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Size selectivity and catch efficiency of bottom trawl with a double sorting grid and diamond mesh codend in the North-east Atlantic gadoid fishery

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ABSTRACT

This study investigated the size selectivity and catch efficiency in the North-east Atlantic demersal trawl fishery targeting cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). The use of a sorting grid followed by a size selective codend is compulsory in this fishery. Experimental fishing was conducted with a commercially rigged trawl, flexigrid section, and diamond-mesh codend. The flexigrid section is a dual sorting system and all fish that escaped from the two grids in the flexigrid system and the codend were retained in separate covers. This allowed us to estimate the combined size selectivity of the system, as well as the separate contributions from the first grid, second grid, and codend. The catch efficiencies for cod and haddock below and above the minimum reference length (MRL) were quantified by estimating the values for a set of exploitation pattern indicators. The results showed that most fish escaped from the flexigrid section. Only a few fish below the MRL entered the codend and nearly all of them subsequently escaped through the codend meshes. The probability of retaining undersized cod and haddock was low with the combined system. Furthermore, the results showed that the probability of escape was high through the second grid in the system for fish above the MRL, and this finding was supported by the exploitation pattern indicators. In particular, the estimated exploitation pattern indicators showed that using the current MRL and the fish size distributions encountered during the trials, no haddock and only 2.3 % of cod below the MRL were retained by the gear. However, 77.4 % of the haddock and 16.0 % of the cod above the MRL were found to escape, thereby indicating poor catch efficiency, especially for haddock. These results demonstrate the importance of supplementing size selectivity research with estimates of the actual catch efficiency using the gear employed, which were quantified using exploitation pattern indicators in this study.

1. Introduction

Several types of size and species selective processes take place during trawling. Some of these are unintended, e.g., escape under the fishing line (Ingólfsson and Jørgensen, 2006; Brinkhof et al., 2017a,b), whereas others aim to manipulate the species (Engås and Godø, 1989; Krag et al., 2010) and size (Sistiaga et al., 2010, 2016) composition in the codend catch, e.g., various sorting grids and codend mesh sizes. The aim of manipulating the size and species composition in the catch from a trawl is to mitigate the bycatch of unwanted species and/or of juvenile fish belonging to commercial species below the minimum reference length (MRL). In the North-east Atlantic bottom trawl fishery, the MRL values for cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) are 44 cm and 40 cm, respectively. The compulsory gear configuration includes the use of a codend with a minimum mesh size of 130 mm and a sorting grid section with grid(s) at a minimum bar-spacing of 55 mm. Currently, the regulations allow the use of three different types of grids; Sort-X (Larsen and Isaksen, 1993), which is rarely used due to its large size and heavy weight, Sort-V (Jørgensen et al., 2006), and the flexigrid (Sistiaga et al., 2016). Due its low weight and maneuverability, the flexigrid is the most widely used grid system in the fishery at present. Unlike Sort-V, which comprises a single steel grid and offers a single escape opportunity for fish, the flexigrid comprises two flexible grids and it enables a dual sequential size selection process (Fig. 1a). The size selection process in the grid section has two components because it comprises two separate grids, and it is also sequential because only fish that do not escape through the first grid can have an opportunity to escape through the second grid. In addition to offering the first

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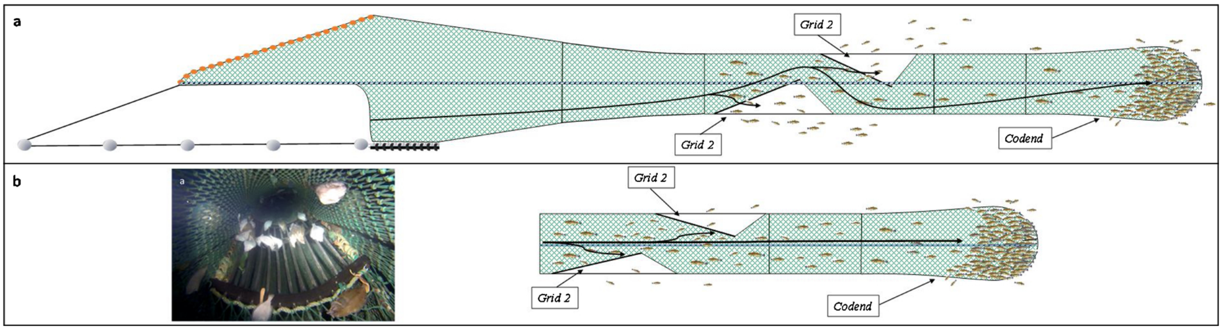

Fig. 1. Trawl rigging used in the Barents Sea gadoid fishery with a flexigrid and diamond mesh codend (a). The arrows illustrate the paths of fish with a correctly mounted flexigrid (a), and a flexigrid with a reduced inclination angle (b).

possibility of escape for fish, the first grid simultaneously operates as a lifting panel toward the second grid, which should increase the probability of fish making contact with the second grid (Fig. 1a) (Grimaldo et al., 2015). The flexigrid system is also designed to exploit the species-specific behavior of fish, i.e., cod are generally considered to try to escape downward whereas haddock tend to escape upward (Krag et al., 2010; Winger et al., 2010; Sistiaga et al., 2016).

