the cruises between the two gears. The analysis was carried out for each species and gear separately as follows: Let n_{li} be the number belonging to length class l of a specific species caught and length measured in fishing haul i with that specific gear (standard or experimental). Based on this information, the size frequency distribution D_n_l and the cumulative size frequency distribution CD_n_L were obtained by:

$$D\_n_l = \frac{\sum_{i=1}^{h} n_{il}}{\sum_{i=1}^{h} \sum_{l} n_{il}}$$

$$CD\_n_L = \frac{\sum_{i=1}^{h} \sum_{l=0}^{L} n_{il}}{\sum_{i=1}^{h} \sum_{l} n_{il}} \qquad (1)$$

The summations of i and l in formula (1) are over the h hauls conducted during the cruise with the specific gear and length classes l, respectively. The term CD_n_L quantifies the proportion (in number of fish) of a total catch up to a given length class L.

For each species separately the fraction of the catch that consisted of undersized individuals, i.e. fish below the minimum target size (MTS), was quantified for both the standard and experimental gears by:

$$nDiscardRatio = 100 \times \frac{\sum_{i=1}^{h} \sum_{l=0}^{MTS} n_{il}}{\sum_{i=1}^{h} \sum_{l} n_{il}} \quad (2)$$

Eq. (2) provides the value for the species and the gear specific discard ratio in percentage (%).

The analysis according to Eqs. (1) and (2) was conducted using the statistical analysis tool SELNET (Herrmann et al., 2012; Melli et al., 2020), and the double bootstrapping technique implemented with this tool was used to estimate 95% confidence intervals (CIs). The double bootstrapping method considered both the between-haul variability in the structure of the population captured in the gear and the within-haul variability due to limited numbers of the species captured in that specific haul (Herrmann et al., 2017). Specifically, the double bootstrap procedure accounted for between-haul variability by selecting hauls h with replacement from the total number of hauls h conducted with the specific gear. Within-haul uncertainty was accounted for by resampling with replacement from the catch of the species. The number resampled in the haul in this inner bootstrap loop equaled the total number of individuals of the species length measured in the catch for the selected haul. One thousand bootstrap repetitions were conducted and used to estimate the 95% Efron percentile CIs (Efron, 1982) for D_n_l and CD_n_L.

2.3. Catch comparison and catch ratio analysis

Using the catch data from the sea trials, we conducted length-dependent catch comparison and catch ratio analyses (Herrmann et al., 2017; Sistiaga et al., 2015) to determine whether there was a difference in catch efficiency and/or fish length between the standard and the experimental gear. The analysis was carried out independent for each species following the description below.

To assess the relative length-dependent catch comparison rate (CC_l) of changing from standard to experimental gear, we used Eq. (3):

$$CC_l = \frac{\sum_{j=1}^{h} \left\{ \frac{ns_{lj}}{qs_j} \right\}}{\sum_{j=1}^{h} \left\{ \frac{ns_{lj}}{qs_j} + \frac{ne_{lj}}{qe_j} \right\}} \quad (3)$$

where ns_{lj} and ne_{lj} are the number n of fish of the species investigated caught per length class l for the standard (s) and experimental (e) gear, respectively, in pair j of the alternated tows. Terms qs_j and qe_j are the subsampling ratios introduced to account for unequal towing time between the standard gear (ts_j) and the experimental gear (te_j) in the pair j. Following Eighani et al. (2018) qs_j and qe_j were calculated as:

$$qs_j = \frac{ts_j}{max(ts_j, te_j)}$$
$$qe_j = \frac{te_j}{max(ts_j, te_j)} \quad (4)$$

In Eq. (3), h is the number of tows made with the experimental and standard gear. The functional description of the catch comparison rate $CC(l,\mathbf{v})$ expressed by Eq. (3) was obtained using maximum likelihood estimation by minimizing Eq. (5):

$$-\sum_{j=1}^{h} \sum_{l} \left\{ \frac{ns_{lj}}{qs_j} \times ln\left[CC\left(l, \mathbf{v}\right)\right] + \frac{ne_{lj}}{qe_j} \times ln\left[1.0 - CC\left(l, \mathbf{v}\right)\right] \right\} \quad (5)$$

In Eq. (5), $\mathbf{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\mathbf{v})$. When the catch efficiency of the two trawls is equal, the catch comparison rate would be 0.5.

A catch comparison rate value with 95% confidence intervals (CIs) below 0.5 would imply there is a significant length-dependent catch effect for length class l with fewer fish of length class l caught in the standard gear, and vice versa for a catch comparison rate above 0.5. The experimental CC_l was modeled by the function $CC(l,\mathbf{v})$:

$$CC\left(l, \mathbf{v}\right) = \frac{exp\left[f\left(l, v_0, \ldots, v_k\right)\right]}{1 + exp\left[f\left(l, v_0, \ldots, v_k\right)\right]} \quad (6)$$

