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Make it simpler and better: T90 codend improves size selectivity and catch efficiency compared with the grid-and-diamond mesh codend in the Northeast Atlantic bottom trawl fishery for gadoids

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ABSTRACT

The use of a sorting grid followed by a size-selective codend with minimum 130 mm mesh size is compulsory in the Northeast Atlantic demersal trawl fishery targeting cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and saithe (*Polachius virens*). However, sorting grids cause some disadvantages, which possibly can be solved by removing the grid and improving codend selectivity, thus making the construction simpler. This study compared the size selectivity and catch efficiency of two diamond-meshed codends turned 90° (T90) with two different mesh sizes (135 and 145 mm) with those of a sorting grid followed by a diamond-mesh codend. The results showed that the T90 145-mm codend caught 7.0% fewer cod and 8.2% fewer saithe above the minimum reference length (MRL) compared with the compulsory configuration. By contrast, compared with the compulsory configuration, the T90 135-mm codend increased the capture of cod above the MRL by 4.4%, from 80.4% to 84.8%, of haddock by 14.1% from 45.2% to 59.3%, and of saithe by 16.0% from 59.7% to 75.7%. The increased catch of fish below the MRL was minor and far below the regulated limits. Our results demonstrate that a simple T90 codend represents an advantageous alternative to the more complex selection system with a rigid sorting grid currently enforced in the Northeast Atlantic demersal trawl fishery.

1. Introduction

The stocks of Northeast Arctic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and saithe (*Pollachius virens*) are the three most important species for the Northeast Atlantic bottom trawl fleet in terms of catch volume and yield. These three species are frequently targeted simultaneously, especially cod and haddock. On average, ~70% of the annual total allowable catch, which is equally divided between Russia and Norway, is caught by bottom trawls. The advised quota for 2020 was set to 689 672, 215 000, and 171 982 metric tons for cod, haddock, and saithe, respectively (ICES, 2019). The technical regulations for the trawl configurations currently enforced by the management authorities comprise, among others, a sorting grid with a minimum bar spacing of 55 mm, and a codend mesh size of a minimum 130 mm. The bar spacing and mesh size are intended to release fish below the minimum reference length (MRL), which is 44 cm for cod, 40 cm for haddock, and 45 cm for saithe (Ministry of Trade, Industry and Fisheries, 2020). Out of three different sorting grids that are allowed to be used, the flexigrid is the most common (Sistiaga et al., 2016; Brinkhof et al., 2020). Size-selective sorting grids were developed and introduced to the fishery in 1993 and became mandatory in 1997. Before 1993, this fishery was struggling with a high retention of juvenile fish because of poor size selectivity in the diamond-mesh codends that were then in use. This was solved by adding a size-selective sorting grid to assist the codend size selection However, recent studies demonstrated varying results regarding the size-selective performance of the flexigrid. Sistiaga et al. (2016) demonstrated high retention rates of fish below the MRL, whereas Brinkhof et al. (2020) demonstrated that the flexigrid retained low rates of fish below the MRL, but high rates of fish above the MRL, the latter especially for haddock. Loss of fish above the MRL subsequently leads to increased fishing effort and, thus, greater fuel consumption, seabed impacts, and higher amounts of nontarget bycatch (Brinkhof et al.,

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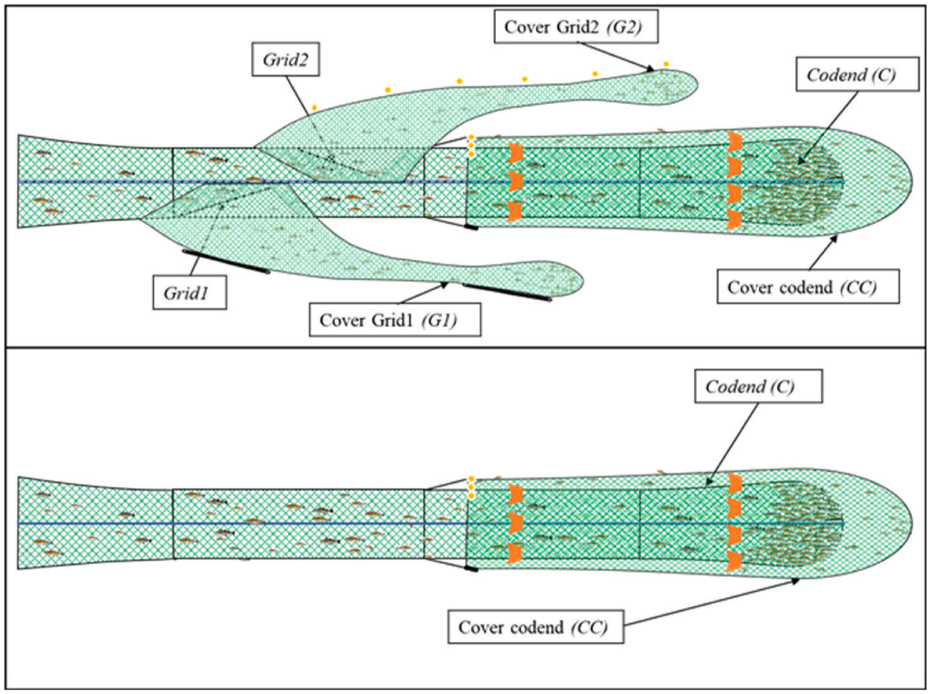

Fig. 1. Illustration showing the experimental design using during the trials. Upper, the compulsory configuration with the flexigrid and the 130-mm diamond-meshed codend (C) with the covers covering the first grid (G1), second grid (G2), and codend (CC). Lower, the experimental design applied for both T90-codends tested, with a covered codend (CC).

2020). Another challenge with the current selective grids is the saturation of the grid with fish when the entry rates of fish into the trawl is high, which reduces its selective capacity and can lead to excessively large catches (Grimaldo et al., 2014; Sistiaga et al., 2016; Ingolfsson and Brinkhof, 2020). Under such circumstances, the grids work like an obstacle ('bottleneck') in the trawl section, causing a reduction in the water flow, which again leads to fish not falling back into the codend but remaining positioned in front and behind the grid and in the extension section. Subsequently, when large quantities of fish are located in front of the codend they will not trigger the catch sensor, which is located on the codend, making monitoring of the catch quantity unreliable, possibly leading to excessively large catches.

A possible solution to these issues is making the construction simpler by removing the grid and improving selectivity in the codend. A previous study from the same fishery demonstrated similar size selectivity in a diamond-meshed codend with a 155-mm mesh size compared with the legislated configuration, which comprises a sorting grid with a 55-mm bar spacing followed by a diamond-meshed codend with 130 mm mesh size (Jørgensen et al., 2006). However, the meshes in a regular diamond-mesh codend, in this study referred to as T0, follow the machine production direction N of net panels, and tend to close under the tension from the catch and the water pressure during trawling, reducing its size-selective properties (Herrmann et al., 2007, 2013; Wienbeck et al., 2011). One way to keep the meshes open during towing is to rotate the mesh orientation by 90° to the towing direction (further referred to as T90). Multiple studies have documented the improved size selectivity of roundfish, such as gadoids and *Sebastes* spp. in T90-codends compared with regular T0 codends (Herrmann et al., 2007, 2013; Wienbeck et al., 2011; Bayse et al., 2016; Cheng et al., 2020).

Therefore, the purpose of the current study was to address the following questions:

- What is the size selectivity and catch efficiency of cod, haddock, and saithe with the legislated configuration comprising the flexigrid and diamond-mesh codend?
- What is the size selectivity and catch efficiency when the flexigrid is removed and the T0 codend substituted with a T90 codend with 135-mm mesh size?
- What is the size selectivity and catch efficiency when the flexigrid is removed and the T0 codend is substituted with a T90 codend with a 145-mm mesh size?
- Is there any difference in size selectivity and catch efficiency between these three configurations?