The dual size selection performance of the flexigrid was investigated previously by Sistiaga et al. (2016). However, Sistiaga et al. (2016) did not consider the selective process in the codend, which occurs after the fish has passed through the flexigrid section in the gear. Therefore, the total size selectivity process comprises a sequence of three processes. Sistiaga et al. (2016) showed that large proportions of cod and haddock below the MRL were not released through the flexigrid, and thus, they entered the codend. However, the probability of escape from the codend for these fish has yet to be quantified, which implies that the total size selectivity of the flexigrid combined with a legal codend is unknown. A possible explanation for the large proportions of fish below the MRL reported in Sistiaga et al. (2016) that are not size selected in the flexigrid section, is the free passage that was observed between the two grids (Fig. 1b). In order for the flexigrid section to sort fish efficiently, the fish that enter this section need to make selectivity contact with at least one of the two grids in the system. A higher degree of selectivity contact is more likely to be ensured if the possibility of free passage (passing through the grid section without actually hitting any of the grids) through the grid is minimized. High grid inclination angles prevent free passage because the spaces between the netting panels in the section and the grids are reduced, thereby forcing fish to actively change their swimming direction to avoid contact with the grids (Fig. 1a). Contrary, low inclination angles increase the likelihood of free passage because the spaces between the netting panels in the section and the grids are larger (Fig. 1b). A common claim amongst fishers is that well-used flexigrid sections (as the one applied in Sistiaga et al. (2016)) release less fish than new flexigrid sections. A possible mechanism for this is that hauling large catches onboard will cause the meshes in the flexigrid section to stretch, which will result in a permanently larger mesh size and length. Given that the grids are mounted over a length of ca. 3.7 m (23½ meshes by 160 mm mesh length), a minor increase in mesh length size would cause a lower grid angle than the intended 25°, subsequently reducing contact probability and the release efficiency for fish.

Estimating the size selectivity of a specific type of gear alone does not give a complete assessment of whether it is well suited for a certain fishery. Achieving an acceptable exploitation pattern for fish stocks depends on the size selective properties of the gear, but also on the size structure of the fish population available in the fishing grounds. Exploitation pattern indicators can supplement size selection estimates (Wienbeck et al., 2014) by providing quantitative information about the suitability of gear for the specific fishing situation in terms of the capture pattern and efficiency. This information can then allow a detailed quantitative evaluation of the exploitation pattern and capture efficiency for the most common gear in the North-east Atlantic bottom trawl fishery.

Considering the issues mentioned above, the present study investigated the performance of a gear setup comprising a flexigrid and legal diamond mesh codend in order to address the following research questions: i) What are the individual contributions of the flexigrid and legal diamond mesh codend to the overall size selectivity of the gear setup used in the North-east Atlantic gadoid fishery? ii) What is the catch efficiency of fish above and below the MRL for the compulsory size selective sorting device used in this fishery? iii) Is there any difference in the size selective performance of a new flexigrid section with the intended grid angles of 25° and a well-used section with lower grid angles?

2. Material and methods

2.1. Study area, trawl rigging, and data collection

Fishing trials were conducted in the southern North-east Atlantic off the coast of North Norway between February 27 and March 15, 2018. The trials were conducted onboard the research vessel R/V "Helmer Hanssen" (63.8 m length overall, 4080 HP). The trawl setup comprised a pair of Injector Scorpion otter boards (3100 kg and 8 m^2), followed by 3 m long backstraps, which were connected to the sweeps by 7 m (diameter (Ø)19 mm) long chains. The sweeps were 60 m long with a Ø53 cm bobbin inserted in the middle to mitigate excessive abrasion on the them. The 46 m long ground gear comprised 18.9 m long rockhopper gear in the middle with Ø53 cm rubber discs, followed by a 14 m long chain (Ø19 mm) with three bobbins (Ø53 cm) on each side of the rockhopper gear. The trawl employed was a two-panel Alfredo No. 3, built of 155 mm (nominal mesh size) polyethylene (PE) meshes. The opening of the trawl has a circumference of 420 meshes, a fishing line of 19.2 m long and a headline length of 36.5 m.

A two-panel flexigrid section, which is the most common configuration in the North-east Atlantic bottom trawl fishery, was inserted before the extension piece of the trawl (Fig. 2). The grids mounted in this section were 150 cm long and 95.5 cm wide, with a bar spacing of 55 mm, and they were mounted to maintain an angle of 25° while fishing (for further details of the construction of the flexigrid section, see Sistiaga et al., 2016). A 9.3 m long extension piece (59.9 meshes) with 100 meshes in circumference was inserted between the section with the flexigrid and codend. The 11 m long codend had a mesh size of 133 ± 5.1 mm (mean ± SD) and was made of knotted netting built from single Ø8 mm braided PE twine (Euroline Premium, Polar Gold) in the lower panel and double knotted Ø4 mm braided PE twine in the upper panel. The mean mesh size was estimated based on 80 measurements (2 rows of 20 meshes on each panel) following the guidelines in Wileman et al. (1996). A cover was mounted over each of the grids to capture fish that escaped through the grids (Fig. 2). To avoid blocking

