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Original Article

Managing size selectivity: the relevance of compulsory and alternative selection devices in the Northeast Atlantic bottom trawl fishery

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Two decades of use of the compulsory selectivity gear configuration in the Northeast Atlantic bottom trawl fishery, which consists of a rigid sorting grid followed by a diamond mesh codend, have revealed problems with performance and efficiency. Size selectivity gear alternatives to this configuration are being pursued, and recent studies of codends with shortened lastridges have reported promising results. In this study, we compared the size selectivity and catch efficiency for cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) caught using a sorting grid with 55 mm bar spacing followed by a 130 mm knotted diamond mesh codend (i.e. the compulsory gear) that same configuration but considering only the catch in the 130 mm diamond mesh codend (regular codend), and an alternative knotless codend with shortened lastridge ropes and a thinner twine. We also addressed the question of whether size-selective gear is even needed to avoid exceeding the bycatch limits of the fishery. Our results demonstrated that the alternative codend improved size selectivity by reducing the loss of fish above minimum legal size (*MLS*), with a minor increase in the retention of fish below *MLS*, compared to the compulsory combined grid and codend configuration. The regular codend also reduced the loss of fish above *MLS*, but the retention of haddock below *MLS* approached the legal limit of 15% by number. Our results also showed that the abundance of cod below *MLS* in the fishing area during the trials was low. They also suggested that spatial and seasonal closures in combination with a flexible choice of selection device and modern monitoring tools could be an alternative to rigid enforcement of the use of selective fishing gear.

Keywords: codend, demersal trawl fishery, shortened lastridges, size selectivity, sorting grid.

Introduction

Demersal trawl fisheries have traditionally relied on diamond mesh codend selection to obtain exploitation patterns that comply with the management objectives of the fishery. However, additional devices have been tested in several fisheries and, in some cases, implemented to supplement the selectivity of diamond mesh codends (Kennelly and Broadhurst, 2021; Melli *et al.*, 2020). For instance, the use of a sorting grid with 55 mm bar spacing in addition to a codend with a minimum mesh size of 130 mm has been compulsory in the Barents Sea gadoid fishery since 1997. In this fishery, three different sorting grids are allowed today (Sort-X, Sort-V, and Flexigrid), but only the latter two are currently used by the fishing fleet (Grimaldo *et al.*, 2015; Sistiaga *et al.*, 2016, Brinkhof *et al.*, 2020).

Northeast Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) are the two most important commercial gadoid species in the Barents Sea demersal trawl fishery in terms of value and quantity (Yaragina *et al.*, 2011; ICES, 2021). The fishery is regulated by a general discard ban and a minimum legal size (*MLS*) of 44 cm for cod and 40 cm for haddock. In addition, catches can contain a maximum of 15% of fish below *MLS* in numbers per haul; if exceeded, the areas become temporarily closed for fishing (Ministry of Trade, Industry, and Fisheries, 2020).

There is extensive documentation showing that in general, sorting grids can contribute to the sustainability of fisheries by reducing the catch of fish below *MLS* (e.g. Sistiaga *et al.*, 2010; Brinkhof *et al.*, 2020). However, several recent studies demonstrated that the properties of the grids used in the Barents Sea could vary substantially under different conditions (e.g. population of fish being fished) and that grids may not provide as sharp and stable selectivity as earlier presumed (Sistiaga *et al.*, 2016; Brinkhof *et al.*, 2020).

Cod and haddock are often caught mixed in the fishery, and substantial morphological and behavioural differences have been reported between the species. These differences make optimal selectivity for both species simultaneously difficult (Sistiaga *et al.*, 2011; Brinkhof *et al.*, 2020, 2022). Further, the bar spacing in the grid and mesh size in the codend are intended to achieve the desired exploitation pattern for cod but not for haddock. Haddock have a lower *MLS* than cod, a more active escape behaviour in the net, and a morphology more suitable to passing between the bars in the grid (Tschernij and Suuronen, 2002; Sistiaga *et al.*, 2011; Grimaldo *et al.*, 2018). Therefore, losses of large quantities of haddock above *MLS* can be

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a problem in the fishery (Brinkhof *et al.*, 2020). This poses a management dilemma between prioritizing the desired exploitation pattern for cod and the lack of efficiency for fishing haddock.

Since the introduction of the sorting grids in the Barents Sea, there has been controversy about whether the use of a grid in the fishery is necessary to obtain the desired exploitation patterns for cod and haddock (Jørgensen *et al.*, 2006). During the last two decades, fishermen have reported several impracticalities with the use of grids: capacity problems at high entry densities; maneuverability challenges in bad weather; and reduced water flow inside the grid section and the codend, which causes fish to block the grid, subsequently creating operational problems for catch control sensors (Grimaldo *et al.*, 2014; Sistiaga *et al.*, 2016). Thus, several recent studies from the Barents Sea demersal trawl fishery have focused on alternatives to the sorting grid and investigated the potential of different mesh configurations in the codend, such as codends with square mesh sections, T90 codends (turning the orientation of the meshes 90 degrees perpendicular to the towing direction), and codends with shortened lastridge ropes (Ingolfsson and Brinkhof, 2020; Brinkhof *et al.*, 2022; Sistiaga *et al.*, 2022).

Codends with shortened lastridge ropes as an alternative to grids are of interest among fishermen because of their simplicity and initial promising results (Ingolfsson and Brinkhof, 2020). In standard diamond mesh codends, lastridge ropes are normally slightly shorter (e.g. ca. 5%) than the stretched length of the codend meshes, and they are fixed to the selvedges in such a way that as the catch accumulates in the codend and tension builds, most of the load is held by these ropes. Additionally, shorter lastridge ropes will begin to bear the load earlier as the catch accumulates, which will keep the netting in the codend tensionless and the meshes open during the fishing process. The properties added to the codend by shortening lastridge ropes have been shown to improve the selective properties of the codend (Isaksen and Valdemarsen, 1990; Lök *et al.*, 1997; Ingolfsson and Brinkhof, 2020). Sistiaga *et al.* (2022) recently compared selectivity results obtained with sorting grids during the last two decades and codends with shortened lastridge ropes and concluded that the latter may be a simpler alternative to sorting grids for the fishery. However, despite the promising selectivity results obtained with this codend configuration, no study has directly compared the selection properties of grids combined with diamond mesh codends and codends with shortened lastridge ropes.

Considering the challenges posed by the use of sorting grids in conjunction with the seasonal and spatial variations of the population structures of cod and haddock, including periods and areas with a low mix of juvenile fish, we also questioned whether selectivity devices such as grids, panels, and mesh size regulation are needed in this fishery.

Thus, the goals of this study were to answer the following research questions:

- What is the consequence to the catch patterns of removing the Sort-V grid and fishing with the regular diamond mesh codend alone in the Barents Sea gadoid fishery?
- Do the size selectivity and catch efficiency change when replacing the Sort-V grid and regular diamond mesh codend with an alternative knotless codend with shortened lastridge ropes, and thinner twine?
- Is it even necessary to use any size-selective gear (e.g. grids, panels, and regulation on codend mesh size)?

Material and methods

Fishing trials

We conducted the experimental fishing in the southern Barents Sea from 19 to 28 February 2021 onboard the R/V "Helmer Hanssen". The area was located between N 71° 20' E 25° 17 and N 71° 14 E 25° 02, with depths ranging between 290 and 305 m. Two identical Alfredo 3 trawls were towed alternately using a set of Injector Scorpion otter boards (3100 kg, 8 m^2). The otter boards were connected to 60-m-long sweeps with 3-m-long backstraps followed by 7-m-long connector wires. A Ø53 cm steel bobbin was inserted in the middle of the sweeps to protect the sweeps from excessive abrasion. The sweeps were connected to the 46-m-long ground gear, which consisted of an 18.9-m-long rock-hopper gear (Ø53 cm) in the middle followed by 14-m-long (Ø19 mm) chains with three equally spaced steel bobbins on the sides (Ø53 cm). The rock-hopper gear was attached to the 19.2-m-long fishing line. The headline of the trawls was 36.5 m long. We used two-panel trawls that were 420 meshes in circumference and built entirely of polyethylene (PE) netting with 155 mm mesh size.