2. Materials and methods

Fishing trials were conducted onboard the research vessel R/V 'Helmer Hanssen' (63.8 m, 4080 HP) in the southern Barents Sea, off the coast of North Norway between February 29, 2020 and March 14, 2020. The trawl comprised a set of Injector Scorpion otter boards (weighing 3100 kg, with an area of 8 m^2), followed by 3-m long backstraps and 7-m long connector chains. The sweeps were 60-m long. To avoid excessive abrasion on the sweeps, a Ø53-cm bobbin was inserted in the middle. The total length of the ground gear was 46 m and comprised a 14-m-long chain (Ø19 mm) and three equally spaced bobbins (Ø53 cm) on each side, with a 18.9 m long rockhopper gear (Ø53 cm) in the center. The trawl used was an Alfredo 3, a two-panel trawl built of 155-mm polyethylene (PE) meshes with a circumference of 420 meshes. Its fishing line was 19.2-m long and the length of the headline was 36.5 m.

Three different trawl configurations were applied, one configuration similar to that applied in the commercial fishery, and two experimental configurations. The compulsory configuration comprised a flexigrid inserted between the trawl and the extension piece, and a diamond-meshed codend (Fig. 1). The flexigrid comprised two flexible grids made of high-density polypropylene (HDPE), each 150-cm long and 95.5-cm wide, with a bar spacing of 55 mm (for more details on the flexigrid, see Sistiaga et al., 2016). Between the flexigrid and the codend, a 9.3-m long extension piece (60 meshes) was inserted. The diamond-meshed codend (T0) was 11-m long, constructed from single Ø8-mm braided PE twine (Euroline Premium, Polar Gold), and had a mesh size of 129.5 ± 4.8 mm (mean ± SD). To collect the fish escaping

Table 1

Overview of the hauls conducted during the sea trials showing trawl configuration, haul number, depth (at start), towing time, and number of fish caught in the codend (nC), cover codend (nCC), first grid cover (nG1), and second grid cover (nG2) for all three species.

Trawl configuration	Haul No.	Depth (m)	Towing time (hh:mm)	No. of cod				No. of haddock				No. of saithe			
				nC	nCC	nG1	nG2	nC	nCC	nG1	nG2	nC	nCC	nG1	nG2
T0 - 130 mm, and Flexigrid	1	296	01:03	990	17	127	49	15	6	6	52	–	–	–	–
	2	297	00:52	377	8	56	68	14	3	7	41	14	0	9	17
	3	290	01:00	405	2	30	39	12	0	21	30	14	1	1	17
	4	294	00:30	507	11	31	41	16	1	20	42	31	8	14	54
	5	291	00:21	334	7	26	30	7	0	11	25	88	19	41	115
	6	296	00:44	388	5	19	43	22	21	21	77	88	15	44	77
	7	295	00:42	556	8	29	81	44	15	16	153	63	8	39	65
	8	292	00:30	852	17	32	39	40	9	9	21	68	24	10	56
	9	297	00:30	317	1	9	32	19	3	12	37	38	10	8	68
	10	296	00:54	691	16	45	61	44	11	30	100	41	6	1	33
T90–135 mm	1	292	00:30	270	99			117	108			5	7		
	2	294	01:01	944	584			95	140			35	19		
	3	292	01:02	221	405			154	385			13	19		
	4	304	01:00	821	258			113	144			52	32		
	5	298	00:36	1085	427			93	136			14	11		
	6	299	00:30	780	609			83	110			16	25		
	7	295	00:55	1354	527			125	174			30	19		
	8	311	01:00	250	123			29	138			11	25		
	9	301	00:43	1016	660			89	132			6	31		
	10	304	01:00	346	222			57	186			1	2		
T90–145 mm	1	285	00:46	688	229			12	78			19	21		
	2	286	00:25	609	219			23	79			6	5		
	3	289	00:15	1713	809			59	83			7	24		
	4	292	00:28	2073	717			23	72			5	4		
	5	290	00:50	450	147			11	63			1	8		
	6	289	00:30	256	93			11	61			2	10		
	7	290	01:00	510	198			6	138			10	16		
	8	291	00:34	870	193			12	85			7	9		
	9	292	00:26	334	156			9	144			2	7		
	10	292	00:33	602	229			44	100			2	12		

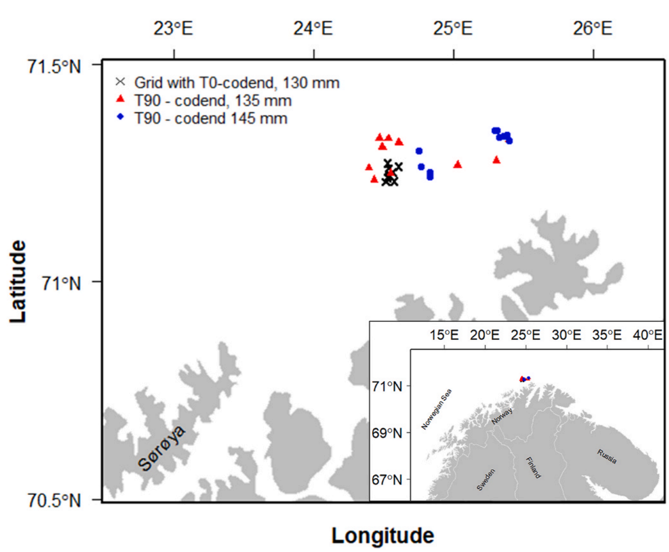

Fig. 2. Map of the area where the 30 hauls were conducted.

through the grids, a cover was mounted over each of the escape outlets. To avoid the covers from blocking the outlets, two longitudinal chains (2 × 5 kg) and seven floats (Ø200 mm) were mounted on the first and second grid cover, respectively (Fig. 1). Codend escapees were collected in a 20-m-long cover covering the entire length of the codend. To ensure that the cover stayed clear from the codend meshes, the foremost part of the cover was equipped with six floats (Ø200 mm) at the top, three kites at both sides, and 12-kg chains at the bottom. To ensure sufficient clearance of the cover around the catch bulk in the codend, 12 kites were attached on the aft part of the cover (Fig. 1). All three covers had a nominal mesh size of 50 mm and were strengthened by an outer layer of larger mesh netting.

In the two experimental designs, the flexigrid was removed and substituted with a two-panel extension section followed by a two–four-panel transition section. The first experimental configuration comprised a T90 codend with a mesh size of 135.5 ± 2.4 mm (mean ± SD). The second codend tested was a T90 codend with a mesh size of 147.6 ± 6.0 mm (mean ± SD). The codends were constructed from double Ø4-mm braided PE twine. Both codends were 4 × 12 meshes in circumference and 11-m long. To catch the codend escapees, the same cover as described in the section above was applied (Fig. 1). All mesh measurements were conducted applying an OMEGA gauge and following the procedure described by Wileman et al. (1996).

During towing, the distance between the otter boards, trawl height, and catch volume was monitored by Scanmar sensors. All cod, haddock, and saithe longer than 20 cm were caught and their length measured to the nearest centimeter.

2.1. Modeling and estimation of size selection in the T90 codends

Analysis of each species was performed separately using the same method described hereafter. The applied experimental design (Fig. 1) for the test of the T90 codends enabled analysis of the collected catch data as binominal data, where individuals, retained either by the codend cover or by the codend itself, were used to estimate the size selection in the codend (i.e., length-dependent retention probability). The size selectivity between the hauls with the same codend is expected to vary (Fryer, 1991). In this study, we were interested in the size selection averaged over hauls, because this would provide information about the average consequences for the size selection process when applying the codend in the fishery. We tested different parametric models $r_{codend}(l, \boldsymbol{v}_{codend})$ for the codend size selection. $\boldsymbol{v}_{codend}$ is a vector comprising the parameters of the model. The purpose of the analysis was

Table 2
Selectivity results showing the L50, SR, and exploitation pattern indicators for cod, haddock, and saithe for the three different trawl configurations tested. Values in parentheses represent 95% confidence intervals. The fit statistics in terms of the p-value, deviance, and degrees of freedom (DOF).