In Eq. (6) f is a polynomial of order k with coefficients $v_0 - v_k$, such that $\mathbf{v} = (v_0, \ldots, v_k)$. The values of the parameters $\mathbf{v}$ describing $CC(l,\mathbf{v})$ are estimated by minimizing Eq. (5). We considered f of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4 as our experience from prior studies (Krag et al., 2015; Santos et al., 2016) has demonstrated that this provides a model that can sufficiently describe the catch comparison curves between two fishing gears. Leaving out one or more of the parameters $v_0 \ldots v_4$, at a time resulted in 31 additional candidate models for the catch comparison function $CC(l,\mathbf{v})$. Among these models, the catch comparison rate was estimated using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017). Specifically, the models were ranked and weighted in the estimation according to their $AICc$ values (Burnham and Anderson, 2002). The $AICc$ is calculated as the AIC (Akaike, 1974), but it includes a correction for finite sample sizes in the data. Models that resulted in $AICc$ values within $+10$ of the value of the model with the lowest $AICc$ value ($AICc_{min}$) were considered for the estimation of $CC(l,\mathbf{v})$ following the procedure described in Katsanevakis (2006) and in Herrmann et al. (2015). We use the name combined model for the result of this multi-model averaging and calculated it using Eq. (7):

$$CC\left(l, \mathbf{v}\right) = \sum_i w_i \times CC\left(l, \mathbf{v}_i\right)$$
$$with$$
$$w_i = \frac{exp(0.5 \times (AICc_i - AICc_{min}))}{\sum_j exp\left(0.5 \times (AICc_j - AICc_{min})\right)} \quad (7)$$

where the summations are over the models with an $AICc$ value within $+10$ of $AICc_{min}$. The ability of the combined model to describe the experimental data was based on the p-value, which is calculated based on the model deviance and degrees of freedom (Wileman, 1996; Herrmann et al., 2017). Thus, suitable fit statistics for the combined model to describe the experimental data sufficiently well should include a p-value >0.05 and a deviance value within approximately two times the degrees of freedom.

To provide a direct relative value of the catch efficiency between fishing the experimental and the standard gear, the following catch ratio $CR(l,\mathbf{v})$ equation was used:

$$CR\left(l, \mathbf{v}\right) = \frac{CC\left(l, \mathbf{v}\right)}{\left[1 - CC\left(l, \mathbf{v}\right)\right]} \quad (8)$$

Thus, if the catch efficiency of both gears is equal, $CR(l,\mathbf{v})$ will be 1.0.

Likewise, for the catch pattern analysis we used a double bootstrapping method to estimate the CIs for the catch comparison and catch ratio curves. However, the resampling technique differed. Specifically, the procedure applied here accounts for uncertainty due to between tow variation by selecting h paired tows with replacement from the h paired tows available during each bootstrap repetition. Within each resampled tow, the data for each length class was resampled in an inner bootstrap to account for the uncertainty in the tow due to a finite number of fish being caught and length measured in the paired tow. The inner resampling of the data in each length class was performed prior to the raising of the data with subsampling factors qs_j and qe_j to account for the additional uncertainty due to the subsampling (Eigaard et al., 2012). The resulting data set obtained from each bootstrap

Table 1

Overview of the hauls conducted and the number of fish of each species captured during the data collection period. E denotes the test gear and S the standard trawl setup. The "sampling factor" shows the factor applied to standardize within-pair towing time. *: missing values.

Haul	Time (day:hour: minute)	Towing time (min)	Latitude (N)	Longitude (E)	Depth (m)	Sampling factor (q)	No cod (n)	No haddock (n)	No redfish (n)
1E	01:05:09	91	7154.012	02449.995	263	1.000	205	116	69
1S	01:07:46	90	7154.769	02440.659	277	0.989	105	50	28
2S	01:20:24	60	7136.969	02540.526	280	1.000	1047	172	10
2E	01:02:40	30	7133.948	02540.779	281	0.500	801	84	7
3E	02:07:01	43	7136.108	02548.260	283	0.478	699	98	29
3S	02:11:20	90	7134.920	02542.777	283	1.000	381	515	41
4S	02:16:02	60	7135.040	02554.408	285	1.000	170	29	9
4E	02:18:00	50	7135.123	02543.039	279	0.833	613	99	12
5E	02:22:17	19	7133.600	02544.887	280	0.442	359	*	1
5S	03:00:41	43	7131.338	02548.155	276	1.000	448	*	14
6S	03:04:00	60	7132.492	02545.984	280	1.000	584	17	7
6E	03:06:47	60	7129.954	02546.595	285	1.000	492	56	13
7E	03:10:09	59	7137.491	02545.908	288	0.492	206	192	69
7S	03:12:12	120	7134.934	02546.259	284	1.000	273	213	29
8S	03:15:01	118	7138.043	02540.200	282	1.000	404	36	12
8E	03:17:54	68	7132.670	02529.159	287	0.576	723	113	9
9E	03:22:51	54	7135.182	02532.811	281	0.885	615	135	15
9S	04:03:06	61	7135.787	02535.727	*	1.000	551	87	6
10S	05:02:08	75	7134.330	02530.939	286	0.962	715	94	13
10E	05:05:43	78	7132.933	02531.581	289	1.000	1180	140	24
11E	05:12:31	75	7135.006	02554.644	290	1.000	1072	290	30
11S	05:18:28	24	7136.675	02557.306	290	0.320	435	46	5

repetition was analyzed as described above and therefore also accounted for uncertainty in model selection and model averaging because the multimodel inference was included (Grimaldo et al., 2018). Based on the bootstrap results, we estimated the Efron percentile 95% CIs (Efron, 1982) for both the catch comparison and catch ratio curve. We performed 1000 bootstrap repetitions. The catch comparison and catch ratio analysis was conducted with the analysis tool SELNET which was also used in the catch pattern analysis.