One trawl was rigged to mimic the gear used in the commercial fishery. The trawl belly was followed by a section with a Sort-V grid (1750 × 1234 mm) with a bar spacing of 54.8 ± 1.1 mm (mean ± *SD*). An extension piece was inserted between the grid section and the codend. The codend, hereafter referred to as regular codend, was constructed of two panels, which were 12 m long and 60 meshes in circumference. It was built of single braided Ø8 mm hotmelt PE twine (Polar Gold) with a mesh size of 133.8 ± 2.2 mm (mean ± *SD*) (hereafter referred to as 130 mm). To catch the escapees from the grid, a cover was mounted over the escape outlet. The cover had an inner mesh size of 45.8 ± 1.5 mm (mean ± *SD*). It was covered with a large mesh netting on the outside to ensure sufficient strength, and it was equipped with seven floats to avoid blockage of the outlet (Figure 1). To catch the codend escapees, the entire length of the codend was covered with a cover. To ensure that the cover stayed clear of the codend, the front part of the cover was rigged with six floats, six kites, and a 12 kg piece of chain on the top, side, and bottom of the codend cover, respectively. Additionally, 12 kites were attached to the cover around the bulk of the catch in the codend (Figure 1). The cover had a mesh size of 51 ± 1.3 mm (mean ± *SD*) and was strengthened with an outer layer of large mesh netting in the aft area.

The other trawl was equipped with an extension piece in place of the grid section. This section was followed by two- to four-panel transition piece mounted just in front of the codend (Figure 1). The codend, hereafter referred to as the alternative codend, was a four-panel (4 × 15 meshes in circumference) codend built of knotless braided Ø6 mm PE twine (Euroline). The codend had a mesh size of 131 ± 1.3 mm (mean ± *SD*), and the lastridge ropes of the codend were shortened by 15% with respect to the netting. We chose this codend for the tests because the minimum mesh size for the codend in the fishery is 130 mm, four-panel codend constructions have been reported to oscillate less than two-panel codend constructions (O'Neill *et al.*, 2003; Sistiaga *et al.*, 2016), and the effect of shortened lastridge ropes in a four-panel codend is expected to be higher

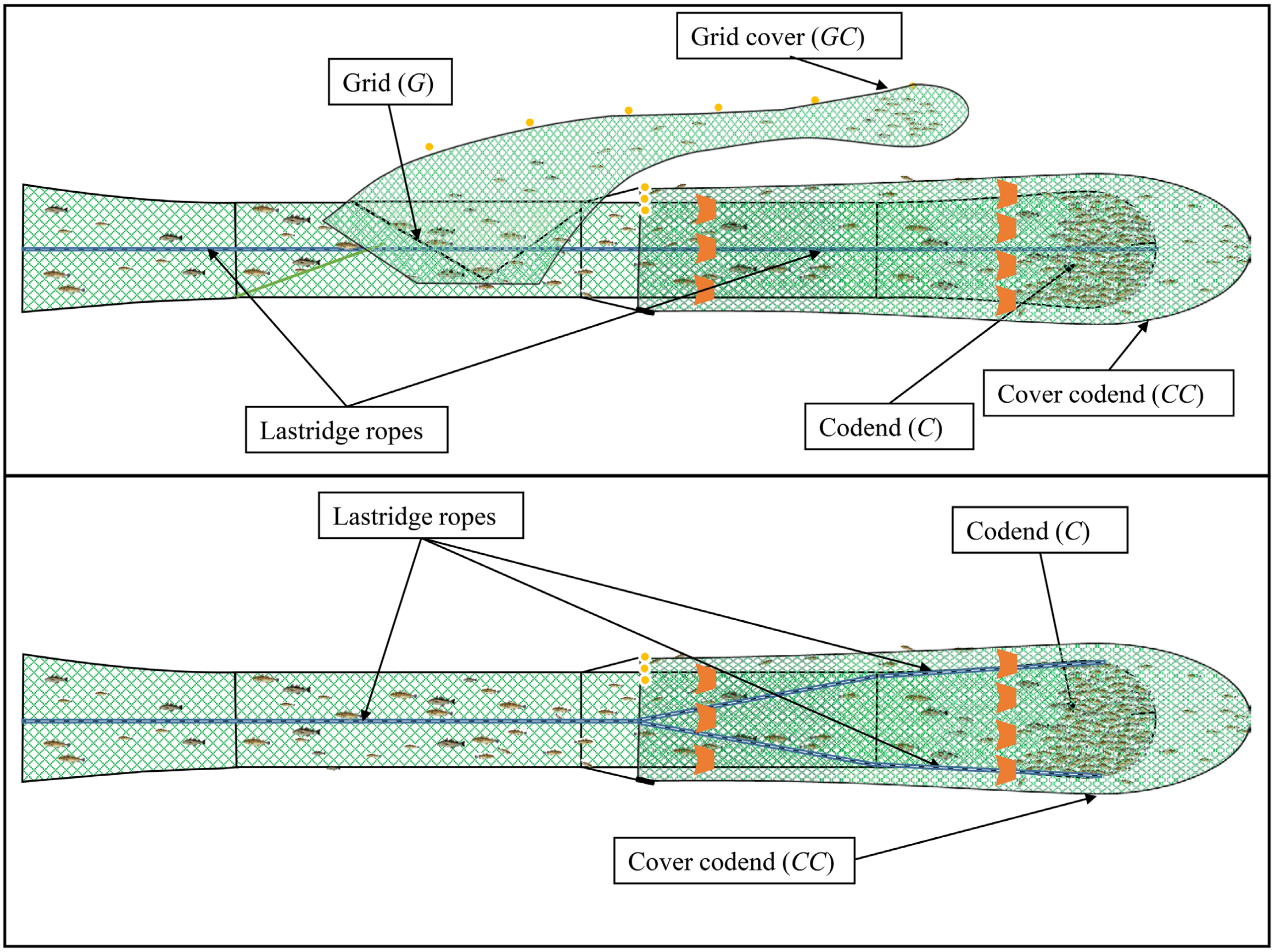

Figure 1. Illustration showing the experimental design employed during the trials. Upper: the conventional configuration with the Sort-V grid (*G*) and the regular codend (*C*) with covers covering the grid (*GC*) and codend (*CC*). Lower: the experimental configuration with the alternative codend (*C*) and the covered codend (*CC*).

than or at least as high as that in a two-panel codend. To catch the escapees, the entire length of the codend in this trawl was covered with a cover. The cover was identical to the one used on the other trawl and had a mesh size 41 ± 1.1 mm (mean ± *SD*). All mesh and bar spacing measurements were conducted using an OMEGA gauge following the procedure described in Wileman *et al.* (1996).

The trawl performance was monitored continuously by a set of trawl door sensors, a trawl height sensor, and a catch volume sensor, all from Scanmar. The catch in each compartment was stored onboard in separate holding bins. The length of all cod and haddock above 20 cm was measured to the nearest centimetre below.

Statistical analysis

Modelling and estimation of the size selection

The analysis of each species was done separately using the same method described here. The applied experimental design (Figure 1, lower) for the test of the codend (*C*) enabled analysis of the collected catch data as binomial data, where individuals, either retained in the codend cover (*CC*) or in the codend itself, were used to estimate the size selection in the codend (i.e. length-dependent retention probability). With the same codend, the size selectivity is expected to vary between hauls (Fryer, 1991). However, in this study, we were interested in the size selection combined over all hauls because this would form about the overall consequences for the size selection process when applying the specific codend in the fishery. We tested different parametric models $r_{\text{codend}}(l, v_{\text{codend}})$ for the codend size selection. The v_{codend} is a vector consisting of the parameters of the model. The purpose of the analysis was to estimate the values of the parameter v_{codend} that make experimental data (combined over all hauls) most likely to be observed. For this purpose, the following expression was minimized, which corresponded to maximizing the likelihood for the observed experimental data:

$$-\sum_{j=1}^{m}\sum_{l}\left\{nC_{lj}\times ln\left(r_{\text{codend}}\left(l, v_{\text{codend}}\right)\right)\right. \left. + nCC_{lj}\times ln\left(1.0 - r_{\text{codend}}\left(l, v_{\text{codend}}\right)\right)\right\}. \quad (1)$$

The outer summation in expression (1) included the hauls conducted with the specific codend and the inner summation over length classes *l* in the data. Four different models were chosen as candidates to describe $r_{\text{codend}}(l, v_{\text{codend}})$ for each species individually: *Logit*, *Probit*, *Gompertz*, and *Richards*. The first three models were fully described by the selection parameters *L50* (length of fish with 50% probability of being retained) and *SR* (difference in length between fish with 75% and 25%

probability of being retained, respectively), while the *Richards* model required one additional parameter ($1/\delta$) that described the asymmetry of the curve. The formulas for the four selection models is provided in Appendix A, while additional information regarding these models can be found in Lomeli (2019). Evaluating the ability of a model to describe the data was based on calculating the corresponding *p*-value, which expressed the likelihood of obtaining at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. Therefore, for the fitted model to be a candidate to model the size selection data, this *p*-value, which was calculated based on the model deviance (*D*) and the degrees of freedom (DOF), should not be <0.05 (Wileman *et al.*, 1996). Specifically, *D* has an approximate χ^2 distribution when the model is correct, and the *p*-value is therefore calculated for a χ^2 distribution with *D* and DOF as parameters (Wileman *et al.*, 1996). Here, we have taken advantage of that the number of fish in most length classes are expected to be high due to that the analysis is carried out for data combined over hauls. For DOF, we use the number of length classes in the experimental data minus the number of selection parameters. In case of a poor fit statistics (p-value < 0.05), the deviation residuals were inspected to determine whether the poor result was due to structural problems when modelling the experimental data using the different selection curves or if it was due to overdispersion in the data (Wileman *et al.*, 1996). Selection of the best model among the four considered in (1) was based on comparing the Akaike information criterion (AIC) values for the models. The selected model was the one with the lowest AIC value (Akaike, 1974).