	Flexigrid and T0 - 130 mm			T90 - 135 mm			T90 - 145 mm		
	Cod	Haddock	Saithe	Cod	Haddock	Saithe	Cod	Haddock	Saithe
L50 (cm)	52.7 (51.7–53.8)	51.9 (50.4–54.5)	54.5 (53.0–55.5)	50.2 (48.6–51.8)	49.0 (47.6–50.1)	50.8 (49.1–52.2)	55.1 (54.5–56.3)	51.6 (49.9–53.8)	56.2 (54.8–59.0)
SR (cm)	8.1 (7.3–9.0)	9.2 (6.7–9.4)	7.3 (6.4–8.8)	9.7 (8.9–10.5)	8.8 (7.6–10.0)	7.7 (5.9–9.8)	12.1 (11.1–13.0)	8.45 (6.9–10.5)	8.5 (5.0–14.6)
nP- (%)	3.9 (1.8–6.3)	1.5 (0.6–3.1)	4.5 (1.7–8.4)	10.7 (8.4–13.2)	5.5 (3.3–8.4)	9.1 (2.5–18.8)	5.1 (3.0–6.7)	4.3 (0.7–7.8)	3.2 (0.4–10.8)
nP + (%)	80.4 (76.0–84.5)	45.2 (38.7–54.0)	59.7 (53.3–68.1)	84.8 (81.4–88.3)	59.3 (54.0–65.3)	75.7 (69.4–82.3)	73.4 (68.6–77.5)	48.4 (38.3–56.9)	51.5 (42.7–60.2)
DnRatio (%)	0.6 (0.2–1.0)	0.1 (0.0–0.2)	0.2 (0.0–0.5)	1.5 (0.9–2.1)	0.3 (0.1–0.5)	0.3 (0.0–0.8)	0.8 (0.4–1.2)	0.3 (0.1–0.5)	0.1 (0.0–0.6)
Model	Triple Logit	Triple Logit	Triple Logit	Richard	Logit	Probit	Probit	Richard	Logit
AIC	3826.32	1971.51	2432.57	7637.68	2540.08	337.89	7651.2	711.48	147
p-value	0.0868	0.167	0.032	0.631	0.0007	0.996	0.893	0.608	0.609
DOF	178	92	86	88	53	39	97	46	37
Deviance	157.1	105	111.7	83	91.8	19.5	80.1	42.8	34

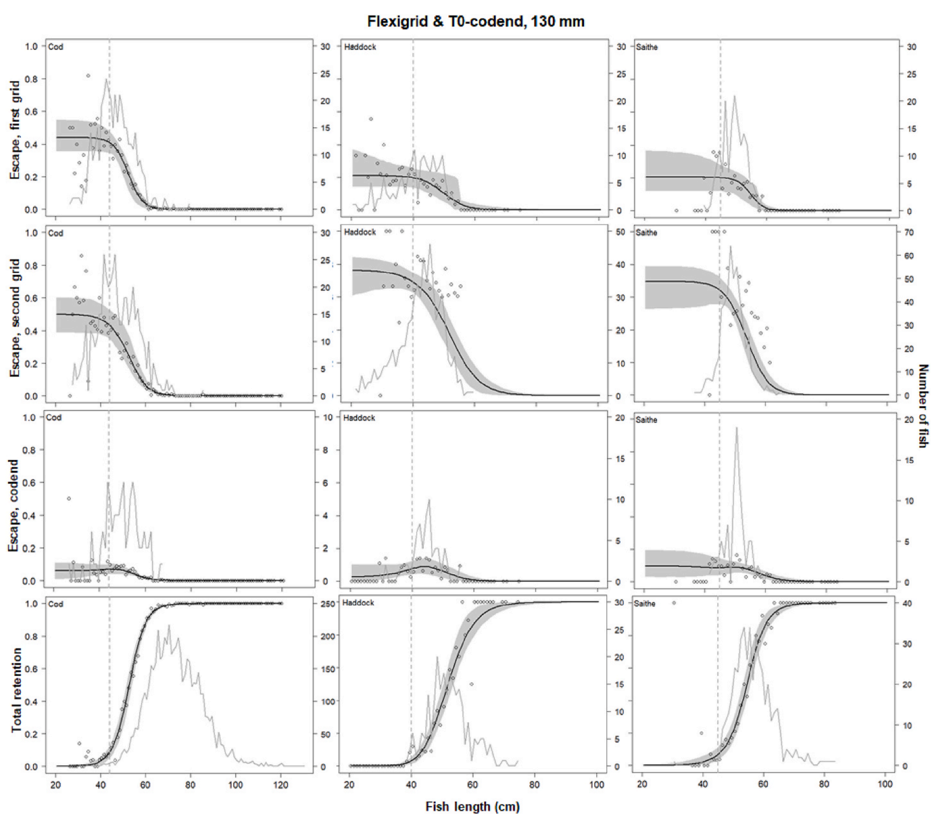

Fig. 3. Length-dependent probabilities of escape from the compulsory gear configuration (flexigrid with T0 130-mm codend) through the first grid, second grid, and codend, and the combined retention of both cod (left column), haddock (middle column), and saithe (right column). The solid curves represent the models fitted to the data (circles) with the 95% confidence intervals (gray area). The frequency curves in gray represent the number of fish caught in each length class in each compartment. The stippled vertical gray lines denote the minimum reference lengths for cod (44 cm), haddock (40 cm), and saithe (45 cm).

to estimate the values of the parameters $\boldsymbol{v}_{codend}$ that make experimental data (averaged over hauls) most likely to be observed. Therefore, the values for the parameters $\boldsymbol{v}_{codend}$ for the selection model $r_{codend}(l, \boldsymbol{v}_{codend})$ were obtained using maximum likelihood estimation based on the experimental data pooled over hauls j (1 to m) by minimizing:

$$G(l, \boldsymbol{v}_{codend}) = -\sum_{j=1}^{m}\sum_{l}\{nC_{lj} \times ln(r_{codend}(l, \boldsymbol{v}_{codend})) + nCC_{lj} \times ln(1.0 - r_{codend}(l, \boldsymbol{v}_{codend}))\}. \quad (1)$$

where nC_{lj} and nCC_{lj} denote the number of fish caught in haul j with length l that were collected in the codend (C), and in the cover (CC) (Fig. 1). The outer summation in equation (1) comprises the hauls conducted with the specific T90 codend and the inner summation over length classes l in the data. Four different models were chosen as basic candidates to describe $r_{codend}(l, \boldsymbol{v}_{codend})$ for each codend and species individually: Logit, Probit, Gompertz, and Richard. These four models are the described and recommended for modeling codend size selection in the ICES manual for selectivity (Wileman et al., 1996). The first three models are fully described by the two selection parameters L50 (length of fish with a 50% probability of being retained) and SR (difference in length between fish with 75% and 25% probability of being retained, respectively), whereas the Richard model also requires one additional parameter (1/δ), which describes the asymmetry of the curve. The formulas for the four selection models, together with additional information, can be found in Lomeli (2019). Evaluating the ability of a model to describe the data sufficiently is based on calculating the corresponding p-value, which expresses the probability of obtaining at least as big a