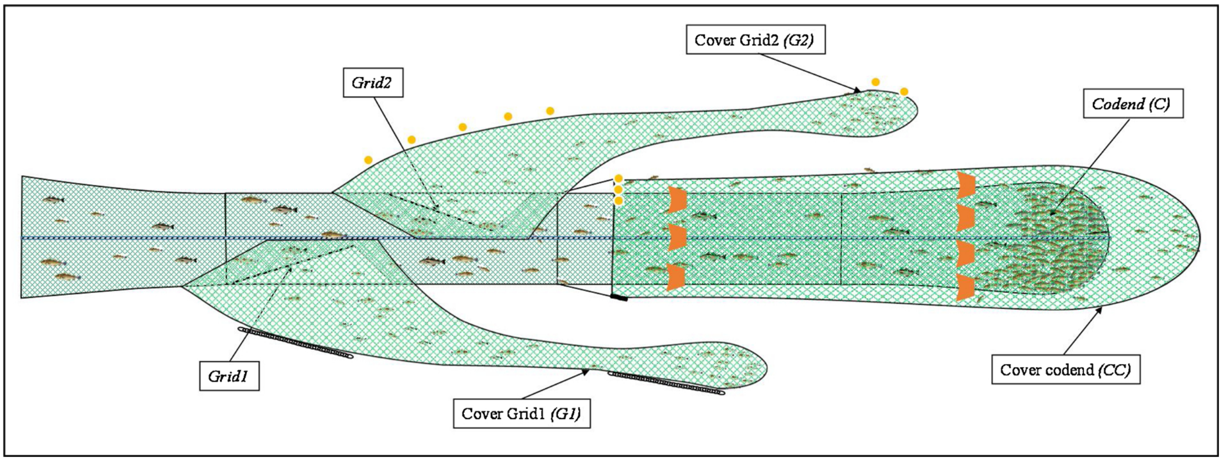

Fig. 2. Illustration of the experimental setup used in the trials.

fish passage through the grids, we attached longitudinal chains (2 × 5 kg) to the cover over the outlet of the first grid and seven floats (Ø200 mm) on the cover installed over the outlet of the second grid. Codend escapees were retained in a 20 m long cover, which covered the entire length of the codend. To keep the cover 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. In addition, 12 kites (tapered from 62 cm to 30 cm) were attached on the aft part of the cover to ensure sufficient clearance of the cover around the catch bulk in the codend. The nominal mesh size of all three covers was 50 mm and they were strengthened by an outer layer of larger mesh netting.

The trawl was monitored by Scanmar acoustic sensors measuring door spread, trawl height, and catch volume. The catch sensor was set to approximatley 2 metric tons and the towing durations were determined accordingly. The total length was measured to the nearest centimeter below for all the cod and haddock measuring above 20 cm retained in either the codend or any of the three covers.

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

Fish that entered the flexigrid section first entered the zone of the first grid (*Grid1*) (Fig. 2) and fish that did not escape through the first grid drifted further back into the zone of the second grid (*Grid2*), where they had an additional opportunity to escape. Thus, the size selection of the flexigrid can be regarded as a dual sequential process (Sistiaga et al., 2016). Only fish that did not escape through the first grid were exposed to the second grid. A fish that entered the flexigrid section only entered the codend if it did not escape through either the first or second grid. Fish that entered the codend had a final chance to escape through the codend meshes. Hence, the combined fish retention for the flexigrid and codend can be modeled by:

$$r_{combined}(l) = 1.0 - e_{Grid1}(l) - e_{Grid2}(l) - e_{Codend}(l) \tag{1}$$

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

Similar to other previous studies of sorting grids (Sistiaga et al., 2010; Larsen et al., 2016, 2018), the size selection process for the fish that contacted the first grid was modeled 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 it 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 contact with the grid, the *CLogit* model assumes a traditional *Logit* size selection model (Wileman et al., 1996) defined by the parameters *L50* (length at which the fish has a 50 % chance of escaping through the grid) and *SR* (difference between the lengths at which a fish has 75 % and 25 % chances of escaping through the grid). Thus, $e_{Grid1}(l)$ was modeled by:

$$e_{Grid1}(l, \boldsymbol{v_{Grid1}}) = \frac{C_{Grid1}}{1 + \exp(\frac{\ln(9)}{SR_{Grid1}} \times (l - L50_{Grid1}))} \tag{2}$$

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 $e_{Grid2}(l)$:

$$e_{Grid2}(l, \boldsymbol{v_{Grid1}}, \boldsymbol{v_{Grid2}}) = \frac{C_{Grid2}}{1 + \exp(\frac{\ln(9)}{SR_{Grid2}} \times (l - L50_{Grid2}))} \times (1.0 - e_{Grid1}(l, \boldsymbol{v_{Grid1}})) \tag{3}$$

where $\boldsymbol{v_{Grid2}} = (C_{Grid2}, L50_{Grid2}, SR_{Grid2})$. For the second grid, Eq. (3) 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, so $e_{Codend}(l)$ was modeled based on the *Logit* size selection model (similar to that used by Sistiaga et al. (2010)):

$$e_{Codend}(l, \boldsymbol{v_{Grid1}}, \boldsymbol{v_{Grid2}}, \boldsymbol{v_{codend}}) = \frac{1}{1 + \exp(\frac{\ln(9)}{SR_{codend}} \times (l - L50_{codend}))} \times (1 - e_{Grid1}(l, \boldsymbol{v_{Grid1}})) \times (1 - e_{Grid2}(l, \boldsymbol{v_{Grid1}}, \boldsymbol{v_{Grid2}})) \tag{4}$$

where $\boldsymbol{v_{Codend}} = (L50_{Codend}, SR_{Codend})$. For codend escape, Eq. (4) accounts for the condition that the fish has not previously escaped through the first or second grid.