Once the specific size selection model was identified for a particular species and codend, bootstrapping was applied to estimate the confidence limits for the average size selection. We applied the software tool SELNET (Herrmann *et al.*, 2012) for the size selection analysis and utilized the double bootstrap method implemented in this tool to obtain the confidence limits for the size selection curve and the corresponding parameters. This bootstrapping approach was identical to the one described in Millar (1993) and takes both within-haul and between-haul variations into consideration. The hauls for each codend were used to define a group of hauls. To account for between-haul variation, an outer bootstrap resample with replacement from the group of hauls was included in the procedure. Within each resampled haul, the data for each length class were bootstrapped in an inner bootstrap with replacement to account for within-haul variation. Each bootstrap resulted in a combined data set, which then was analysed using expression (1) and the selected model to estimate the selection parameters and selection curve. Thus, each bootstrap run resulted in a set of values for the selection parameters and the retention probability at different fish lengths (selection curve). For each species analysed, 1000 bootstrap repetitions were conducted to estimate the Efron percentile 95% confidence limits (Efron, 1982; Herrmann *et al.*, 2012).

Compared to the alternative codend (Figure 1, lower), the size selection for the standard gear with the Sort-V grid combined with the regular codend (Figure 1, upper) was more complex because there were two selection processes that occurred in the grid and codend, respectively. This combined selection system is sequential and only fish that do not escape through the grid will enter the codend to experience the second selection process here. This is reflected in the experimental design, in which we used two covers to collect fish escaping through each of the selection areas. For a fish to be retained in this, it needs to be retained by both processes:

$$r_{\text{combined}}\left(l\right) = r_{\text{Grid}}\left(l\right) \times r_{\text{Codend}}\left(l\right), \quad (2)$$

where $r_{\text{Grid}}(l)$ and $r_{\text{Codend}}(l)$ represent the retention probabilities in the sections with the grid and codend, respectively, conditioned the fish enters the specific section.

In this study, similar to other previous studies including sorting grids (Sistiaga *et al.*, 2010; Larsen *et al.*, 2016, Larsen *et al.*, 2018b; Brinkhof *et al.*, 2020), we modelled the size selection for the grid based on a *CLogit* size selection model (Herrmann *et al.*, 2013a). In the *CLogit* model, the parameter *C* was assumed to be length-independent, and it quantified the probability that a fish entering the grid zone contacted the grid with an orientation that provides it with a length-dependent probability of escaping through the grid (selectivity contact). For the fish that made selectivity contacts with the grid, the *CLogit* model assumed a traditional *Logit* size selection model defined by the parameters *L50* and *SR*. Thus, $r_{\text{Grid}}(l)$ was modelled by (Appendix B)

$$r_{\text{Grid}}\left(l, v_{\text{Grid}}\right) = 1.0 - \frac{C_{\text{Grid}}}{1 + \exp(\frac{\ln(9)}{SR_{\text{Grid}}} \times \left(l - L50_{\text{Grid}}\right)}, \quad (3)$$

with the parameter vector $v_{\text{Grid}} = (C_{\text{Grid}}, L50_{\text{Grid}}, SR_{\text{Grid}})$.

The codend was a traditional diamond mesh codend with a single mesh size attached to a sorting grid section, so we modelled $r_{\text{Codend}}(l)$ using the same four models described earlier for the codend with shortened lastridges. Thus, $r_{\text{Codend}}(l,\ v_{\text{codend}})$ was modelled by *Logit*, *Probit*, *Gompertz*, or *Richard* depending on which model had the lowest AIC value for the model fit to the experimental data [expression (4)].

We used Equations (2) and (3) to model the size selection in the combined size selection system consisting of the Sort-V grid followed by the standard codend. We performed the analysis separately for each species. For the combined size selection, *L50* and *SR* were obtained based on a numerical method implemented in the analysis tool SELNET. This method was identical to the one applied by Sistiaga *et al.* (2010).

Catch data were collected using the three-compartment experimental design shown in Figure 1 (upper), which included the codend (*C*), the grid cover (*G*) to collect fish that escaped through the first grid, and the cover (*CC*) surrounding the codend to collect fish that escaped through the codend meshes. For each haul *j*, we had the number of individuals with length *l* collected in the codend (nC_{lj}), grid cover (nG_{lj}), and codend cover (nCC_{lj}). Thus, the species-specific size selection in the Sort-V grid combined with the standard codend and combined over *m* hauls was obtained by minimizing the following expression with respect to the parameters v_{Grid} and v_{codend} in the model described by Equations (2) and (3):

$$\begin{aligned} -\sum\nolimits_{j=1}^{m}\sum\nolimits_{l}\{&(nC_{l\,j} + nCC_{l\,j}) \times \ln(r_{\text{Grid}}(l, \mathbf{v_{Grid}})) \\ &+ nG_{l\,j} \times \ln(1.0 - r_{\text{Grid}}(l, \mathbf{v_{Grid}})) \\ &+ nC_{l\,j} \times \ln r\text{Codend}l, \mathbf{vcodend} \\ &+ nCCl\,j \times \ln 1.0 - r\text{Codend}l, \mathbf{vcodend}\} \end{aligned} \quad (4)$$

Minimizing (4) with respect to its parameters is equal to maximizing the likelihood of the observed experimental data under the assumption that Equations (2) and (3) described the multinominal probabilities of observing a fish with length *l* in the codend or covers conditioned by the fish that entered the

Table 1. Overview of the hauls conducted during the sea trials.

Haul No.	Trawl configuration	Towing time	Number of cod			Number of haddock		
		(hh:mm)	*nGC*	*nC*	*nCC*	*nGC*	*nC*	*nCC*
1	Alternative codend	00:31	–	284	32	–	104	148
2	Sort-V and regular codend	00:45	101	583	1	145	50	1
3	Sort-V and regular codend	00:50	46	1 352	3	109	82	2
4	Alternative codend	00:37	–	254	21	–	69	74
5	Alternative codend	00:43	–	521	9	–	38	7
6	Sort-V and regular codend	00:47	99	1 751	9	247	116	5
7	Sort-V and regular codend	00:44	71	431	4	298	66	23
8	Alternative codend	00:45	–	293	17	–	83	88
9	Alternative codend	00:39	–	482	6	–	80	93
10	Sort-V and regular codend	00:47	64	648	1	129	33	3
11	Sort-V and regular codend	00:32	67	457	3	141	52	3
12	Alternative codend	01:01	–	42	1	–	109	20
13	Alternative codend	01:21	–	278	20	–	150	179
14	Sort-V and regular codend	00:47	52	574	2	179	56	6
15	Sort-V and regular codend	00:36	56	355	1	188	63	10
16	Alternative codend	01:13	–	561	13	–	212	183
17	Alternative codend	01:00	–	1 189	16	–	161	187
18	Sort-V and regular codend	00:57	39	337	3	312	68	4
19	Sort-V and regular codend	00:38	16	167	3	230	69	2
20	Alternative codend	00:42	–	466	14	–	112	105

For each haul, towing time and number of fish caught in each compartment are provided.

combined selection system consisting of a Sort-V grid section and regular codend.

As for the codend with shortened lastridge ropes, we evaluated the ability of the model [Equations (2) and (3)] to describe the experimental data based on the *p*-value, model deviance vs. DOF, and how the model curves reflected the length-based trend in the data (Wileman *et al.*, 1996). We conducted the analysis using the software tool SELNET.

Estimation of difference in size selectivity between selection systems

The difference in size selectivity $\Delta r(l)$ between configuration *x* and *y* was estimated by

$$\Delta r(l) = r_y(l) - r_x(l). \tag{5}$$

The 95% confidence intervals for $\Delta r(l)$ were obtained based on the two bootstrap population results for $r_x(l)$ and $r_y(l)$, respectively. As they are obtained independently of each other, a new bootstrap population of results for $\Delta r(l)$ was created following Larsen *et al.*, (2018a):

$$\Delta r(l)_i = r_y(l)_i - r_x(l)_i \; i \in [1 \ldots 1000]. \tag{6}$$

Finally, based on the bootstrap population, Efron 95% percentile confidence limits were obtained for $\Delta r(l)$ as described above.