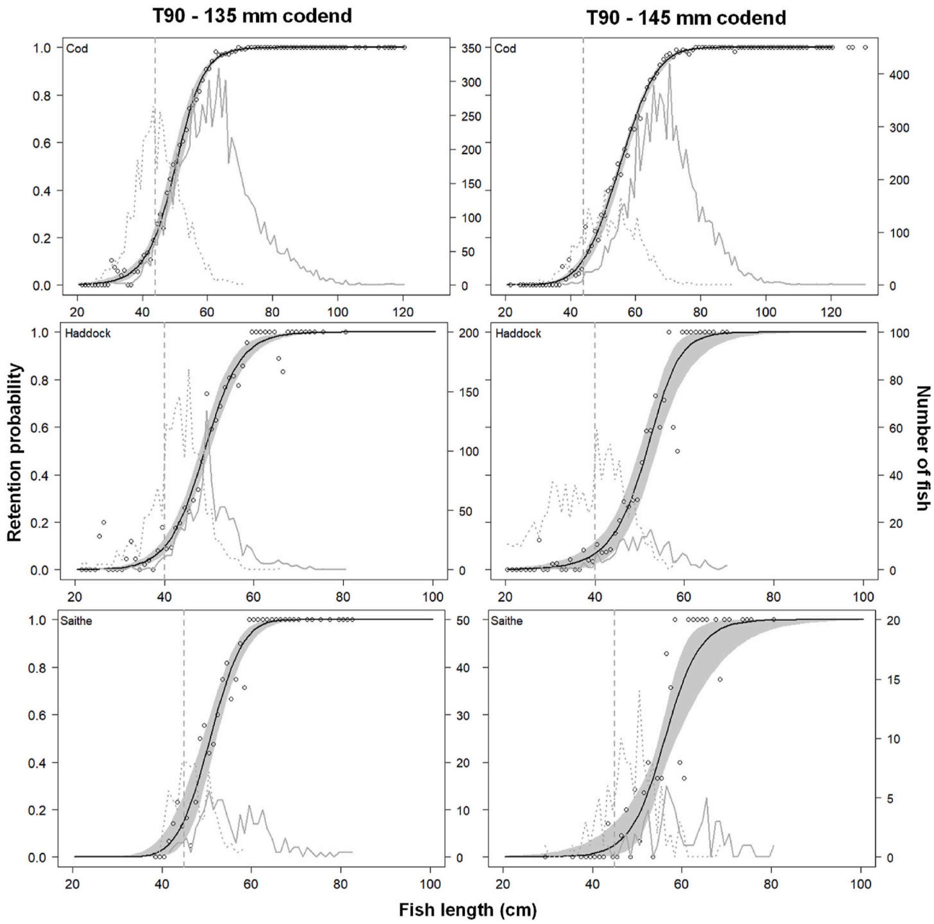

Fig. 4. Length-dependent probabilities of retention in the gear configuration with the T90 135-mm codend (left column), and T90 145-mm codend (right column) for cod (upper row), haddock (middle row), and saithe (lower row). The solid curves represent the models fitted to the data (circles) with the 95% confidence intervals (gray area). The frequency curves in gray represent the number of fish caught in each length class in the cover (dotted line), and codend (solid line). The stippled vertical gray lines denote the minimum reference lengths for cod (44 cm), haddock (40 cm), and saithe (45 cm).

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, *p*-value should not be < 0.05 (Wileman et al., 1996). In case of a poor fit statistic ($p < 0.05$), the residuals were inspected to determine whether the poor result was the result of structural problems when modeling the experimental data using the different selection curves or whether it was because of overdispersion in the data (Wileman et al., 1996). Selection of the best model among the four considered in equation (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 T90 codend, bootstrapping was applied to estimate the confidence intervals (CIs) for the average size selection. We applied the software tool SELNET (Herrmann et al., 2012) for the size-selection analysis and used the double bootstrap method implemented in this tool to obtain the CIs for the size-selection curve and the corresponding parameters. This bootstrapping approach is identical to that described by Millar (1993) and takes both within-haul and between-haul variation into consideration. The hauls for each T90 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 'pooled' set of data, which was then analyzed using the identified selection model. Thus, each bootstrap run resulted in an average selection curve. For each species analyzed, 1000 bootstrap repetitions were conducted to estimate the Efron percentile 95% CIs (Herrmann et al., 2012).

2.2. Modeling the size selection processes in the flexigrid and codend

Compared with the T90 codends (Fig. 1, lower), the size selection for the standard gear with a flexigrid combined with a T0 codend (Fig. 1, upper) was more complex because there were three selection processes: first grid, second grid, and codend. This was also reflected in the experimental design of three covers to collect fish escaping through each of the selection processes involved. For this system, Brinkhof et al. (2020) modeled the combined size selection by using equation (2):

$$r_{combined}(l) = 1.0 - e_{Grid1}(l) - e_{Grid2}(l) - e_{Codend}(l), \tag{2}$$

where $e_{Grid1}(l)$, $e_{Grid2}(l)$, and $e_{Codend}(l)$ represent the escape probabilities through the first grid, second grid, and codend, respectively.

In this study, we applied the approach developed and described by Brinkhof et al. (2020) to model and estimate the combined size selection for the flexigrid and T0 codend. Specifically, similar to previous studies of sorting grids (Sistiaga et al., 2010; Larsen et al., 2016, 2018), Brinkhof et al. (2020) modeled the escape probability for the two grids based on a *CLogit* size selection model (Herrmann et al., 2013). In the *Clogit* model, the parameter *C* is assumed to be length independent, and quantifies the probability that a fish entering the grid zone contacts the grid with an orientation that provides it with a length-dependent probability of escaping through the grid (selectivity contact). For the fish that make selectivity contacts with the grid, the *CLogit* model assumes a traditional *Logit* size selection model defined by the parameters *L50* and *SR*. Thus, $e_{Grid1}(l)$ was modeled by Equation (3):

$$e_{Grid1}(l, \boldsymbol{v}_{Grid1}) = \frac{C_{Grid1}}{1 + \exp\left(\frac{\ln(9)}{SR_{Grid1}} \times \left(l - L50_{Grid1}\right)\right)}, \tag{3}$$