2.4. Testing for absolute size selection

The size selectivity in the experimental gear relies on the fish utilizing the large meshes ahead of the quality preserving segment in the aft to attempt escape (Fig. 1). Fish entering the quality preserving segment in the aft will have no chance to escape due to the very small mesh size here. In the extreme case that no fish utilize the escape option ahead of the quality preserving segment in the experimental gear, this gear will act as a control gear that simply samples the population structure on the fishing ground available for the gear. In that situation the pairs of standard and experimental gear tows can be considered as a paired gear experiment (Wileman, 1996) to assess the size selectivity in the standard gear. Under these circumstances, the null hypothesis H_0 of no size selection in the experimental gear, an estimate of the size selection $rs\,(l, \boldsymbol{vs})$ in the standard gear can be made using the paired data in Eq. (5) (Lövgren et al., 2016; Sistiaga et al., 2016):

$$-\sum_{j=1}^{h}\sum_{l}\left\{\frac{ns_{lj}}{qs_j}\times ln\left[\frac{SP\times rs\,(l,\boldsymbol{vs})}{SP\times rs\,(l,\boldsymbol{vs})+1.0-SP}\right]+\frac{ne_{lj}}{qe_j}\right.$$
$$\left.\times ln\left[\frac{1.0-SP}{SP\times rs\,(l,\boldsymbol{vs})+1.0-SP}\right]\right\} \qquad (9)$$

where $\boldsymbol{vs}$ is a vector of the parameters in the size selection model for the standard gear. The parameter SP (split parameter) quantifies the proportion of fish entering the standard gear compared to the sum in both gears (standard and experimental), which is assumed to be length independent. For the standard gear design with the grid followed by a size selective codend, it is well-established that the combined size selection of the grid and the

codend can be approximated by a logit selection model (Sistiaga et al., 2009):

$$rs\,(l, \boldsymbol{vs}) = \frac{exp\left(\frac{ln(9.0)}{SR}\times(l-L50)\right)}{1.0+exp\left(\frac{ln(9.0)}{SR}\times(l-L50)\right)}$$
$$\boldsymbol{vs} = (L50, SR) \qquad (10)$$

L50 is the length of the fish with a 50% chance of retention providing it enters the gear (Wileman, 1996). The parameter SR is the selection range (=L75–L25).

The rationale for using the logit curve for the combined size selection curve in the standard gear is that those fish that are not exposed to size selection by the grid will be subsequently size selected by the codend. Therefore, using the logit size selection model in Eq. (9) we test whether H_0 can be rejected, which would prove a size selection in the experimental gear. Contrarily, not being able to reject H_0 implies that based on the collected experimental data, we cannot rule out the extreme situation of "no size selection" in the experimental gear. Based on the logit size selection model Eq. (10) for $rs\,(l, \boldsymbol{vs})$, we minimize Eq. (9) with respect to $\boldsymbol{vs}$. Then, we use the fit statistics in terms of the corresponding p-value that provide the probability to obtain at least as big a deviation between the experimentally obtained length-dependent catch share rate between the standard and the experimental gear by chance. In case the p-value > 0.05, we cannot rule out that the deviation between the modeled curve (relying on the assumption of no size selection in the experimental gear) and the experimentally obtained rates is coincidental. Contrarily, if the p-value is < 0.05, it is unlikely that the deviation between the modeled curve and the experimental data is a coincidence, which would challenge the assumption of the model, making it likely that at some level size selection occurred in the experimental gear. If H_0 is not rejected, we use the $rs\,(l, \boldsymbol{vs})$ curve obtained as an estimate for size selection for the standard gear.

3. Results

3.1. Data collection

During the sea trials a total of 22 hauls were carried out, 11 with the standard gear, and 11 with the experimental gear (Table 1). The towing times for the different hauls varied between 19 and 120 min and the sampling factors applied to standardize

Table 2
Discard ratio (percentage of catch below minimum target size). Values in brackets represent 95% confidence bands.

Gear	Cod	Haddock	Redfish
Standard gear	0.25 (0.07–0.55)	0.22 (0.00–0.85)	0.00 (0.00–0.00)
Experimental gear	5.11 (3.82–6.79)	25.28 (17.36–37.05)	5.76 (1.06–9.68)

the within-pair towing time varied between 0.320 and 1.000. In the 22 hauls carried out during the experimental period, cod, haddock and redfish were caught in sufficiently high numbers to be included in the data analysis. A total of 12,078 cod, 2582 haddock and 452 redfish were caught and length measured.