Estimation of exploitation pattern and catch efficiency indicators

To evaluate how each of the selection systems performed in the specific fishery, we estimated three exploitation pattern indicators (*nP*−, *nP*+, and *dnRatio*) separately for each species. *nP*− and *nP*+ quantify the retention efficiency for fish below and above the *MLS* (as percentages), respectively, whereas *dnRatio* denotes the percentage of undersized fish in the codend catch in numbers. In fisheries in which undersized specimens are returned to the sea, this corresponded to the discard ratio. However, Norwegian fisheries have a full discard ban. These indicators could be used to summarize the catch patterns for specific gear in a specific fishery. The size selection properties (*L50* and *SR*) provide information that is independent of the size structure of the population encountered by the gear during the fishing process, whereas these indicators depended directly on the size structure, thereby providing additional information to facilitate evaluation of the catch performance of the selective system (Wienbeck *et al.*, 2014). The indicators were estimated for the different gear designs considered as follows:

$$nP^- = 100 \times \frac{\sum_{l<MLS}\{r(l) \times nPop_l\}}{\sum_{l<MLS}\{nPop_l\}}$$

$$nP^+ = 100 \times \frac{\sum_{l>MLS}\{r(l) \times nPop_l\}}{\sum_{l>MLS}\{nPop_l\}}$$

$$dnRatio = 100 \times \frac{\sum_{l<MLS}\{r(l) \times nPop_l\}}{\sum_{l}\{r(l) \times nPop_l\}}, \tag{7}$$

where $r(l)$ is the selection curve for the gear and $nPop_l$ is the population entering the selection system. For this population, we summed cover and codend catches over all hauls for each experiment reported here. A bootstrap population of results was obtained for $nPop_l$ based on the double bootstrap method, with the inner resampling conducted on the population of fish aggregated from codend and cover. Specifically, this bootstrap approach considered both the between-haul variability in the structure of the population entering the gear and the within-haul variability due to limited numbers of fish entering the gear in that specific haul (Mytilineou *et al.*, 2020). We then estimated the indicators nP^-, nP^+, and *dnRatio* with uncertainties for each species and gear using the bootstrap set for $r(l)$ and $nPop_l$, specifically, by first calculating the values for the indicators based on the result of each bootstrap repetition for $r(l)$ and $nPop_l$ synchronous in (7) to obtain a bootstrap set for the indicator values. Efron 95% *CI*s were estimated for each of the indicators based on the resulting bootstrap set. Ideally, for a target species, *nP*− and the *dnRatio*

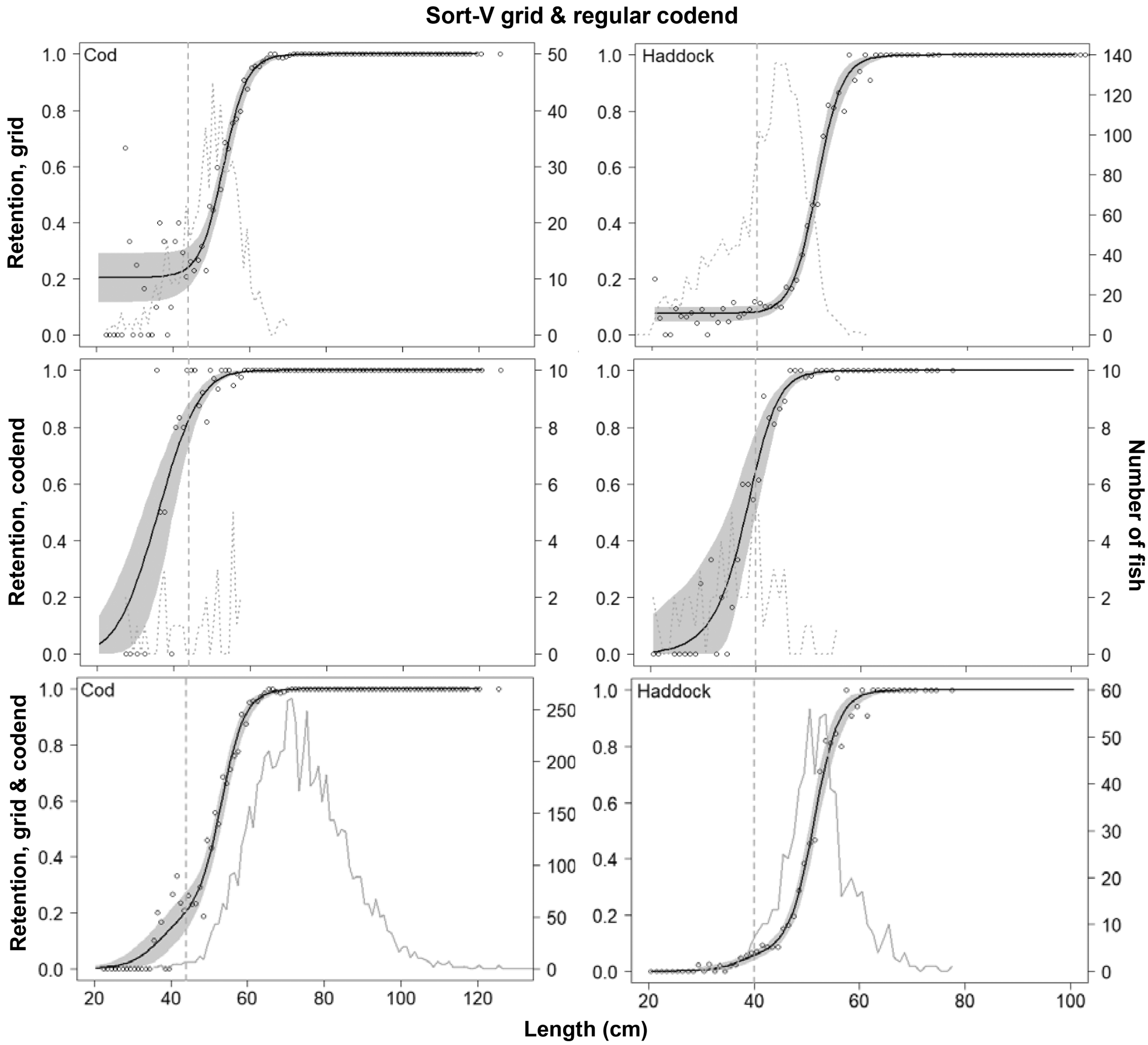

Figure 2. Length-dependent probabilities of escape in the conventional gear configuration (Sort-V with regular codend) as well as the combined retention for both cod (left column) and haddock (right column). The solid curves represent the models fitted to the data (circles) with the 95% *CI*s (grey area). The frequency curves in grey represent the number of fish that retained in the covers (dotted line), and codend (solid line). The stippled vertical grey lines denote the *MLS* for cod (44 cm) and haddock (40 cm).

should be low (close to 0%), whereas *nP+* should be high (close to 100%), which would indicate retention of all individuals over the *MLS* that enter the codend.

Results

We conducted 20 hauls during the cruise, alternating between the configuration with the Sort-V grid and regular codend and the configuration with the alternative codend (Table 1). During the trials, 11815 cod and 4894 haddock were caught and length measured (Table 1).

The models used to describe the escape and retention of haddock and cod for the different configurations reflected the main trends in the experimental data well (p-value > 0.5; Figs. 2–4, Table 2). For one case, the p-value was < 0.05, but inspection of the residuals demonstrated that the poor fit statistics were caused by overdispersion in the experimental data (Table 2).

Sort-V grid and regular codend

The size selectivity curves for both cod and haddock caught with the Sort-V grid and regular codend configuration demonstrated that with this configuration, most fish escaped through the grid and few fish did so through the codend meshes (Figure 2). Furthermore, the retention probability curves showed that few fish below *MLS* were caught with this configuration. However, the curves also showed that a large proportion of fish above *MLS* escaped, especially haddock (Figure 2). This was corroborated by the catch pattern indicator *nP-*, which showed that the catch efficiency for fish below *MLS* (*nP-*) were 11.89% (*CI*: 5.90–17.25) for cod and 1.54% (*CI*: 0.75–2.53) for haddock (Table 2). The retention efficiency *nP+* of cod above *MLS* was 92.5% (*CI*: 89.61–94.52), but that for haddock was only 32.09% (*CI*: 27.57–37.37) (Table 2). The *dnRatio* of 0.40% (*CI*: 0.18–0.87) and 2.95% (*CI*: 1.37–4.71) for cod and haddock, respectively, was far below the legislated limit of 15%. The L50 values were similar for both species (∼51 cm).