We used Eqs. (1)–(4) to model the size selection in the combined size selection system comprising a flexigrid followed by a diamond mesh codend. Modeling was performed separately for cod and haddock.

2.3. Data analysis and parameter estimation

Catch data were collected using the four-compartment experimental design shown in Fig. 2, which included the codend (*C*), cover over the first grid (*G1*) to collect fish that escaped through the first grid, cover over 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 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

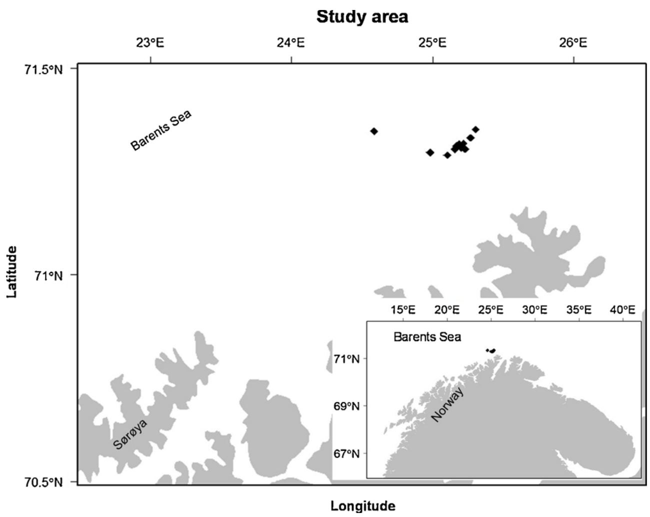

Fig. 3. Map of the area where the 12 trawl hauls were conducted.

minimizing the following function with respect to the parameters $\boldsymbol{v}_{\boldsymbol{Grid}1}$, $\boldsymbol{v}_{\boldsymbol{Grid}2}$, and $\boldsymbol{v}_{\boldsymbol{codend}}$ in the model comprising Eqs. (1)–(4):

$$-\sum_{j=1}^{m}\sum_{l}\{nC_{lj}\times ln(r_{combined}(l,\ \boldsymbol{v}_{\boldsymbol{Grid}1},\ \boldsymbol{v}_{\boldsymbol{Grid}2},\ \boldsymbol{v}_{\boldsymbol{codend}}))$$
$$+\ nG1_{lj}\times ln(e_{Grid1}(l,\ \boldsymbol{v}_{\boldsymbol{Grid}1}))+nG2_{lj}\times ln(e_{Grid2}(l,\ \boldsymbol{v}_{\boldsymbol{Grid}1},\ \boldsymbol{v}_{\boldsymbol{Grid}2}))$$
$$+\ nCC_{lj}\times ln(e_{Codend}(l,\ \boldsymbol{v}_{\boldsymbol{Grid}1},\ \boldsymbol{v}_{\boldsymbol{Grid}2},\ \boldsymbol{v}_{\boldsymbol{codend}}))\} \tag{5}$$

where the inner summation is over the length classes l in the experimental data and the outer summation is over the experimental fishing hauls j (from 1 to m).

Minimizing (5) with respect to its parameters is equal to maximizing the likelihood of the observed experimental data under the assumption that Eqs. (1)–(4) describe the multi-nominal 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 the model (Eq. (1)–(4) to describe the experimental data was evaluated based on the p-value, 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). The p-value expresses the likelihood of obtaining at least as large a discrepancy between the fitted model and the observed experimental data by coincidence. Data analysis was conducted using SELNET software (Herrmann et al., 2012, 2013).

We accounted for the uncertainties due to between-haul variation in size selection and catching a finite number of fish in the individual hauls by using a double bootstrap method to obtain Efron 95 % percentile confidence intervals (CIs) (Efron, 1982) for the parameters and the curves for Eqs. (1)–(4) (Sistiaga et al., 2010; Herrmann et al., 2012). We conducted 1000 bootstrap iterations for each species.

Based on the CLogit model and by inserting the values of the selection parameters for the first ($\boldsymbol{v}_{\boldsymbol{Grid}1} = (C_{Grid1},\ L50_{Grid1},\ SR_{Grid1}\ )$) and second ($\boldsymbol{v}_{\boldsymbol{Grid}2} = (C_{Grid2},\ L50_{Grid2},\ SR_{Grid2}\ )$) grids, we obtained the size selection curves for the two grids conditioned by the fish that arrived in the grid zones. Similarly, based on the Logit model and by inserting the values of the selection parameters for the codend ($\boldsymbol{v}_{\boldsymbol{Codend}} = (L50_{Codend},\ SR_{Codend}\ )$), we obtained the size selection curve for the fish that entered the codend. By incorporating this estimate into the bootstrap procedure described above, we also obtained the 95 % CIs for the standalone size selection curves for the two grids and the codend. The comparison between the results obtained by Sistiaga et al. (2016) and the results in the present study was done by investigating if there is overlap between the CIs.