3.2. Catch patterns

A comparison of the length-dependent catch densities and cumulative catch densities of cod, haddock and redfish between the standard gear and the experimental gear showed clear significant differences. Those differences were in all three cases the largest for the smallest sizes of fish, and while the standard gear practically did not catch any undersized fish, the new gear tested caught substantial numbers of them. For cod, the length classes of up to 50 cm were represented in significantly higher proportions in the catch when the experimental gear was used than when the standard gear was used (Fig. 3a). The cumulative density plots showed that in the experimental gear the catch would consist of a larger proportion of smaller cod than in the standard gear (Fig. 3d). Specifically, 5.11% of the cod caught with the new gear were below the minimum target size (< 44 cm), while this was only 0.25% for the cod caught with the standard gear (Table 2). Regarding haddock, length classes of up to 42 cm were captured in significantly higher proportions when the experimental gear was used (Fig. 3b). As observed for cod, from the cumulative density plot the catch in the experimental gear consisted of a larger proportion of smaller haddock than the standard gear (Fig. 3e). When the minimum target size of 40 cm for haddock is considered, the results show that over 25% of the haddock captured with the experimental gear were undersized, whereas the proportion of undersized haddock caught with the standard grid and codend gear was only 0.22% (Table 2). For redfish, the results followed the same patterns as for cod and haddock. The new gear caught significantly higher proportions of smaller-sized fish than the standard grid and codend gear (Fig. 3c, f). In fact, while the standard grid and codend gear did not capture any undersized redfish, almost 6% of the redfish caught with the gear were smaller than the minimum size of 30 cm (Table 2).

3.3. Catch comparison analysis

The catch comparison analysis showed that the models used represented the data well (Fig. 4 a–c). The fit statistics in Table 3 show that for all three species the p-values are above 0.05 and the degrees of freedom are of the same magnitude as the deviance, meaning that the discrepancies observed between the model and the data are most likely a coincidence.

The catch ratio curves show in general values <1.00 for the smallest length classes, which means that the standard gear captures fewer small fish than the experimental gear. For cod, the catch ratio curve shows that the standard gear catches significantly less cod below 60 cm than the experimental gear (Fig. 4d). Further, the catch ratio becomes lower with decreasing fish size, which means that the difference between the sorting ability of the two gears tested increases with decreasing fish size. As both gears fish equal when $CR = 1.00$ (100%), the results show for example that at 60 cm the standard gear was estimated to catch only 67.16% of what would be captured with the experimental gear, whereas at 40 cm it was estimated to catch only 3.04% of what would be caught with the experimental gear (Table 3). For haddock, the catch ratio results also showed that the experimental gear captured significantly more smaller-sized fish (ca. < 48 cm) than the standard gear and that this difference increased with decreasing fish size (Fig. 4e). While at 50 cm the standard gear estimated to catch 80.54% of what was captured with the experimental gear, at 30 cm this difference was estimated to be 0.30% (Table 3). As for cod and haddock, the catch ratio plot for redfish shows that the new gear configuration catches more redfish of all sizes than the standard grid and codend configuration. This difference decreased with fish size and was significant for length classes up to ca. 48 cm (Fig. 4f). At 30 cm, which is the minimum targeted size for redfish, the standard gear was estimated to catch 9.18% of what would be caught with the experimental gear, whereas at 50 cm, this difference was estimated to increase to 64.77% (Table 3).

3.4. Testing the hypothesis of no size selection in experimental gear

The p-values for the null hypothesis of no size selection in the experimental gear were at least 0.05 for all three species investigated (Table 4), which implies that we cannot falsify the hypothesis for any species. This means that based on the hypothesis testing we cannot rule out the extreme case of no size selection in the experimental gear implying no escape through the large mesh segment of the experimental gear (Fig. 1). Under the assumption of no size selection in the experimental gear, we obtain an estimate for the size selection in the standard gear (Fig. 5). The estimated values for the size selection parameter L50 for the standard gear are 53.3, 50.9 and 46.2 cm for cod,
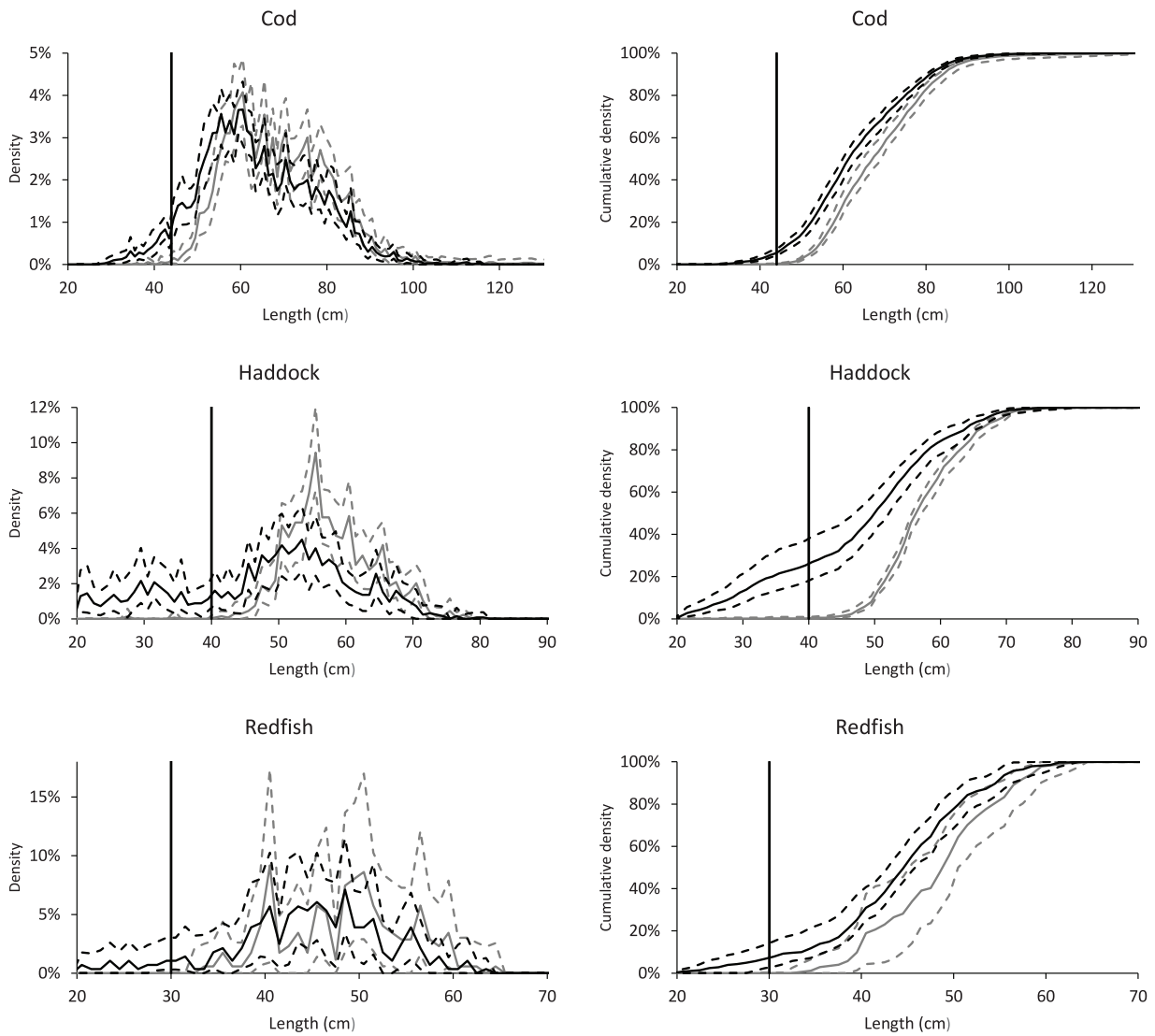
Table 3
Catch ratio results at different lengths and fit statistics for the catch comparison analysis for cod, haddock and redfish. Values in brackets represent 95% confidence limits. n/a denotes no fish of this length class were caught.