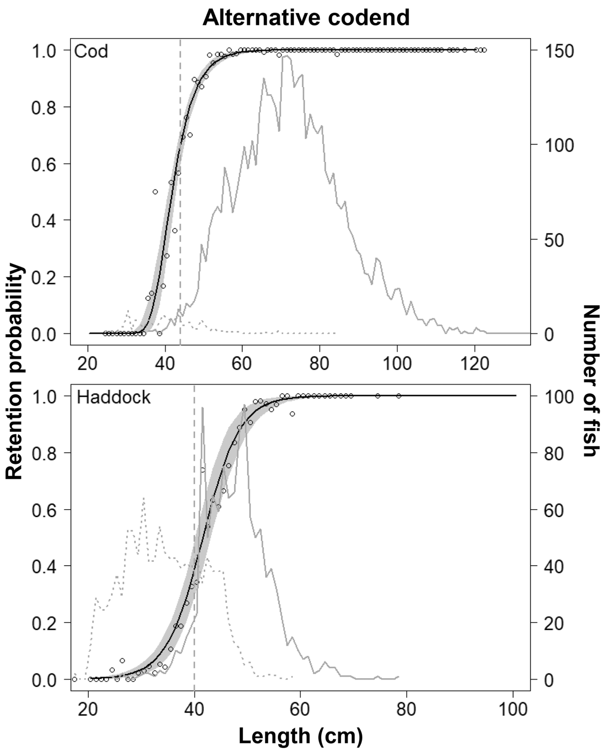

Figure 3. Length-dependent probabilities of retention in the gear configuration with the alternative codend for cod (upper) and haddock (lower). The solid curves represent the models fitted to the data (circles) with the 95% *CI*s (grey area). The frequency curves in grey represent the number of fish caught in each length class in the codend cover (dotted line) and codend (solid line). The stippled vertical grey lines denote the *MLS* for cod (44 cm) and haddock (40 cm).

The analysis of the Sort-V plus regular codend enabled us to separate the selectivity of the grid and codend [Equation (2)]. Therefore, we were able to provide an estimate for what the selectivity would be if the regular codend was used without the grid (Figure 2). Especially for cod, fishing with a regular codend with a mesh size of 130 mm without a sorting grid would retain a large proportion of fish below the *MLS* while releasing few fish above *MLS* (Figure 2). The L50 value of 35.9 cm for cod and 38.2 cm for haddock are well below the *MLS* (Table 2). The catch indicators estimated nearly complete retention of fish above the *MLS* for both species (Table 2). However, the retention efficiency below the *MLS* (*nP-*) was estimated to be 57.41% (*CI*: 34.07–70.04) for cod and 20.53% (*CI*: 10.77–41.06) for haddock (Table 2). The *dnRatio* was still below the limit of 15%, at 1.78% (*CI*: 0.82–3.54) and 12.42% (*CI*: 6.91–22.37) for cod and haddock, respectively (Table 2).

Alternative codend

For the alternative codend with, the *L50* values were also similar for both species (~41 cm) and thus close to the *MLS*. This meant that this configuration caught more fish both above and below the *MLS*, as demonstrated by the size selectivity curves for both cod and haddock (Figure 3). This was also corroborated by the catch pattern indicators, which showed that the catches efficiency in the alternative codend was 27.58% (*CI*: 17.55–33.91) for cod below the *MLS* (*nP-*) and 10.19% (*CI*: 6.59–14.37) for haddock below the *MLS* (Table 2). On the other hand, the catch efficiency above *MLS* (*nP+*) in the alternative codend increased to 98.89% (*CI*: 98.33–99.28) for cod and 77.55% (*CI*: 70.22–85.25) for haddock compared to the catches with the Sort-V and regular codend configuration. The *dnRatio* for cod was 0.87% (*CI*: 0.42–1.66) and that for haddock was 7.69% (*CI*: 5.05–10.04), which were still far below the legislated limit of 15% for both species (Table 2).

Comparison of size selectivity and catch efficiency between the configurations

Comparing the size selectivity curves for the Sort-V and regular codend with those for the alternative codend demonstrated a significant difference for nearly all length classes for both cod and haddock (Figure 4). The delta plots corroborated this finding and demonstrated that the alternative codend compared to the Sort-V and regular codend configuration retained significantly more cod and haddock, especially fish above *MLS* (Figure 4). The catch pattern indicators demonstrated that the relative difference in catch efficiency between the alternative codend and the Sort-V with regular codend significantly affected the retention of cod and haddock both above and below *MLS* (Table 3). The relative *dnRatio* also increased significantly for both species (Table 3).

Comparing the results between the combined Sort-V and codend configuration and the regular codend alone demonstrated that the latter retained significantly more cod and haddock both above and below the *MLS* (Figure 5, Table 3). Similar results were obtained when comparing the alternative codend with the regular codend, but the difference was significant for fewer length classes (Figure 5, Table 3).

It is important to note that the numbers in Table 3 are relative differences between the gear configurations. When considering the actual differences in Table 2, it is clear that the *dnRatio* was still far below the limit of 15%, except for haddock caught with the regular codend, which was 12.42% (*CI*: 6.91–22.37) (Table 2). The reason for the small differences in *dnRatio* and the large differences in relative values is because few fish below *MLS* were present in the area during the survey, especially cod (Figure 6).

If the population of fish in the area is the same as the population entering the trawl, combining the catch retained in the codend and the covers represents the fished population. This premise enabled us to estimate the catch pattern indicators based on a non-selective gear. Fishing with a non-selective gear in the area and period when the cruise was conducted would result in a *dnRatio* of 3.13% (*CI*: 1.84–6.07) for cod and 38.79% (*CI*: 32.62–43.95) for haddock. This was corroborated by the population length distribution presented in Figure 6. Table 4 shows the exploitation patterns for each gear compared to a non-selective gear. The Sort-V with regular codend configuration had the largest reduction in fish below *MLS* but also of fish above *MLS* compared to a non-selective gear (Table 4). Fishing without a grid and only the regular codend resulted in the smallest reduction of fish both above and below *MLS*. Compared to a non-selective gear the alternative codend had a high reduction in fish below *MLS* and a relatively small reduction in fish above *MLS* (Table 4).

Discussion

The use of selectivity devices in trawls to reduce bycatch, either unwanted sizes or species has gained much attention worldwide in recent decades (Walsh *et al.*, 2002; Graham,

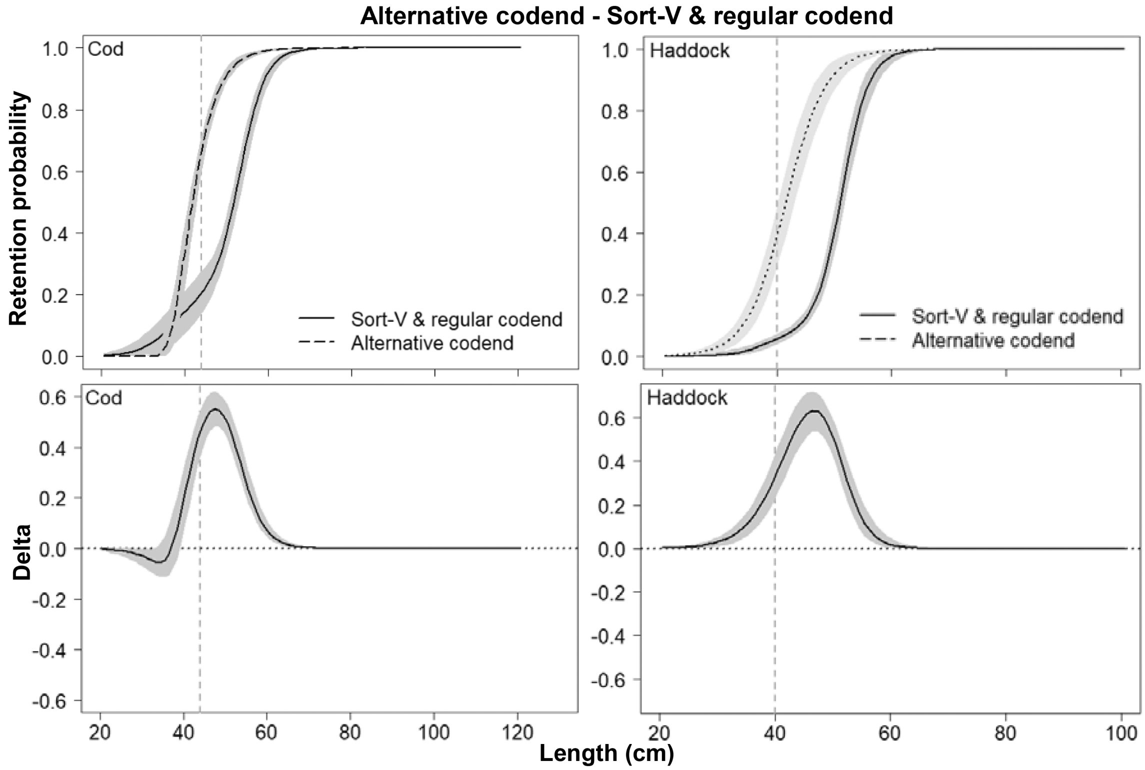

Figure 4. Comparison of the estimated length-dependent retention probabilities of the two gear configurations tested (upper row) and differences in the selection properties between the gears expressed as delta retention probability (lower row) for cod (left column) and haddock (right column). Grey areas represent the 95% *CI*s. The stippled vertical grey lines denote the *MLS* for cod (44 cm) and haddock (40 cm).