2.4. Estimation of exploitation pattern indicators

To evaluate how the flexigrid combined with the codend would perform in the specific fishery situation, three exploitation pattern indicators nP–, $nP+$, and $dnRatio$ were estimated separately for cod and haddock using the catch data collected in the four compartments (Fig. 2). $nP-$ and $nP+$ quantify the retention efficiency for fish below and above the MRL (as percentages), respectively, whereas $dnRatio$ represents the discard ratio in numbers and it denotes 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 an evaluation of the catch performance of the selective system (Wienbeck et al., 2014). For the current selective system (flexigrid combined with codend) and experimental setup (Fig. 2), these indicators are given by:

$$nP- = 100\times\frac{\sum_j\sum_{l<MRL}(nC_{jl})}{\sum_j\sum_{l<MRL}(nC_{jl}+nG1_{jl}+nG2_{jl}+nCC_{jl})}$$
$$nP+ = 100\times\frac{\sum_j\sum_{l>MRL}(\mathrm{nC_{jl}})}{\sum_j\sum_{l>MRL}(nC_{jl}+nG1_{jl}+nG2_{jl}+nCC_{jl})}$$
$$dnRatio = 100\times\frac{\sum_j\sum_{l<MRL}(nC_{jl})}{\sum_j\sum_{l}(nC_{jl})} \tag{6}$$

where the sum of j is over the hauls and l is over the length classes.

Table 1
Overview of the hauls conducted showing the haul number, depth, towing time (Tt), and numbers of cod and haddock caught in each compartment.

			Number of cod				Number of haddock			
Haul No.	Depth (m)	Tt (hh:mm)	*nC*	*nG1*	*nG2*	*nCC*	*nC*	*nG1*	*nG2*	*nCC*
1	301	01:00	81	14	56	0	8	50	125	1
2	305	00:20	610	28	88	14	17	14	41	10
3	299	00:15	158	2	15	5	7	7	16	2
4	299	00:20	262	14	23	12	10	1	23	3
5	300	00:20	287	21	31	3	10	17	25	1
6	302	00:30	193	15	36	2	7	3	26	2
7	300	00:31	222	15	44	14	11	12	22	5
8	300	00:21	708	15	29	5	12	4	15	1
9	299	00:30	62	12	35	1	3	26	54	1
10	302	01:00	158	16	46	5	13	74	143	11
11	298	01:30	175	41	105	11	21	106	190	11
12	297	01:30	221	21	51	7	12	44	85	2