Length (cm)	CR (%)		
	Cod	Haddock	Redfish
20	0.00 (0.00–0.00)	1.24 (0.00–5.36)	3.11 (0.00–8.24)
30	0.04 (0.01–0.25)	0.30 (0.01–0.89)	9.18 (0.469–19.17)
40	3.04 (1.68–5.27)	5.23 (2.32–10.92)	29.67 (14.00–44.36)
50	27.41 (18.44–38.91)	80.54 (44.32–145.60)	64.77 (32.94–124.00)
60	67.16 (42.33–98.39)	185.13 (102.23–328.44)	87.49 (22.91–528.40)
70	81.73 (53.97–120.83)	135.12 (81.96–241.64)	n/a
80	78.26 (58.71–104.91)	790.78 (31.63–191.52)	n/a
90	81.05 (67.98–96.64)	n/a	n/a
Number of pairs	11	10	11
p-value	0.08	0.09	0.54
Degree of freedom	96	55	39
Deviance	115.76	69.18	37.42

Fig. 3. Plots a–c show the densities of the different length classes of respectively cod, haddock and redfish captured, respectively, with the experimental gear (black) and the standard gear (gray). Plots d–f show the cumulative densities of cod, haddock and redfish captured, respectively, with the experimental gear (black) and the standard gear (gray). The stippled curves represent the 95% confidence bands whereas the vertical lines represent the minimum target size for each species.

Table 4

Results for the hypothesis testing regarding no size selection in the experimental gear (H_0): model parameter values and fit statistics. Values in brackets represent 95% confidence limits.

Species	Cod	Haddock	Redfish
L50 (cm)	53.28 (50.92–56.28)	50.85 (48.68–53.48)	46.18 (32.50–76.12)
SR (cm)	8.48 (6.77–11.82)	6.43 (4.95–9.12)	9.18 (0.469–19.17)
SP	0.44 (0.37–0.53)	0.64 (0.51–0.75)	0.50 (0.26–0.95)
Number of pairs	11	10	11
p-value	0.08	0.09	0.54
Degree of freedom	98	57	41
Deviance	122.64	75.11	37.83

haddock and redfish, respectively (Table 4). These L50 values are all well above the minimum target sizes of 44, 40 and 30 cm, demonstrating low catch efficiency of legal sized fish close to the minimum size for the standard gear. This low catch efficiency for sizes of fish around the minimum target size is also clear from the size selection curves included in Fig. 5.

Besides the fit of the logit size selection curve to the experimental data (under the assumption of no size selection in the experimental gear), Fig. 5 also includes the catch comparison curves estimated in the previous section (without any assumption regarding size selectivity in any of the gears). From the similarity between the two curves it is obvious that imposing the assumptions of the H_0 hypothesis (logit size selection in the standard gear and no size selection in the experimental gear), does not hamper the ability to model the experimental catch sharing rates between the standard and experimental gear for any of the three species.