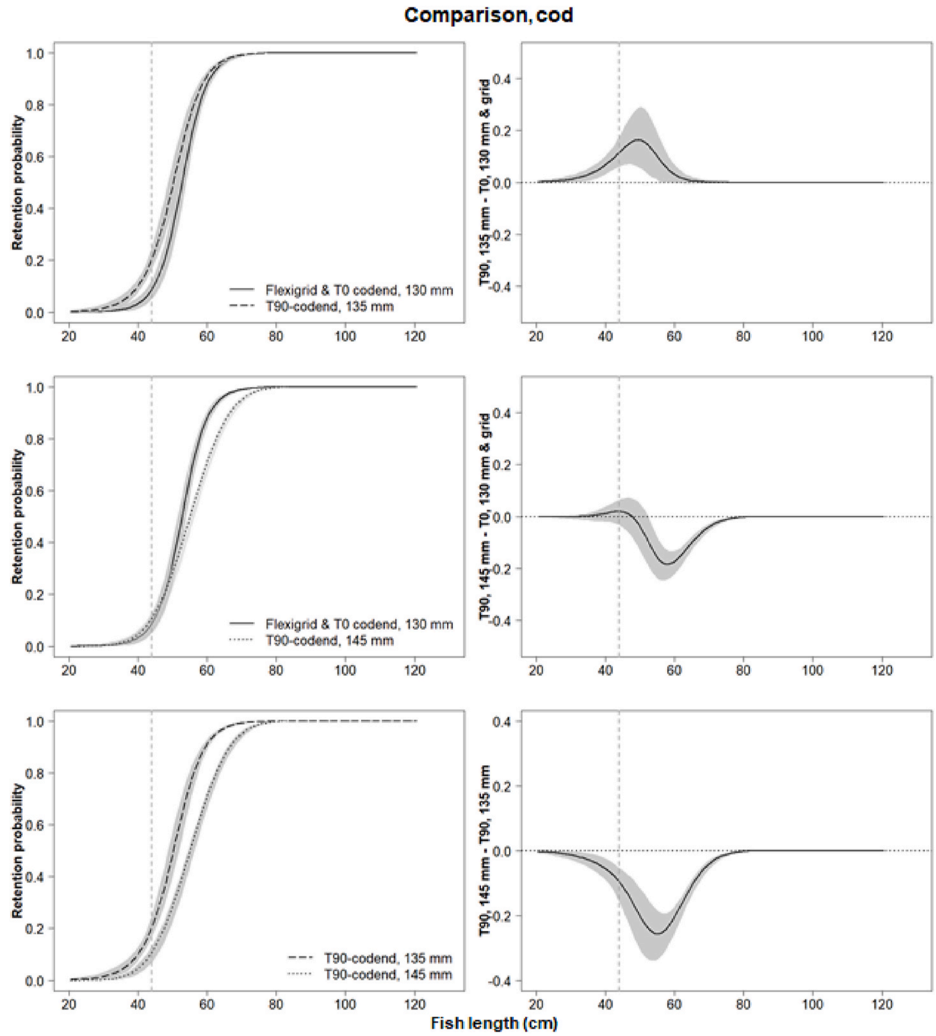

Fig. 5. Comparison of the estimated length-dependent probabilities of retention of cod for the three gear configurations tested (left column), and differences in the selection properties between the gears expressed as delta retention probability (right column). Gray areas represent the 95% confidence intervals. The stippled vertical gray lines denote the minimum reference length for cod (44 cm).

with the parameter vector $\boldsymbol{v}_{Grid1} = (C_{Grid1}, L50_{Grid1}, SR_{Grid1})$. Similar considerations were made regarding the escape probability through the second grid to yield the following model for $e_{Grid2}(l)$ (equation (4))

$$e_{Grid2}(l, \boldsymbol{v}_{Grid1}, \boldsymbol{v}_{Grid2}) = \frac{C_{Grid2}}{1 + \exp\left(\frac{\ln(9)}{SR_{Grid2}} \times \left(l - L50_{Grid2}\right)\right)} \times (1.0 - e_{Grid1}(l, \boldsymbol{v}_{Grid1})), \tag{4}$$

where $\boldsymbol{v}_{Grid2} = (C_{Grid2}, L50_{Grid2}, SR_{Grid2})$. For the second grid, equation (4) accounts for the condition that the fish in the second grid zone has not previously escaped through the first grid.

The codend was a traditional diamond-mesh codend with a single mesh size attached to a sorting grid section; thus, $e_{Codend}(l)$ was modeled based on the *Logit* size selection model (similar to that used by Sistiaga et al. (2010)) (equation (5)):

$$e_{Codend}(l, \boldsymbol{v}_{Grid1}, \boldsymbol{v}_{Grid2}, \boldsymbol{v}_{codend}) = \frac{1}{1 + \exp\left(\frac{\ln(9)}{SR_{codend}} \times \left(l - L50_{codend}\right)\right)} \times (1 - e_{Grid1}(l, \boldsymbol{v}_{Grid1})) \times (1 - e_{Grid2}(l, \boldsymbol{v}_{Grid1}, \boldsymbol{v}_{Grid2})), \tag{5}$$

where $\boldsymbol{v}_{Codend} = (L50_{Codend}, SR_{Codend})$. For codend escape, equation (5) accounts for the condition that the fish has not previously escaped through the first or second grid.

We used Equations (2)–(5) to model the size selection in the combined size-selection system comprising a flexigrid followed by the T0 codend. Estimation was performed 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 that applied by Sistiaga et al. (2010).

Catch data were collected using the four-compartment experimental design shown in Fig. 1a, which included the codend (C), cover of the first grid ($G1$) to collect fish that escaped through the first grid, cover of the second grid ($G2$) to collect fish that escaped through this grid, and the cover (CC) surrounding the codend to collect fish that escaped through the codend meshes. Thus, for each haul j, we had the number of

Table 3
Difference in the catch pattern indicators between the three different configurations. Values in parentheses represent 95% confidence intervals and the values in bold demonstrate significant differences between two configurations.

Species	Gear	nP- (%)	nP+ (%)	DnRatio (%)
Cod	T90 - 135 mm vs. Flexigrid and T0 - 130 mm	**6.81 (3.41–10.15)**	**4.43 (1.39–8.15)**	**0.89 (0.40–1.15)**
	T90 - 145 mm vs. Flexigrid and T0 - 130 mm	1.20 (−1.86–3.68)	**−6.99 (-10.24–-4.09)**	0.24 (−0.20–0.66)
	T90 - 135 mm vs. T90 - 145 mm	**5.61 (2.72–8.87)**	**11.42 (8.62–15.19)**	**0.65 (0.24–1.24)**
Haddock	T90 - 135 mm vs. Flexigrid and T0 - 130 mm	**3.95 (1.73–6.92)**	**14.12 (5.01–22.43)**	**0.17 (0.05–0.33)**
	T90 - 145 mm vs. Flexigrid and T0 - 130 mm	2.71 (−0.76–6.50)	3.20 (−8.86–13.42)	0.16 (−0.03-0.37
	T90 - 135 mm vs. T90 - 145 mm	1.24 (−2.81–5.24)	**10.92 (1.48–21.70)**	0.01 (−0.18–0.24)
Saithe	T90 - 135 mm vs. Flexigrid and T0 - 130 mm	4.66 (−2.82–14.18)	**15.98 (7.60–22.50)**	0.10 (−0.14–0.48)
	T90 - 145 mm vs. Flexigrid and T0 - 130 mm	−1.26 (−6.31–6.56)	**−8.19 (-18.01–0.05)**	−0.03 (−0.28–0.39)
	T90 - 135 mm vs. T90 - 145 mm	5.92 (−4.21–16.66)	**24.17 (15.34–34.11)**	0.13 (−0.29–0.52)

individuals with length l collected in the codend (nC_{lj}), first grid cover ($nG1_{lj}$), second grid cover ($nG2_{lj}$), and codend cover (nCC_{lj}). Thus, the species-specific size selection in the flexigrid combined with the codend and averaged over the m hauls conducted could be obtained by minimizing equation (6) with respect to the parameters $\boldsymbol{v}_{Grid1}$, $\boldsymbol{v}_{Grid2}$, and $\boldsymbol{v}_{codend}$ in the model comprising equations (2)–(5):

$$H(l,\boldsymbol{v}_{Grid1},\ \boldsymbol{v}_{Grid2},\boldsymbol{v}_{codend}) = -\sum_{j=1}^{m}\sum_{l}\{nC_{lj}\times ln(r_{combined}(l,\boldsymbol{v}_{Grid1},\ \boldsymbol{v}_{Grid2},\boldsymbol{v}_{codend})) + nG1_{lj}\times ln(e_{Grid1}(l,\boldsymbol{v}_{Grid1})) + nG2_{lj}\times ln(e_{Grid2}(l,\boldsymbol{v}_{Grid1},\boldsymbol{v}_{Grid2})) + nCC_{lj}\times ln(e_{Codend}(l,\boldsymbol{v}_{Grid1},\ \boldsymbol{v}_{Grid2},\boldsymbol{v}_{codend}))\}, \quad (6)$$

Minimizing equation (6) with respect to its parameters was equal to maximizing the likelihood of the observed experimental data under the assumption that equations (2)–(5) describe the multinominal probabilities for observing a fish with length l in the codend or covers conditioned by the fish that entered the combined selection system comprising a flexigrid section and codend.

The ability of Equations (2)–(5) to describe the experimental data was evaluated based on the p-value and model deviance versus degrees of freedom (DOF), and by inspecting how the model curves reflected the length-based trend in the data (Wileman et al., 1996). Similar to the T90 codends, the data analysis was conducted using the software tool SELNET and uncertainties in estimated size selection were obtained by using the double bootstrap method implemented in this tool.