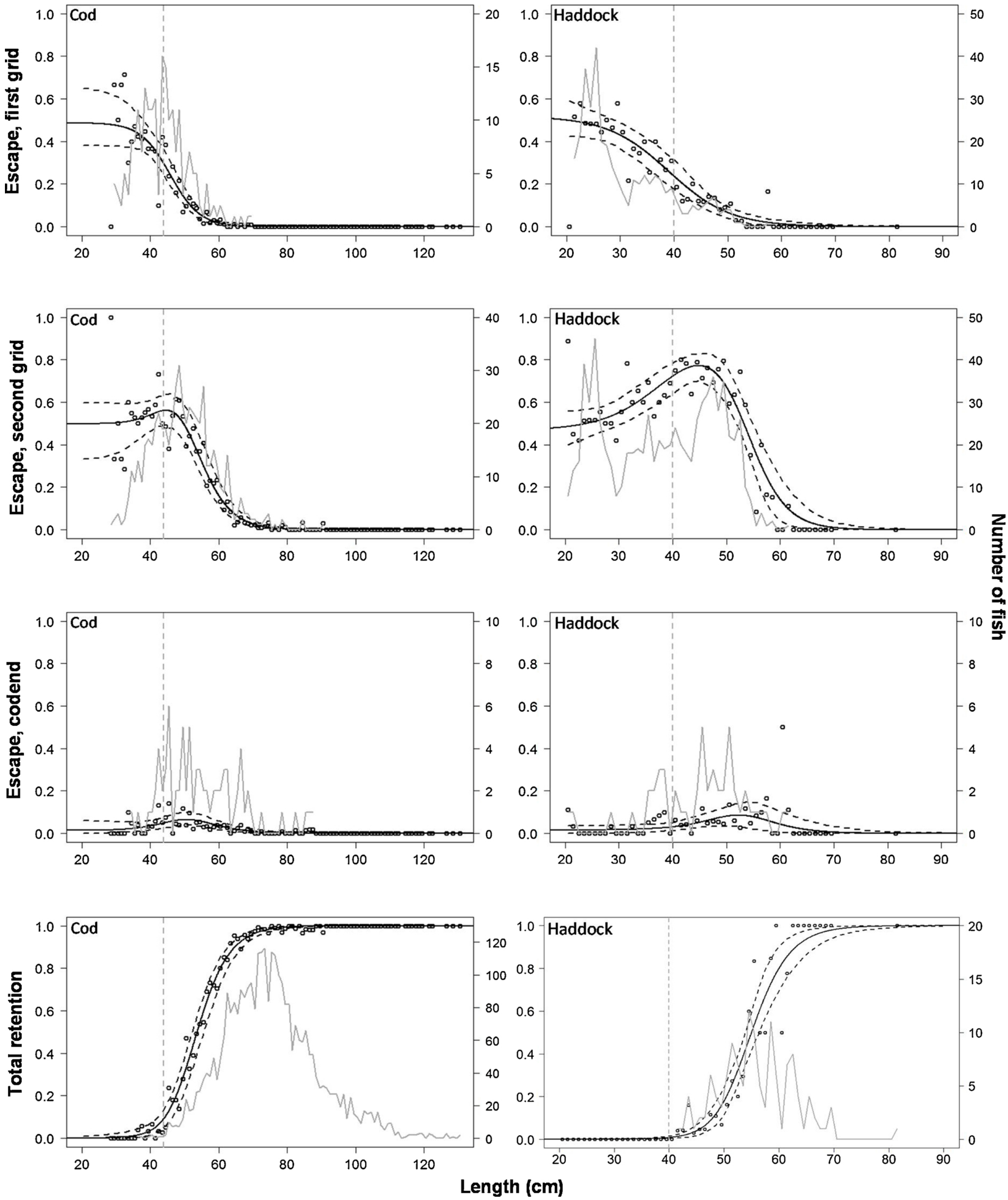

Fig. 4. Length-dependent probabilities of escape through the first grid, second grid, and codend, as well as the combined retention of both cod (left column) and haddock (right column). The solid curves represent the models fitted to the data (circles) with the 95 % CI's (stippled curves). The grey frequency curves represent the number of fish caught in each length class in each compartment. The stippled vertical grey lines denote the MRL for cod (44 cm) and haddock (40 cm).

Ideally, for a target species, *nP−* and *dnRatio* should be low (close to zero), whereas *nP+* should be high (close to 100 %), i.e., retain all individuals over the MRL that enter the codend.

Furthermore, to quantify the extents to which the first grid (*nPEgrid1–* and $nPEgrid1_{+}$), second grid (*nPEgrid2–* and $nPEgrid2_{+}$), and codend (*PEcodend–* and $PEcodend_{+}$) each contributed to the release of cod and haddock separately below and above the MRL, the following six relative release indicators (PE, Percentages of total Escape) were calculated directly based on the collected catch data.

Table 2
Selectivity results showing the *L50*, *SR*, and contact probability (C_{grid}) as well as the exploitation pattern indicator values for cod and haddock for the first grid, second grid, codend, and combined system. Values in parentheses represent 95 % CI's. The fit statistics show the *p*-value, deviance, and DOF for the two species.

	Cod	Haddock
$L50_{Grid\ 1}$ (cm)	46.0 (42.3–49.2)	39.1 (32.3–43.5)
$SR_{Grid\ 1}$ (cm)	9.5 (6.7–11.9)	12.6 (8.5–18.3)
$C_{Grid\ 1}$ (%)	48.7 (38.2–65.7)	53.0 (41.8–69.4)
$L50_{Grid\ 2}$ (cm)	51.8 (50.1–54.2)	53.8 (52.6–55.3)
$SR_{Grid\ 2}$ (cm)	11.3 (9.8–12.6)	7.8 (4.8–10.8)
$C_{Grid\ 2}$ (%)	97.3 (87.6–1.0)	96.8 (93.1–1.0)
$L50_{Codend}$ (cm)	39.8 (31.1–44.9)	46.3 (44.7–48.9)
SR_{Codend} (cm)	14.5 (10.2–20.7)	10.3 (6.4–16.2)
$L50_{Combined}$ (cm)	53.7 (52.3–55.7)	55.0 (53.9–56.4)
$SR_{Combined}$ (cm)	10.3 (9.2–11.2)	7.6 (5.2–9.8)
nP– (%)	2.3 (0.3–5.7)	0.0 (0.0–0.0)
nP+ (%)	84.0 (78.4–89.3)	22.6 (17.7–28.7)
dnRatio (%)	0.2 (0.0–0.4)	0.0 (0.0–0.0)
nPEgrid1– (%)	39.4 (32.7–48.1)	42.1 (37.4–48.1)
nPEgrid1+ (%)	17.5 (12.9–22.6)	11.8 (7.7–16.9)
nPEgrid2– (%)	56.2 (47.5–63.4)	55.9 (50.2–60.7)
nPEgrid2+ (%)	70.6 (64.5–76.3)	80.2 (73.9–85.7)
nPEcodend– (%)	4.4 (1.5–7.9)	1.9 (0.3–3.8)
nPEcodend+ (%)	11.9 (6.8–18.0)	8.0 (3.9–13.2)
p-value	0.84	0.04
Deviance	165.1	119
DOF	184	94

$$nPEgrid1- = 100 \times \frac{\sum_j \sum_{l<MRL} (nG1_{jl})}{\sum_j \sum_{l<MRL} (nG1_{jl} + nG2_{jl} + nCC_{jl})}$$
$$nPEgrid1+ = 100 \times \frac{\sum_j \sum_{l>MRL} (nG1_{jl})}{\sum_j \sum_{l>MRL} (nG1_{jl} + nG2_{jl} + nCC_{jl})}$$
$$nPEgrid2- = 100 \times \frac{\sum_j \sum_{l<MRL} (nG2_{jl})}{\sum_j \sum_{l<MRL} (nG1_{jl} + nG2_{jl} + nCC_{jl})}$$
$$nPEgrid2+ = 100 \times \frac{\sum_j \sum_{l>MRL} (nG2_{jl})}{\sum_j \sum_{l>MRL} (nG1_{jl} + nG2_{jl} + nCC_{jl})}$$
$$nPEcodend- = 100 \times \frac{\sum_j \sum_{l<MRL} (nCC_{jl})}{\sum_j \sum_{l<MRL} (nG1_{jl} + nG2_{jl} + nCC_{jl})}$$
$$nPEcodend+ = 100 \times \frac{\sum_j \sum_{l>MRL} (nCC_{jl})}{\sum_j \sum_{l>MRL} (nG1_{jl} + nG2_{jl} + nCC_{jl})} \quad (7)$$

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 is finite.