4. Discussion

The increased focus on fish quality and welfare in the North-East Atlantic demersal trawl cod and haddock fishery, and the fact that the sequential codend design in Brinkhof et al. (2018) is not commercially employed by fishermen because it implies the use of two subsequent codends and a hydrostatic releaser, suggests the need for a more maneuverable and user friendly design. This new design was demonstrated to have better quality-preserving characteristics than the grid and codend design used in the fishery today (Brinkhof et al., 2021; Sistiaga et al., 2020), but most importantly, it should have selective properties comparable to the gear used by the fleet today.
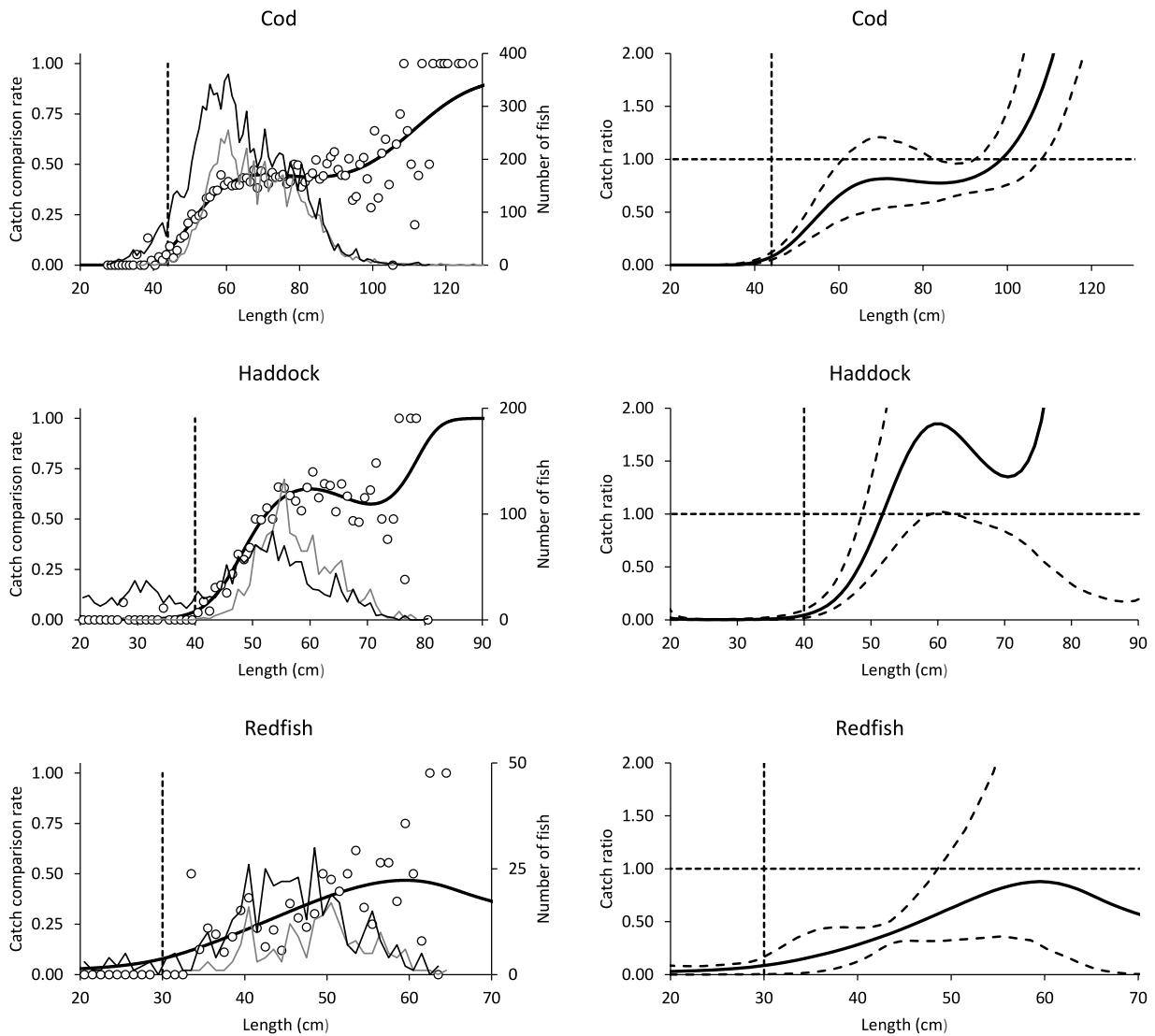
Fig. 4. Catch comparison rate (left column) and catch ratio (right column) for cod, haddock and redfish for the standard gear versus the experimental gear. The circle marks represent the experimental rates. The thick black curve represents the modeled rate and thin stippled curves represent the corresponding 95% confidence limits. The thin gray and black curves represent the population of fish captured in standard and experimental gear, respectively. The horizontal black stippled line shows the expected rate in case of no difference in catch efficiency between gears. The vertical line represents the minimum target size.

The results of the present study showed that the selective properties of the new experimental gear tested were significantly different from those obtained with the standard gear used by the fleet in the North-East Atlantic demersal fishery today. For all three species investigated, cod, haddock and redfish, the experimental gear caught significantly higher proportions of undersized fish than the standard gear. It is obvious that overall, the experimental gear cannot be considered as an alternative to the standard gear used by the fleet, independent on whether it implies any improvement related to catch quality. Thus, the design presented by Brinkhof et al. (2018), which significantly reduced external damages on trawl-caught cod, remains as the most realistic configuration for quality preservation in this fishery, even though further work is required to overcome some of the challenges identified for that gear.