2.3. Estimation of difference in size selectivity between selection systems

The difference in size selectivity $\Delta r(l)$ between two selection systems x and y was estimated by equation (7):

$$\Delta r(l) = r_y(l) - r_x(l) \quad (7)$$

where x and y represent one of the T90 codends or flexigrid. The 95% CIs for $\Delta r(l)$ were obtained based on the two bootstrap population results for $r_x(l)$ and $r_y(l)$, respectively. Given that they were obtained independently of each other, a new bootstrap population of results for $\Delta r(l)$ was created using equation (8) (Larsen et al., 2018):

$$\Delta r(l)_i = r_y(l)_i - r_x(l)_i \ i \in \ [1\ldots1000] \quad (8)$$

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

2.4. Estimation of exploitation pattern and catch efficiency indicators

To evaluate how each of the three selection systems performed in the specific fishery, three exploitation pattern indicators ($nP-$, $nP+$, and *dnRatio*) were estimated separately for each species. $nP-$ and $nP+$ quantified the retention probability, i.e. for fish below and above the MRL (as percentages), respectively, whereas *dnRatio* represented the discard ratio in numbers and denoted the percentage of undersized fish in the codend catch. These indicators can be used to summarize the catch patterns for specific gear in a specific fishery. The size-selection properties provide information that is independent of the size structure of the population encountered by the gear during the fishing process, whereas these indicators depend directly on the size structure, thereby providing additional information to facilitate evaluation of the catch performance of the selective system (Wienbeck et al., 2014). For the flexigrid combined with codend and experimental setup (Fig. 1a), these indicators were given by equation (9):

$$nP- = 100\times\frac{\sum_j\sum_{l<MRL}(nC_{jl})}{\sum_j\sum_{l<MRL}(nC_{jl}+nG1_{jl}+nG2_{jl}+nCC_{jl})}$$
$$nP+ = 100\times\frac{\sum_j\sum_{l>MRL}(nC_{jl})}{\sum_j\sum_{l>MRL}(nC_{jl}+nG1_{jl}+nG2_{jl}+nCC_{jl})}, \quad (9)$$
$$dnRatio = 100\times\frac{\sum_j\sum_{l<MRL}(nC_{jl})}{\sum_j\sum_{l}(nC_{jl})}$$

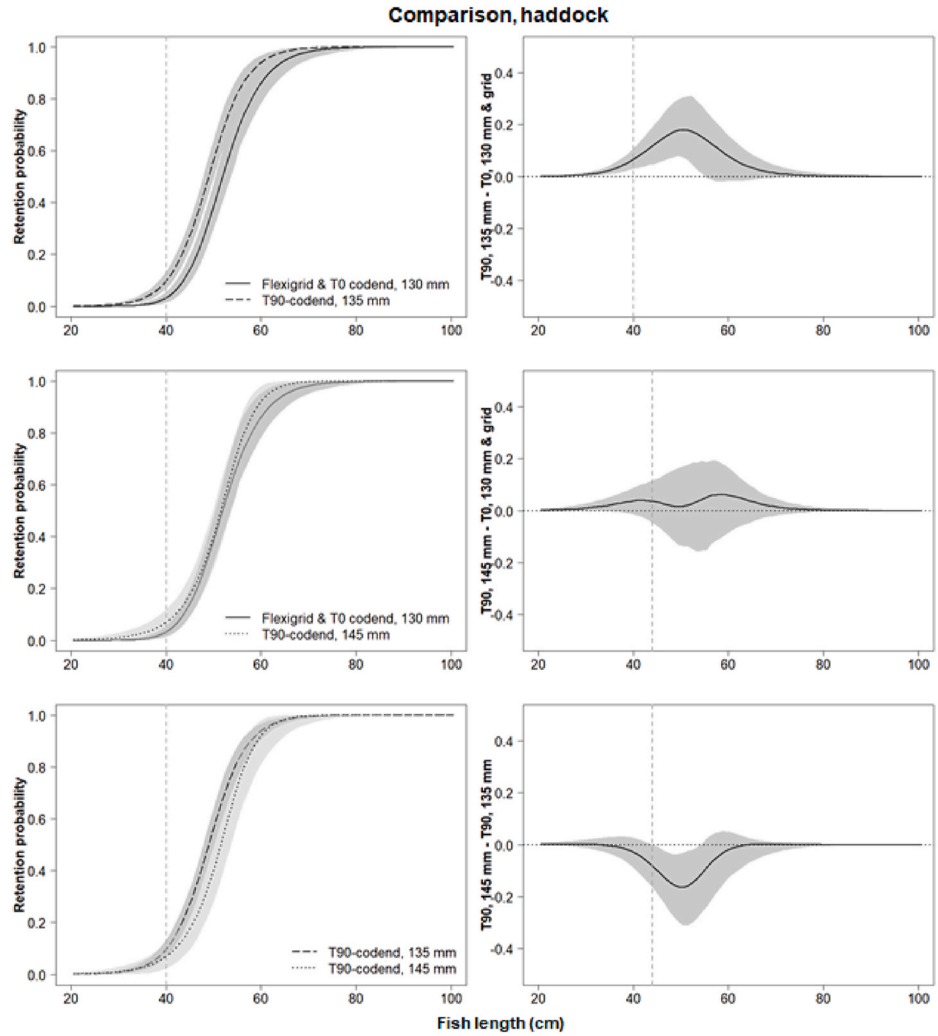

Fig. 6. Comparison of the estimated length-dependent probabilities of retention of haddock for the three gear configurations tested (left column), and differences in the selection properties between the gears, expressed as the delta retention probability (right column). Gray areas represent the 95% confidence intervals. The stippled vertical gray lines denote the minimum reference length for haddock (40 cm).

where the sum of j is over the hauls and l is over the length classes. Ideally, for a target species, $nP-$ and $dnRatio$ should be low (close to zero), whereas $nP+$ should be high (close to 100%), that is, retain all individuals over the MRL that enter the codend.

For the T90 codends and experimental design shown in Fig. 1 (lower), the estimation of the indicators simplifies to equation (10):

$$nP- = 100 \times \frac{\sum_{j}\sum_{l<MRL}(nC_{jl})}{\sum_{j}\sum_{l<MRL}(nC_{jl}+nCC_{jl})}$$
$$nP+ = 100 \times \frac{\sum_{j}\sum_{l>MRL}(nC_{jl})}{\sum_{j}\sum_{l>MRL}(nC_{jl}+nCC_{jl})} \tag{10}$$
$$dnRatio = 100 \times \frac{\sum_{j}\sum_{l<MRL}(nC_{jl})}{\sum_{j}\sum_{l}(nC_{jl})}$$

The double bootstrap method described in the previous section was used to estimate the Efron 95% percentile CIs for the indicator values. The CIs considered the effects of variations in both the between-haul selection and the population entering the gear, in addition to the uncertainty in individual hauls because the number of fish caught in each haul was finite.

3. Results

The trials at sea resulted in 30 valid hauls, ten hauls with each of the three trawl configurations (Table 1, Fig. 2). All fish longer than 20 cm in total length were caught and their length measured, which resulted in the total lengths of 28 492 cod, 4754 haddock, and 1755 saithe.

3.1. Selectivity results

Overall, the models used to describe the escape and retention of the three different configurations and the three different species reflected the main trends in the experimental data well ($p > 0.5$) (Table 2). For the cases in which $p < 0.05$, the residuals were inspected, which demonstrated that the poor-fit statistics were caused by overdispersion.