3. Results

3.1. Overview of sea trials

During the sea trials (Fig. 3), we conducted a total of 12 hauls, and measured the lengths of 3989 cod and 1304 haddock (Table 1).

3.2. Selectivity results

Both grids demonstrated large contributions to the escapes of cod and haddock below the MRL (Fig. 4). By contrast, the codend made minor contributions to the escapes of cod and haddock. Furthermore, the combined retention curves showed almost no retention of undersized cod and haddock, thereby demonstrating the high release efficiency of the system for both species (Fig. 4). The modeled escape probabilities for the target sizes of both species showed a high probability of escape through both grids, but especially through the second grid in the upper panel. The codend also contributed to the release of cod and haddock above the MRL, although to a much lower degree than the grids. Furthermore, the overall retention curve shows a low overall retention probability for fish far above the MRL (Fig. 4).

Overall, the model used to describe the escape and retention of both species reflected the main trends in the experimental data well. For cod, this was supported by the fit statistics with a *p*-value of 0.84 (Table 2). For haddock, the *p*-value was 0.04, but this low value was most likely due to a few large fish found in the codend cover. Furthermore, investigating the data showed that during the first three tows, two exceptionally large haddock (60 and 61 cm) and three large cod (82, 85, and 86 cm) were retained in the codend cover (Fig. 4). These fish probably escaped through a broken mesh in the aft of the codend immediately in front of the cod-line, which was detected and fixed after the third tow. It is also possible the fish could have entered the codend cover from the outside, however this is unlikely as the opening in the front of the codend is small. After reanalyzing the data without these large individuals, the fit statistics improved significantly with no significant deviance difference between the model and experimental data for haddock ($p > 0.05$).

The selectivity results showed that the contact probability values for the second grid were significantly larger than the values estimated for the first grid (Table 2). The *L50* values for the second grid were significantly larger than the values estimated for the first grid and the codend. The large values for the second grid were responsible for the high *L50* value determined for the overall selection system ($L50_{combined}$). Furthermore, the values demonstrated that large quantities of fish above the MRL escaped (Table 2). In particular, according to the estimated catch patterns, 84 % of cod and only 22.6 % of haddock above the MRL were retained. By contrast, only 2.3 % of cod and 0.0 % of haddock below the MRL were retained (Table 2). Compared with the first grid, the second grid released slightly more fish below the MRL. However, the majority of the fish above the MRL escaped through the second grid (Table 2). Among the fish above the MRL released by the gear, the second grid was responsible for 70.6 % of the cod and 80.2 % of the haddock that escaped. For fish below the MRL released by the gear, the second grid was responsible for 56.2 % of the cod and 55.9 % of the haddock that escaped. These results demonstrate that most of the releases occurred through the second grid which is installed in the upper panel of the flexigrid section, especially for fish above the MRL (Table 2).

3.3. Comparison with previous flexigrid selectivity studies

Sistiaga et al. (2016) studied the selectivity properties of a flexigrid system similar to that tested in the present study in the North-east Atlantic cod and haddock fishery. The results obtained in the present study and that conducted by Sistiaga et al. (2016) are compared in Fig. 5, which shows that both grids were more efficient at releasing fish above and below the MRL in the present trial. In particular, the difference in the release efficiency for the second grid was large, for both the fish above and below the MRL and for both cod and haddock. These differences demonstrate that the performance of the flexigrid system can be variable. The differences observed in the performance of the first grid were not as large as those for the second grid, but they were still significant for both species and for some sizes of fish above and below the MRL. Due to the difference in the size sorting performance obtained for the individual grids, the combined retention probability for the flexigrid section differed significantly for both cod and haddock and for fish above and below the MRL (Fig. 5).

This difference in the size selective performance was likely due to a difference in the grid angles. The design of a flexigrid section is