2010; Kennely and Broadhurst, 2021). In the Northeast Atlantic demersal trawl fishery for gadoids, most scientific studies conducted in recent years have been devoted to selectivity (Kennelly and Broadhurst, 2021). After the decline and rebuilding of the Northeast Atlantic cod stock in the late 1980s and early 1990s, the importance of strict bycatch regulations became evident, and they were gradually implemented in the fishery (Hammer and Hoel, 2012; Gullestad *et al.*, 2015). The invention, development, and implementation of the rigid sorting grid called the "Nordmøre grid" in the early 1990 in the shrimp trawl fishery nearly mitigated the bycatch of fish, as it released all fish that did not fit between the 19 mm bar spacings (Isaksen *et al.*, 1992; Larsen *et al.*, 2018b). Due to its success, the same but opposite principle of the rigid sorting grid was developed by the same scientists so that it could be used in demersal fish trawls to release most of the fish below the *MLS* (Larsen and Isaksen, 1993). The size-selective sorting grid in demersal trawls with 55 mm bar spacing has been used since 1993, and it became mandatory in 1997. This configuration gave the fishers access to areas that otherwise would be closed for fishing due to too large catches of juvenile fish.

Compared to the poor size selectivity of diamond mesh codends reported in multiple studies (Robertson and Stewart, 1988; Herrmann, 2005a, 2005b; Sala *et al.*, 2008; Wienbeck *et al.*, 2011), the development of the sorting grid mitigated the problem of bycatch of juvenile fish to a large degree. However, the length composition of the stocks of both Northeast Atlantic cod and haddock has changed over recent decades, as has their spatial and seasonal distribution. In some areas and periods of the year, the bycatch limits of 15% undersized fish are exceeded even when using a grid. In other areas and periods, the abundance of juvenile fish was very low. In the current study, we demonstrated that the bycatch of a non-selective gear was 3.13% (*CI*: 1.84–6.07) for cod, which would not exceed the limit in this particular area and time of year. This meant that fishing with a regular diamond mesh codend without a sorting grid would be defendable from a management point of view. However, for haddock, the bycatch limit for a non-selective gear was 38.79% (*CI*: 32.62–43.95) and thus exceeded the limit, while the regular diamond mesh codend provided bycatch levels close to the limit (12.42%, *CI*: 6.91–22.37). Temporal area closures and more flexible choice of selectivity devices combined with modern monitoring tools, such as catch scanners, camera-based control systems, and automatic registration systems, could be an option in this case. This approach would allow fishers to harvest fish with the most efficient gear that minimizes the loss of fish above *MLS*, which would also reduce costs, fuel consumption, and habitat impact while simultaneously being in compliance with the bycatch limits.

The grids were introduced as a solution to the challenges experienced with the diamond mesh codends during the 1980s. At that time, the stock was recovering from overexploitation and catch rates of juvenile cod were high (Yaragina *et al.*, 2011). Even though the grids partly solved these problems, they added complexity to the trawl configuration without actually solving the original problem (i.e. the closing of the meshes in the diamond mesh codend when the catch accumulates in the aft part of the gear). Alternatives to the grid and diamond mesh codend, such as turning the direction of the meshes 45° (i.e. square meshes), have been tested (Krag *et al.*, 2011; Isaksen and Valdemarsen, 1986). T90 meshes have

Table 2. The estimated size selectivity parameters (L50 and SR), catch pattern indicators for the catch below MLS (nP-), catch above MLS (nP+), ratio (dnRatio) in percentage, and fit statistics.

	Sort-V and regular codend		Alternative codend		Regular codend		No selection	
	Cod	Haddock	Cod	Haddock	Cod	Haddock	Cod	Haddock
L50 (cm)	51.74	51.02	41.83	41.76	35.91	38.17	–	–
SR (cm)	9.58	5.68	6.37	7.41	11.5	6.82	–	–
nP- (%)	11.89 (5.90–7.25)	1.54 (0.75–2.53)	27.58 (17.55–33.91)	10.19 (6.59–14.37)	57.41 (34.07–70.04)	20.53 (10.77–41.06)	100.00 (100.00–100.00)	100.00 (100.00–100.00)
nP+ (%)	92.5 (89.61–94.52)	32.09 (27.57–37.37)	98.89 (98.33–99.28)	77.55 (70.22–85.25)	99.45 (99.07–99.79)	91.77 (86.73–95.28)	100.00 (100.00–100.00)	100.00 (100.00–100.00)
ndRatio (%)	0.40 (0.18–0.87)	2.95 (1.37–4.71)	0.87 (0.42–1.66)	7.69 (5.05–10.04)	1.78 (0.82–3.54)	12.42 (6.91–22.37)	3.13 (1.84–6.07)	38.79 (32.62–43.95)
Model	*CLogit × Probit*	*CLogit × Richard*	*Gompertz*	*Logit*	*Probit*	*Richard*	–	–
p-value	1.000	0.999	0.999	0.028	1.000	0.999	–	–
DOF	195	107	94	51	88	49	–	–
Deviance	103.6	59.8	50.2	72	39.6	20.9	–	–

also been tested. Brinkhof *et al.* (2022) compared the size selectivity of a codend built of T90 meshes with the compulsory grid and codend configuration. Their results showed improved size selectivity with the T90 codend (i.e. reduced loss of fish above the *MLS* and no increase in the retention of fish below the *MLS*). However, a draw-back of T90 codends is that the netting softens over time due to wear and tear, causing the meshes to lose their open shape.

Another alternative to improve the selectivity of diamond mesh codends is to reduce the length of the lastridge ropes. In a previous study, Ingolfsson and Brinkhof (2020) demonstrated that a codend with 153 mm mesh size and shortened lastridge ropes retained no fish below the *MLS*. However, large proportions of fish above the *MLS* were also released. Sistiaga *et al.* (2022) also showed that shortening codend lastridge ropes improved the sorting capacity of diamond mesh codends. The alternative codend with shortened lastridges tested in the present study had a mesh size of 131 mm, which is basically the minimum mesh size allowed in the fishery today. Besides the shortened lastridges, the alternative codend tested in this study had a 2 mm thinner twine and was knotless compared to the regular codend. It is unknown to what extend those two additional design factors could have contributed to the difference in selectivity between the alternative and regular codends. For example, Herrmann *et al.* (2013b) and O'Neill and Herrmann (2007) demonstrated that a reduction in twine thickness can improve size selectivity in the codend. The knotless material was chosen because shortening the lastridges in a knotted codend was expected to cause a deformation of the mesh geometry due to the direction of the knots. The use of this alternative codend resulted in increased catch efficiency for cod above *MLS* from 32.09% (*CI*: 27.57–37.37) with the grid configuration to 77.55% (*CI*: 70.22–85.25) with the alternative codend. For haddock, the catch efficiency above *MLS* increased from 32.09% (*CI*: 27.57–37.37) with the grid configuration to 77.55% (*CI*: 70.22–85.25) with the alternative ropes. Compared to the grid configuration, the relative increase in the *dnRatio* was significant with the alternative codend. However, when looking at the absolute numbers, the *dnRatio* for haddock increased from 2.95% (*CI*: 1.37–4.71) to 7.69% (*CI*: 5.05–10.04) and for cod from 0.40% (*CI*: 0.18–0.87) to 0.87% (*CI*: 0.42–1.66). This was due to low numbers of fish below *MLS*, especially cod, during the trial period in the study area. For cod, the alternative codend also had a lower *SR* value compared to the configuration with the grid and regular codend configuration, but this was not observed for haddock.