The compulsory configuration with the flexigrid and the diamond-meshed codend with 130-mm mesh size demonstrated high release efficiency (Fig. 3). For cod, both grids contributed approximately equally to escape, with slightly more cod escaping through the second (upper) grid. For haddock and saithe, approximately four times as many fish escaped through the second grid compared with the first grid. For all three species, escape through the codend meshes was negligible

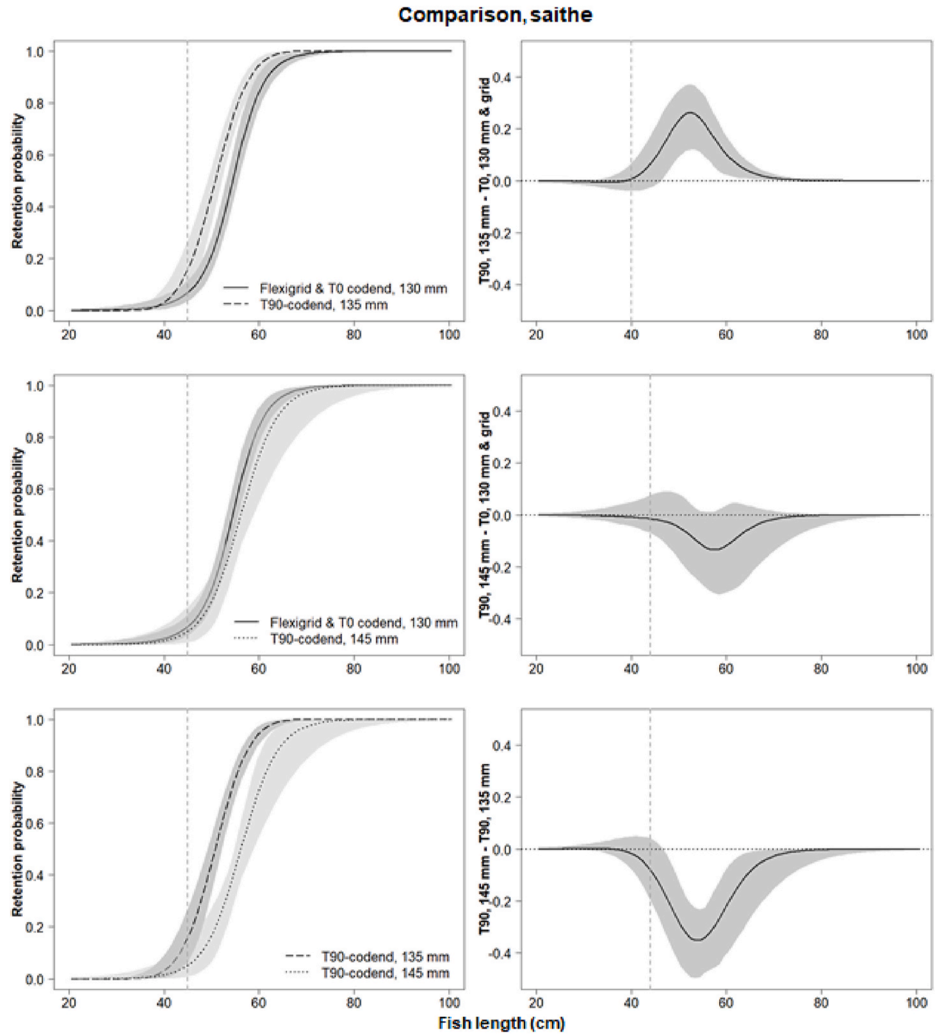

Fig. 7. Comparison of the estimated length-dependent probabilities of retention of saithe for the three gear configurations tested (left column), and differences in the selection properties between the gears expressed as the delta retention probability (right column). Gray areas represent the 95% confidence intervals. The stippled vertical gray lines denote the minimum reference length for saithe (45 cm).

compared with through the grid (Fig. 3). The combined retention curves demonstrated almost no retention of fish below the MRL for all three species. However, the combined retention curves also showed the high release of cod, haddock, and saithe above the MRL (Fig. 3). This was corroborated by the estimated catch pattern indicators, which showed that the compulsory trawl configuration retained 3.9% of the cod below the MRL, and 1.5% and 4.5% of haddock and saithe, respectively (Table 2). However, for fish above the MRL, the compulsory configuration retained 80.4%, 45.2%, and 59.7% of the cod, haddock, and saithe, respectively (Table 2). There was no significant difference between the estimated L50 values between cod, haddock, and saithe (Table 2).

The trawl configuration with the T90 135-mm mesh-sized codend demonstrated high release efficiency for both cod, haddock and saithe with low retention of fish below the MRL (Fig. 4; Table 2). According to the catch pattern indicators 10.7%, 5.5%, and 9.1% of respectively cod, haddock and saithe below the MRL were retained. However, also fish above the MRL managed to escape (Table 2). According to the catch pattern indicators 84.8%, 59.3%, and 75.7% of respectively cod, haddock and saithe above the MRL were retained. The escapement above the MRL was even more present in the trawl configuration with the T90 codend with 145-mm mesh size (Fig. 4). Specifically, 73.4%, 48.4%, and 51.5% of respective cod, haddock and saithe above the MRL were retained (Table 2). However, the retention of fish below the MRL was slightly lower compared to the T90 135-mm codend, i.e., 5.1%, 4.3%, and 3.2% for cod, haddock, and saithe, respectively. (Fig. 4; Table 2). Regarding the L50-values there was no significant difference between the three species for the T90 135-mm codend configuration (Table 2). However, for the T90 145-mm codend configuration, haddock had a lower L50 length compared with cod and saithe that was statistically significant (i.e., no overlap between the CIs).

3.2. Comparison of size selectivity and catch efficiency

Comparing the CIs from the retention probability curves for cod from the compulsory configuration (flexigrid with a T0 130-mm codend) with the T90 135-mm codend shows a significantly difference in size selection (Fig. 5). This is corroborated by the delta plot, which showed that the T90 135-mm codend has higher retention probability for cod both above and below the MRL compared to the compulsory trawl configuration (Fig. 5). By contrast, the T90 145-mm codend released significantly more cod compared with the compulsory configuration with the flexigrid and the T0 130-mm codend. However, as shown by the delta plot, this was only significant for cod above the MRL (Fig. 5). Comparing the size selectivity results from the T90 135-mm codend with the T90 145-mm codend demonstrates a significantly increased release efficiency for cod with the latter codend for nearly all length groups caught (Fig. 5). The catch pattern indicators demonstrated a significant difference for cod in two cases: the T90 135-mm codend retained 10.7% (CI: 8.4–13.2) of the cod below MRL compared with 3.9% (CI: 1.8–6.3) for the T0 130-mm codend, a difference of 6.8% (CI: 3.4–10.5) (Tables 2 and 3). The T90 145-mm codend retained 5.1% (CI: 3.0–6.7), a difference of 5.6% (CI: 2.7–8.8) compared with the T90 135-mm codend (Tables 2 and 3).

For haddock, the T90 135-mm codend released fewer fish compared with the compulsory configuration, especially of haddock above the MRL (Fig. 6). The comparison of the compulsory configuration with the T90 145-mm codend demonstrated no significant differences, indicating that those two trawl configurations have similar size selective properties for haddock. Comparison of the size selectivity between the T90 135-mm codend and the T90 145-mm codend demonstrated a significant higher release of haddock above the MRL for the latter codend (Fig. 6). The catch pattern indicators demonstrated a significant improved catch efficiency for haddock caught with the T90 135-mm codend (59.3% CI: 53.99–65.3) compared with the compulsory configuration (45.2% CI: 38.7–53.95), an increase of 14.1% (CI: 5.0–22.3) (Tables 2 and 3).

For saithe, the T90 135-mm codend had significantly higher retention probability compared with the flexigrid with the T0 130-mm codend (Fig. 7). This significance was only for saithe above the MRL. Comparison of the size selectivity curves between the flexigrid with the T0 130-mm codend and the T90 145-mm demonstrated no significant differences (Fig. 7). By contrast, the difference in size selection between the T90 135-mm codend and the T90 145-mm codend was significantly different, with the latter codend having a higher release probability for saithe above the MRL (Fig. 7). The catch pattern indicators demonstrated a significantly improved catch efficiency for saithe caught with the T90 135-mm codend (75.7% CI: 69.4–82.3) compared with the compulsory configuration (59.7% CI: 53.3–68.1), a difference of 16.0% (CI: 7.6–22.5) and the T90 145-mm codend (51.5%, CI:42.7–60.2), a difference of 24.1% (CI: 15.3–34.1) (Tables 2 and 3). The T90 145-mm codend retained 1.3% fewer saithe compared with the compulsory configuration (Table 3).