The design tested in this study was based on the assumption that the quality preserving section in the experimental gear could create a partial flow blockage and deflect a sufficient portion of the water flow out through the large meshes in front of the quality preserving segment, and thus stimulate fish escape at this point. The water flow in the different parts of the gear could

not be measured, but a post-evaluation based on Gjøsund and Enerhaug (2010) indicates that the netting used in the quality preserving segment did not have a sufficient solidity ratio to cause a strong or even noticeable flow blockage and deflection. This can be discussed in terms of the "open mesh filtering area (porosity ∗ cylinder area) to mouth area ratio" R_A. As a rule of thumb, one may expect the filtration to be high, i.e. that there is no significant flow blockage, if R_A is 3 or higher. The length of the section is L = 10 m and we approximate the diameter of the section to D = 1 m. The net area can then be approximated by the surface area of a 10 m long cylinder with a diameter of 1 m, and the mouth area by a circle with a diameter of 1 m. The ratio between these two areas is 4L/D = 40 (neglecting that there is also a filtering area at the very end of the segment). In order to find R_A, we also need to know the porosity in the segment. In order to expect a noticeable flow blockage, i.e. $R_A < 3$, the porosity must be less than 3/40 = 0.075, i.e. the solidity ratio must be higher than 0.925 (1 − porosity = solidity). In order to get a strong flow blockage, the solidity ratio would need to be even higher.

The netting consisted of meshes with a mesh opening of 6 mm and a 2 mm twine thickness. If the meshes where square meshes,
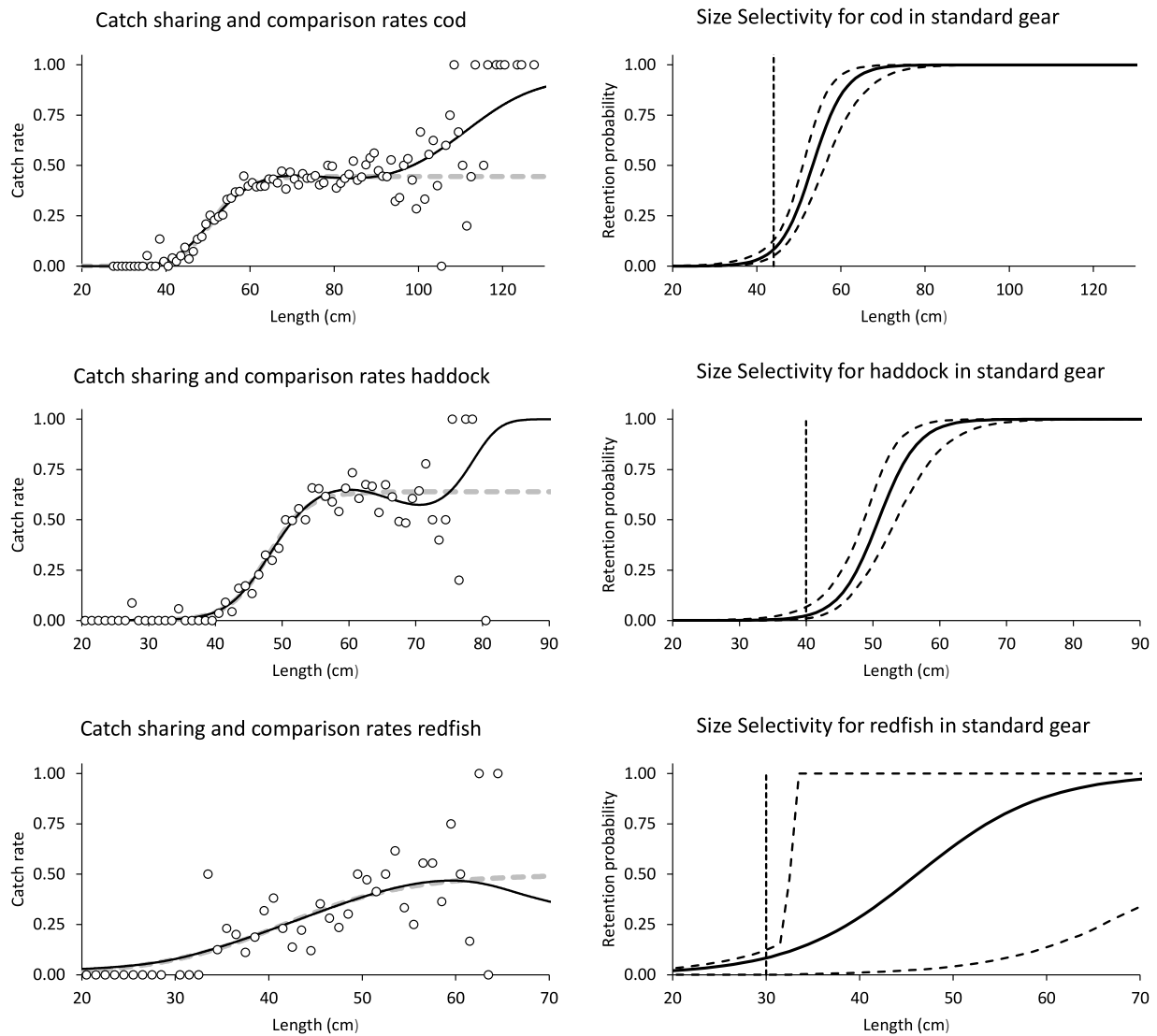
Fig. 5. The left column shows the paired gear catch sharing rate for the standard gear versus the experimental gear (gray stippled curve) for cod, haddock and redfish. The circle marks represent the experimental rates and the black curve represents the catch comparison curve from Fig. 4. The plots in the right column show the size selectivity curves: from the top for cod, haddock and redfish. The thin stippled curves represent the corresponding 95% confidence limits. The vertical line represents the minimum target size.