In addition to improved size selectivity, the proposed alternative codend configuration is also easier and safer to handle on deck compared to the configuration with the grid. Moreover, making such a simple adjustment to improve selectivity is more cost-effective than installing expensive sorting grids. However, regulating codends with shortened lastridge ropes presents a challenge. Both fishers and the law enforcement authorities require a size selection system that is easy to regulate and control and that is not prone to changes under varying circumstances. One issue with shortened lastridge ropes is that they may stretch over time due to heavy loadings over time. Regular PE ropes, spectra, and even chain lastridges can become elongated, subsequently causing the meshes to become more closed and lose their size-selective capacity. This is an issue that should be investigated in a future study. Also, future studies should also test this alternative codend configuration

Table 3. Differences in percentage for the catch pattern indicators between the three configurations for both cod and haddock.

Species	Gear type	*nP-* (%)	*nP+* (%)	*dnRatio* (%)
Cod	Alternative codend—SortV and codend	131.84 (38.14 to 360.59)	6.91 (4.86 to 10.12)	115.84 (30.81 to 327.37)
	Regular codend—SortV and codend	382.57 (172.66 to 893.41)	7.51 (5.31 to 10.80)	341.66 (147.85 to 799.82)
	Alternative codend—Regular codend	−51.96 (−67.92 to −26.00)	−0.56 (−1.14 to −0.16)	−51.13 (−67.35 to −24.88)
Haddock	Alternative codend—SortV and codend	561.97 (250.46 to 1 356.50)	141.64 (107.29 to 180.52)	160.58 (44.62 to 466.95)
	Regular codend—SortV and codend	1 233.57 (508.31 to 3639.82)	185.94 (146.49 to 233.29)	320.89 (104.43 to 977.51)
	Alternative codend—Regular codend	−50.36 (−76.61 to −3.81)	−15.49 (−24.01 to −6.84)	−38.08 (−66.21 to 11.66)

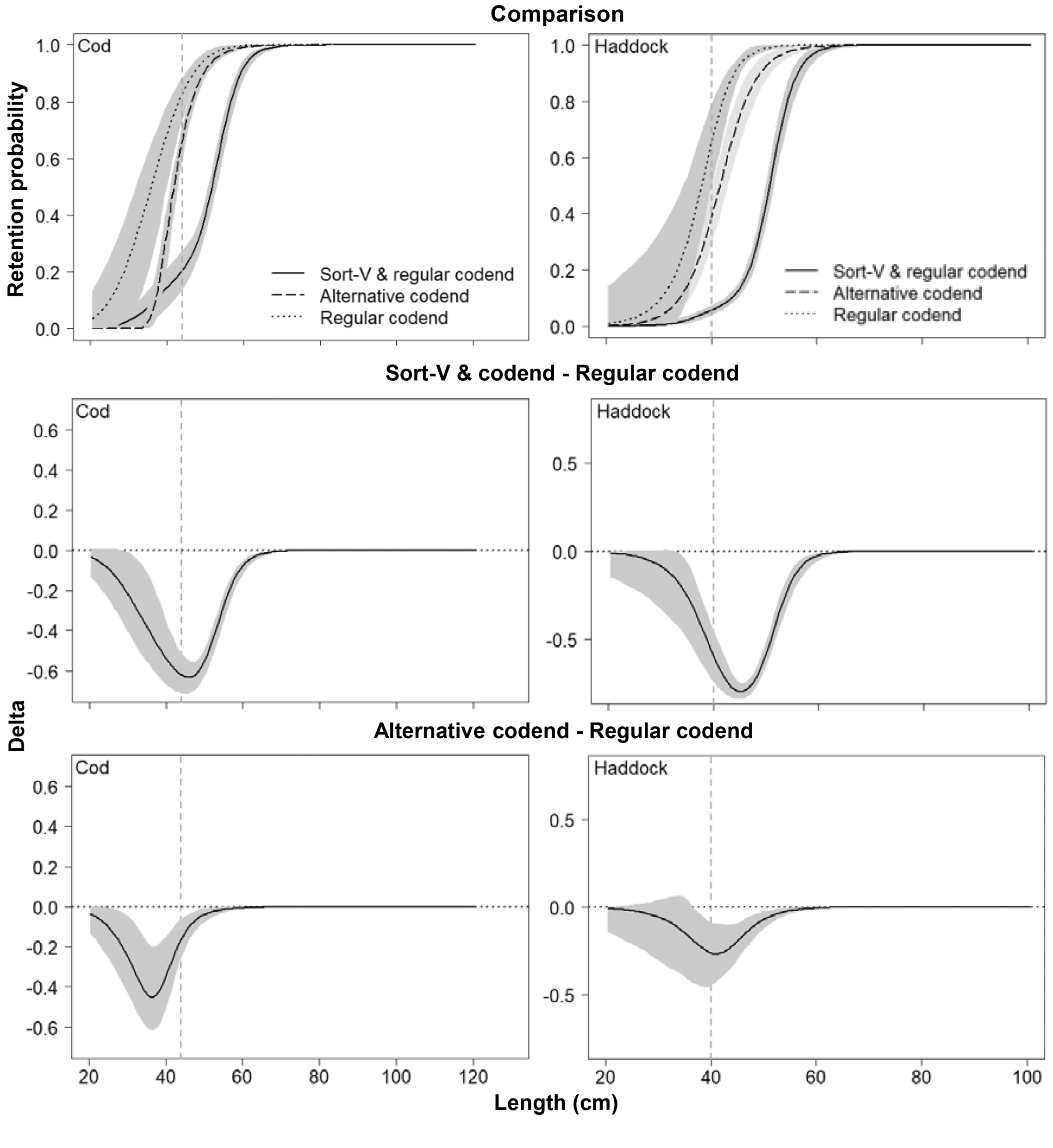

Figure 5. Comparison of the estimated length-dependent retention probabilities for the Sort-V and regular codend configuration, the alternative codend configuration, and the regular codend without the effect of the Sort-V grid (upper row) for cod (left column) and haddock (right column). The differences in selection properties between the Sort-V configuration compared to the regular codend alone (middle row) and between the alternative codend compared to the regular codend without the Sort-V are expressed as delta retention probability. Grey areas represent the 95% *CI*s. The stippled vertical grey lines denote the *MLS* for cod (44 cm) and haddock (40 cm).

in a commercial fishing setting to determine if the selectivity remains satisfactory when fish entry rate is high, which is a factor that is believed to affect selectivity (Jones *et al.*, 2008).

Increased demands on fisheries regarding environmental impact, sustainability, catch quality, and fish welfare have broadened the focus to include both selectivity and bycatch mitigation as well as catch efficiency. It is important to miti-

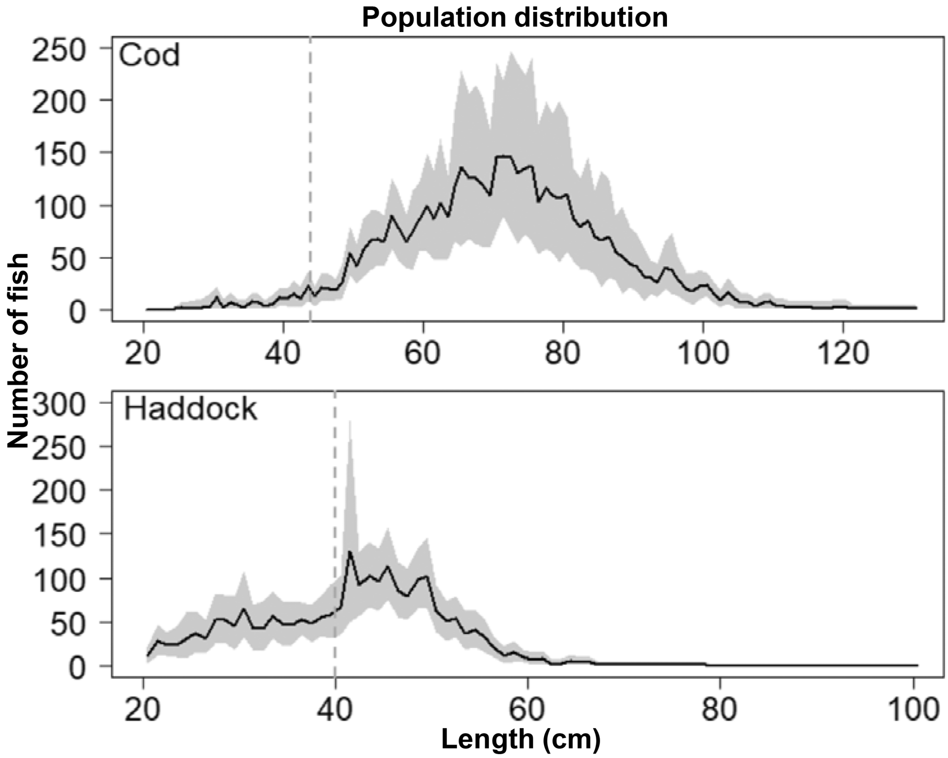

Figure 6. Length distribution of fish caught in the trawl codends and covers (black line). 95% *CI* is represented by the grey areas. Stippled lines denote *MLS* for cod (44 cm) and haddock (40 cm).