4. Discussion

For decades, size selectivity in trawls has received much research attention (Walsh et al., 2002; Graham, 2010; Kennelly and Broadhurst, 2021). In the demersal trawl fishery in the Northeast Atlantic, the focus has been mainly on developing size-selective sorting grids (Jørgensen et al., 2006; Sistiaga et al., 2010, 2016; Grimaldo et al., 2015; Brinkhof et al., 2020). Such grids were developed and enforced in the fishery to help solve the issue of poor size selectivity in the applied diamond-mesh codends.

After many years of declining stock and recruitment, the 1983 year-class of cod was very successful (Nakken and Hylen, 1985; Nakken, 1994) and it became evident that the size-selection system in fish trawls needed improvement to ensure the increased survival of juvenile fish. From 1980 to 1990, Russian–Norwegian management gradually enforced stricter bycatch regulations on commercially important species in the Northeast Atlantic, leading to a bilateral increased effort to improve the selectivity of mobile fishing gear (Hammer and Hoel, 2012; Gullestad et al., 2015). Encouraged by results achieved in the North Sea (Robertson and Stewart, 1988), square mesh trials were attempted in the Northeast Atlantic (Isaksen and Valdemarsen, 1986). During these trials, it was discovered that the mesh shape in the knotless net was distorted, the square mesh codend was difficult to empty when catches exceeded ca. 2 tons, and heavy meshing of redfish (*Sebastes* spp.) negatively affected the selection properties. Given these practical problems and discouraging results, the square mesh codend technique was not adopted by Norwegian–Russian fisheries management.

Parallel to the development of the bycatch excluder device for shrimp trawls (Isaksen et al., 1992), the first version of a size-selective grid for fish trawls was developed (Larsen and Isaksen, 1992). The technique became compulsory for the Barents Sea in 1997 and is believed to have had an important function in rebuilding the Northeast Atlantic fish stocks (Gullestad et al., 2015). The idea of open meshes (in the codend) or slots (in the grid) was, and still is, believed to improve and maintain more acceptable and stable selection characteristics compared with compulsory T0 codends. Additionally, experiments to compare injuries and mortality of escaping individuals during mesh and grid selectivity suggested that grids caused less damage compared with meshes (Ingólfsson et al., 2007).

The flexigrid, which is the most applied selective grid system, has demonstrated varying results, ranging from substantial retention of fish below the MRL (Sistiaga et al., 2016), to negligible retention of fish below the MRL (Brinkhof et al., 2020). Moreover, Brinkhof et al. (2020) also demonstrated that the flexigrid released up to 77.4% of haddock and 16% of cod above the MRL. Loss of fish above the MRL is compensated for by increased fishing effort and, thus, subsequent greater fuel consumption and seabed impacts, as well as increased rates of nontarget bycatch (Brinkhof et al., 2020). Another challenge with the current selective grids has been the saturation of the grid under circumstances with high entry rates, which reduces its selective capacity and can lead to excessively large catches (Grimaldo et al., 2014; Sistiaga et al., 2016; Ingolfsson and Brinkhof, 2020). Under circumstances with high entry rates, the grids work like an obstacle in the trawl section, causing a reduction in water flow. This leads to accumulation of fish behind the grid section and subsequently prevents fish from falling back into the codend. Hence, the catch sensors along the codend kick in late and make it more difficult decide when haul back should start.

In this way, adding additional devices, such as a sorting grid, complicates the trawl configuration. A simpler solution would be to improve the size selectivity in the codend without adding additional devices. As this study demonstrates, one possible solution is to remove the grid and improve selectivity in the codend by rotating the orientation of the meshes 90° to the towing direction, thus forcing the meshes to stay open during towing, enabling sufficient size selection. This study demonstrates that the catch pattern of the configuration with the sorting grid and T0 130-mm codend compared with the configuration with the T90 145-mm codend were similar except for cod and saithe above the MRL, which the latter configuration significantly released more of. By contrast, the T90 135-mm codend significantly improved the catch of cod, haddock, and saithe above the MRL compared with the compulsory configuration. Consequently, the discard ratio increased significantly for cod and haddock. However, according to Norwegian legislation, catches caught above 62°N can comprise a maximum of 15% of cod, haddock, and saithe below the MRL (number of fish) (Ministry of Trade, Industry and Fisheries, 2020). This means that, even though the discard ratio for cod and haddock slightly increased with the T90 135-mm codend, the values are still far below the 15% limit.

In size selectivity studies the power for the modeled size selectivity can be judged from the 95% CI's. The results in this study demonstrate high predictive power since all CI's are narrow for all size classes for all three species investigated in this study. Even though the T90 135-mm codend reduced the release (i.e., increased catch efficiency) of cod, haddock, and saithe above the MRL by 4.4%, 14.1%, and 16.0%, respectively, compared with the compulsory configuration, the actual catch efficiency was still low (Table 3). Compared with the compulsory configuration, the T90 135-mm codend increased the retention rate for cod above the MRL from 80.4% to 84.8%, for haddock from 45.2% to 59.3%, and for saithe from 59.7% to 75.7% (Table 2). Thus, especially for haddock and saithe, the retention rate of fish above the MRL is still low even though the T90 135-mm codend demonstrated the largest improvement compared with the compulsory configuration. Optimally, size selection should be as accurate as possible so that few fish below the MRL are retained and few fish above the MRL escape (i.e., a *L50* equal to the MRL and a narrow *SR*). A major issue that makes it difficult to optimize catch efficiency for all three species simultaneously is the difference in the MRL. According to legislation, the MRL above 62°N is 44 cm for cod, 40 cm for haddock, and 45 cm for saithe (Ministry of

Trade, Industry and Fisheries, 2020). Moreover, although the three different species belong to the same family (Gadidae), they have a slightly different morphology (e.g., widest circumference in relation to length and, thus, different size selective limits, with haddock and saithe being the slimmest). Given that cod is the most important and abundant species fished in the Barents Sea, the management authorities have decided to set the minimum mesh size and grid bar spacings in compliance with the MRL for cod (Yaragina et al., 2011; Ministry of Trade, Industry and Fisheries, 2020).

Hence, to optimize size selectivity for these three gadoid species, future studies could focus on using behavioral differences. For instance, because some results have demonstrated that cod tend to escape downward, whereas haddock tend to escape upward, one could test a flexigrid with a lower bar spacing in the upper grid. Moreover, some trials indicated that the effect of turning the meshes 90° is reduced over time because of the stretching of the material. Another way of forcing meshes to remain open during towing is by shortening the lastridge ropes (Ingolfsson and Brinkhof, 2020), although this requires further study. Removing the grid and improving size selectivity in the codend would cause a cleaner and simpler trawl configuration, mitigating some of the issues previously discussed. Also, from both a fisheries and management perspective, it is important that the size-selective system should not lose fish above the MRL because this would otherwise lead to increased fishing effort and, thus, greater fuel consumption, seabed impact, and higher amounts of nontarget bycatch. It is also important that size selectivity is not comprised (i.e., catches below the MRL exceeding the legal limits) and that the size selective system is easy to mount and to check by the management authorities enforcing the law at sea. Moreover, to avoid selectivity during haul-back and at the surface, which is likely to cause unintended mortality, it is important to document where and when the size selectivity in T90 codends occurs (Madsen et al., 2008, 2012; Grimaldo et al., 2009; Herrmann et al., 2013).

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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