i.e. the mesh opening angle is 90°, the solidity ratio would be 0.64. If the mesh opening angle was 45°, the solidity ratio can be estimated e.g. according to Fredheim and Faltinsen (2003) to approximately 0.8. The mesh opening angle may have been even smaller, and consequently, the solidity higher. However, it becomes increasingly difficult to calculate a correct solidity ratio with decreasing mesh opening angle, and it is then best to perform actual measurements for a small net area. Nevertheless, it seems reasonable to assume that the effective solidity ratio might have been in the range of 0.8–0.9 and thus lower than what is expected to result in a noticeable flow blockage and deflection. Taking into consideration the selectivity results obtained, this indicates that any deflection and water flow out through the meshes in the large mesh segment was too weak to stimulate the release of undersized fish. It can be noted that the porosity of a double layer of netting can be approximated as the square of the porosity of a single layer (depending on the positioning between the two layers). Hence, a quality preserving segment built with netting with a very high solidity ratio, e.g. a double layer of the netting used in these tests, might have resulted in a stronger

blockage and flow deflection which could stimulate undersized fish to escape.

Independent on the level of water blockage achieved in the section, for the large mesh segment in the experimental gear design tested to be effective at releasing fish, the fish needs to contact the meshes in the netting so that they are subjected to a size-dependent probability of escaping through them (Millar and Fryer, 1999; Sistiaga et al., 2010). However, several fish species have been reported to have a preference for staying clear from the netting unless they are stimulated to attempt escape (Wardle, 1993; Glass et al., 1995). This issue applies specially to non-tapered sections and escape panels, where the incentive for fish to contact the netting and attempt escape through can be low. Several studies have shown that unless heavily stimulated, fish follow the main flow and path in the trawl until they reach the codend, making the selective properties of non-tapered netting sections and escape panels generally poor (Grimaldo et al., 2018; Herrmann et al., 2015; Cuende et al., 2020). In the present study, it was intended that due to the potential flow blockage created by the quality preserving segment of the experimental section, most water in the aft of the gear would flow out at the large

mesh section. However, the size selectivity results obtained show that the water flow directed towards the large mesh panel (Fig. 1) was probably not as significant as intended, and certainly not substantial enough to stimulate the escape of any of the three species investigated through the large mesh segment. Several studies have reported species-dependent behavior inside trawls (e.g. Tschernij and Suuronen, 2002; Winger et al., 2010). For example, cod has been observed to be reluctant to attempt escape through netting sections, while haddock are more active inside the trawl and somewhat easier to trigger to attempt escape (Grimaldo et al., 2018). However, the results of this study showed large retention of undersized individuals for haddock as well as cod, which shows again that the design is far from working as intended.

One of the challenges in the North-East Atlantic cod and haddock fishery today is that the compulsory grid and codend configuration employed can at times release substantial quantities of fish larger than the minimum size. This is especially true for haddock, which has a minimum size four cm lower than cod (40 cm vs. 44 cm), has a pronounced lateral compressed body shape and is harvested with the same gear as cod: 55 mm bar spacing grid and a codend with a minimum size of 130 mm (Sistiaga et al., 2016). The catch patterns presented in this study show that the experimental gear captures much larger quantities of undersized fish than the compulsory grid and codend configuration used by the fleet. Fishermen in this area, especially fishermen with low cod quotas, complain that fishing haddock with the standard gear used today is very inefficient and not very environmentally friendly, as a large proportion of the marketable fish that enters the trawl can be released in the aft. Thus, if the experimental gear tested here could be improved to release the undersized fish and at the same time retain most of the fish above the minimum size entering the trawl, it could become a valuable alternative to the gear used in the fishery today.

The experimental design tested in this study did not work as intended, however, reporting negative findings and results have scientific value. In the same way as positive results, negative results can enhance the understanding of fishing gear selectivity and reduce the risk for making the same mistakes numerous times. Further, negative results can be important contributions to literature that avoid forming a biased picture (Csada et al., 1996). Therefore, the results from the present experiment are considered important for advances in the field of fishing gear technology and size selectivity.

CRediT authorship contribution statement

Bent Herrmann: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Manu Sistiaga:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Roger B. Larsen:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Investigation, Data curation, Writing - original draft. **Jesse Brinkhof:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Svein Helge Gjøsund:** Writing - original draft, Project administration, Funding acquisition. **Nadine Jacques:** Investigation, Data curation, Writing - original draft. **Juan Santos:** Investigation, Data curation.

Declaration of competing interest

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

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