Table 4. Percentage difference in the catch pattern indicators showing the contribution of each gear compared to a non-selective gear for both cod and haddock.

Species	Gear type	nP- (%)	nP+ (%)	dnRatio (%)
Cod	SortV and codend—Non-selective gear	−88.1 (−91.1 to −82.75)	−7.50 (10.30 to −5.48)	−87.13 (−93.56 to −81.35)
	Regular codend—Non-selective gear	−42.59 (−65.93 to −29.96)	−0.55 (−0.93 to −0.21)	−43.16 (−66.10 to −31.02)
	Alternative codend—Non-selective gear	−72.42 (−82.45 to −66.09)	−1.11 (−1.67 to −0.72)	−72.22 (82.45 to −66.09)
Haddock	SortV and codend—Non-selective gear	−98.46 (−99.25 to −97.47)	−67.90 (−72.43 to −62.64)	−92.39 (−96.31 to −87.96)
	Regular codend—Non-selective gear	−79.47 (−89.23 to −58.94)	−8.23 (−13.27 to −4.72)	−67.98 (−81.94 to −44.18)
	Alternative codend—Non-selective gear	−89.81 (−93.41 to −85.63)	−22.45 (−29.78 to −14.75)	−80.18 (−86.40 to −74.64)

gate catches of unwanted species and fish below *MLS*, but it also is important to maximize catch efficiency for fish above *MLS*. Reduced catch efficiency of fish above *MLS* requires increased fishing effort for the vessels to catch their quota, which consequently leads to increased seabed impact, fuel consumption, and greenhouse gas emission as well as reduced profitability for the fishers. Furthermore, in areas with intensive fishing activity, fish individuals above *MLS* may be exposed to multiple unnecessary capture processes before they are finally retained by the gear. This is an acknowledged challenge posed by the use of sorting grids. A recent study reported that up to 77.4% of haddock and 16% of the cod above the *MLS* were released through the grid (Brinkhof *et al.*, 2020), and our data corroborated this result.

As this study demonstrated, depending on the length structure of the populations encountered, under some circumstances it was not always necessary to use selective devices to avoid bycatch of fish below *MLS*. In these cases, the loss of larger sizes and thus poor catch efficiency could be solved if fishers were allowed a more flexible choice of selective gear in conjunction with modern monitoring tools (e.g. live camera systems, automatic catch registration systems that are able to identify species, and length measure fish) (van Helmond *et al.*, 2020) as well as spatial and seasonal openings and closures (Graham *et al.*, 2007; Zhou *et al.*, 2010). In cases where this was not possible, a codend with short lastridge ropes provided improved selectivity (increased retention of fish above *MLS* with low increase in fish below *MLS*) compared to the configuration with the grid. Because twine properties such as twine thickness and number of twines are known to affect the selective properties of codends (Herrmann *et al.*, 2013b; Wienbeck *et al.*, 2014), codends with shortened lastridge ropes need to be standardized to achieve optimal size selectivity.

In many fisheries, bycatch issues have been mitigated by developing and implementing additional selectivity devices (Kennely and Broadhurst, 2021). Such devices can improve selectivity, but also entail an additional cost for fishermen and increase the complexity of the gear. In many cases, additional selectivity devices mitigate the symptom and not the cause of poor selectivity in a gear. As demonstrated in this study, making small and simple changes to the gear can improve selectivity without the need for additional gear. Moreover, it is important to consider if the selective gear applied, besides mitigating unwanted species and or sizes, does not also lead to a significant loss of legal and wanted target species and/or sizes. Further, as demonstrated by the catch indicators in this study, the need for selective devices can be questioned under certain circumstances, that is, low abundancy of unwanted sizes and/or species. All these findings are important to consider when applying selectivity devices in fishing gears in different fisheries around the world.

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Author contributions

JB: conceptualization, methodology, validation, formal analysis, resources, investigation, data curation, writing—original draft, writing—review and editing, and visualization.

MS: conceptualization, methodology, validation, formal analysis, investigation, data curation, writing—original draft, writing—review and editing, and visualization.

BH: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing—original draft, writing—review and editing, and visualization.

EG: conceptualization, methodology, investigation, data curation, and writing—original draft.

RBL: conceptualization, methodology, resources, investigation, and writing—original draft.

Competing interest statement

The current work in this study does not involve any competing interest of finical disclosures for any of the authors or institutions.

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Data availability statement

The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

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Appendix A

This appendix describes the four basis s-shaped size selection models *Logit*, *Probit*, *Gompertz*, and *Richards* considered as for candidates for codend size selection in this study:

$$r_{\text{codend}}(l, \mathbf{v}_{\mathbf{codend}}) = \begin{cases} Logit(l, \text{L50}, \text{SR}) = \frac{\exp\left(\frac{\ln(9)}{\text{SR}}\times(\text{l}-\text{L50})\right)}{1.0+\exp\left(\frac{\ln(9)}{\text{SR}}\times(\text{l}-\text{L50})\right)} \\ Probit(l, \text{L50}, SR) \approx \Phi\left(\frac{1.349}{SR}\times(l-\text{L50})\right) \\ Gompertz(l, \text{L50}, SR) \approx \exp\left(-\exp\left(-\left(0.3665+\frac{1.573}{SR}\times(l-\text{L50})\right)\right)\right) \\ Richards(l, \text{L50}, SR, \delta) = \left(\frac{\exp\left(g(0.5^{\delta})+\left(\frac{g(0.75^{\delta})-g(0.25^{\delta})}{SR}\right)(l-\text{L50})\right)}{1.0+\exp\left(g(0.5^{\delta})+\left(\frac{g(0.75^{\delta})-g(0.25^{\delta})}{SR}\right)(l-\text{L50})\right)}\right)^{1/\delta} \\ \text{where} \\ g(r) = \ln\left(\frac{r}{1.0-r}\right) \end{cases}. \tag{A1}$$

The term Φ in the *Probit* model refers to the cumulative distribution function of a standard normal distribution.$\mathbf{v}_{\mathbf{codend}} = (\text{L50}, SR)$ are the parameters that control the shape of the selection curve. The *Richards* model involves an additional parameter δ, which adds flexibility to the selection curve.

Appendix B

This appendix derives Equation (3) for the length-dependent retention probability by the sorting grid.

To escape through the grid, the fish both needs to contact the grid and to be able to pass through it. This is modelled by a length-independent contact probability and a *Logit* size selection model, respectively:

$$e_{\text{Grid}}\left(l, \mathbf{v}_{\mathbf{Grid}}\right) = C_{\text{grid}} \times (1.0 - Logit(l, L50_{\text{Grid},} SR_{\text{Grid}})).$$

If the fish does not escape through the grid, it is retained by it. Therefore

$$r_{\text{Grid}}(l, \mathbf{v}_{\mathbf{Grid}}) = 1.0 - e_{\text{Grid}}(l, \mathbf{v}_{\mathbf{Grid}}) = 1.0 - C_{\text{grid}} + C_{\text{grid}} \times Logit(l, L50_{\text{Grid}}, SR_{\text{Grid}}).$$

Inserting the equation for the *Logit* size selection model in this leads to

$$r_{\text{Grid}}(l, \mathbf{v}_{\mathbf{Grid}}) = 1.0 - C_{\text{grid}} + C_{\text{grid}} \times \frac{\exp\left[\frac{\ln(9)}{SR_{\text{Grid}}}\times(l-L50_{\text{Grid}})\right]}{1.0+\exp\left[\frac{\ln(9)}{SR_{\text{Grid}}}\times(l-L50_{\text{Grid}})\right]} =$$

$$1.0 - C_{\text{grid}}\left(1-\frac{\exp\left[\frac{\ln(9)}{SR_{\text{Grid}}}\times(l-L50_{\text{Grid}})\right]}{1.0+\exp\left[\frac{\ln(9)}{SR_{\text{Grid}}}\times(l-L50_{\text{Grid}})\right]}\right) = 1.0 - \frac{C_{\text{grid}}}{1.0+\exp\left[\frac{\ln(9)}{SR_{\text{Grid}}}\times(l-L50_{\text{Grid}})\right]},$$

which is identical to Equation (3).

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