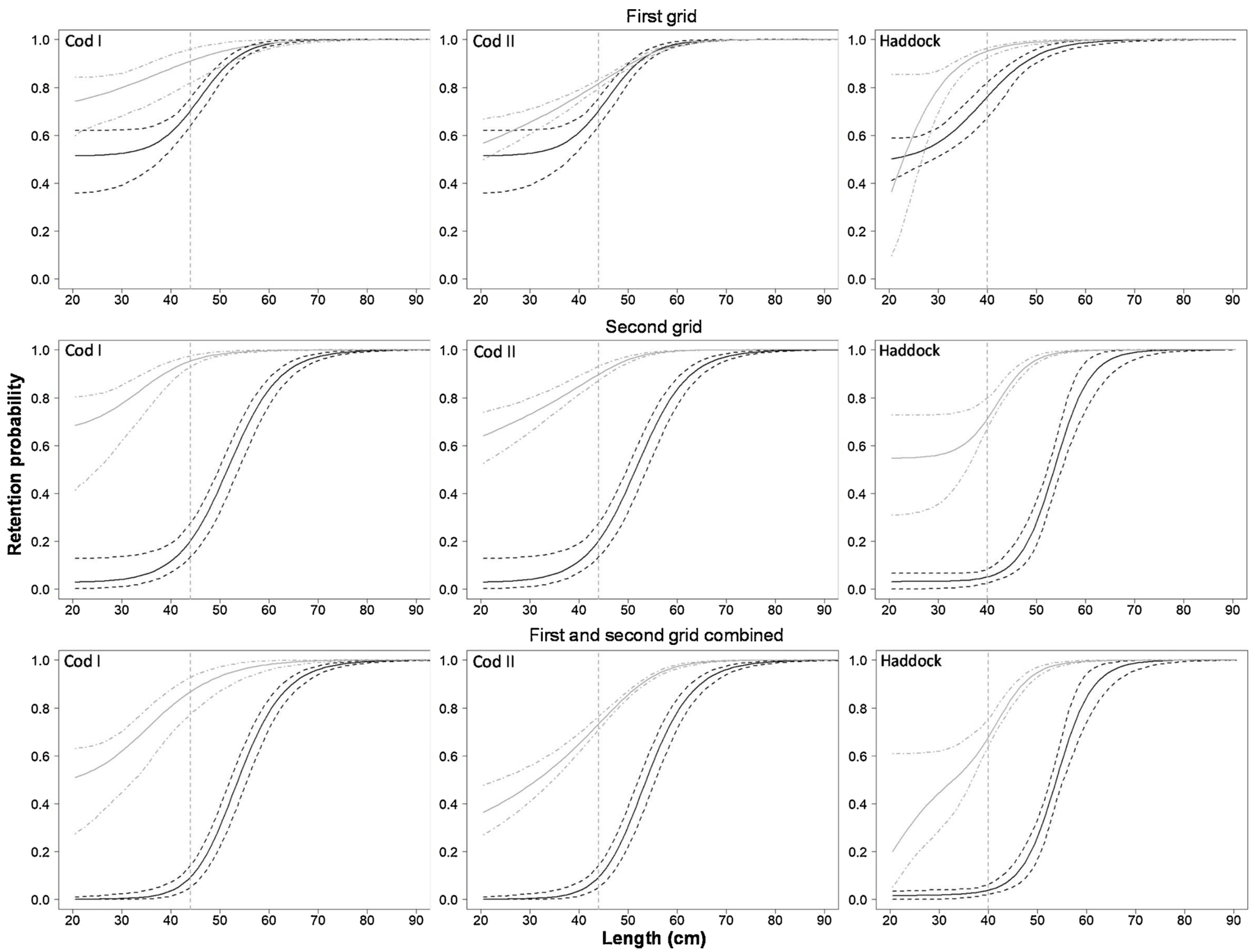

Fig. 5. Retention probabilities for the first grid, second grid, and both grids combined in the present study (black) compared with the results obtained by Sistiaga et al. (2016) (grey) from Bear Island (I) and Hopen (II). Stippled curves represent 95 % CI's. The grey vertical stippled lines represent MRL for cod (44 cm) and haddock (40 cm).

statutory regarding mesh size, circumference and length, grid angles, and grid design. Therefore, it is reasonable to expect that both flexigrid sections were initially identical. However, the flexigrid system in Sistiaga et al. (2016) had been well-used in commercial fishing operations with catches up to 30 000 metric tons, while the flexigrid section used in this study was new and was not exposed to catches above 5000 metric tons. As hypothesized, hauling large catches onboard can possibly cause the meshes to stretch permanently causing a reduction in the angle of the grids. Comparing footage from both studies revealed that the grids in the flexigrid section used in Sistiaga et al. (2016) had a lower angles of attack, which resulted in an opener passage in the section (Fig. 6a) than the flexigrid used in this study (Fig. 6b).

However, different fish entry rates may be a confounding factor. The average entry rates in this study and the study from Sistiaga et al. (2016) were 913.1 ± 701.2 and 3855.7 ± 3072.7 (mean ± SD) fish per hour of towing, respectively.

4. Discussion

The aim of size selectivity in trawls is to reduce the catch of juvenile fish and/or unwanted species, and this problem has been devoted much attention in recent decades (e.g., Walsh et al., 2002; Graham, 2010). Furthermore, several studies have investigated the performance of sorting grids in the North-east Atlantic gadoid fishery (e.g., Jørgensen et al., 2006; Sistiaga et al., 2008; Grimaldo et al., 2015; Sistiaga et al., 2016). However, for the first time, the present study determined the individual contributions and combined size selectivity of the grids and codend in the compulsory sorting system comprising a flexigrid and diamond mesh codend used in the North-east Atlantic cod and haddock fishery. In addition, exploitation pattern indicators were estimated for this fishery for the first time.

In general, the exploitation pattern indicator results showed that the gear comprising a flexigrid section and 130 mm diamond mesh codend retained very few fish below the MRL, demonstrating that the purpose of a grid, which is to release undersized fish, is fulfilled. However, the results also demonstrated that high numbers of fish above the MRL escaped the selection system with the flexigrid, where the second grid in the flexigrid was mainly responsible for escapes. The results obtained in this study demonstrate that in accordance with the regulations regarding size selectivity in force in the North-east Atlantic, no haddock and only 2.3 % of the cod below the MRL were retained. However, we estimated that 77.4 % of the haddock and 16.0 % of the cod above the MRL escaped. Thus, trawlers need to increase their fishing efforts in order to compensate for the loss of legal sized fish, which will entail greater fuel consumption with subsequent greenhouse gas emissions, increase interactions with the seabed, and likely results in higher non-target bycatch amounts. Hence, although size selectivity is important for ensuring the sustainable management of fish stocks, the low

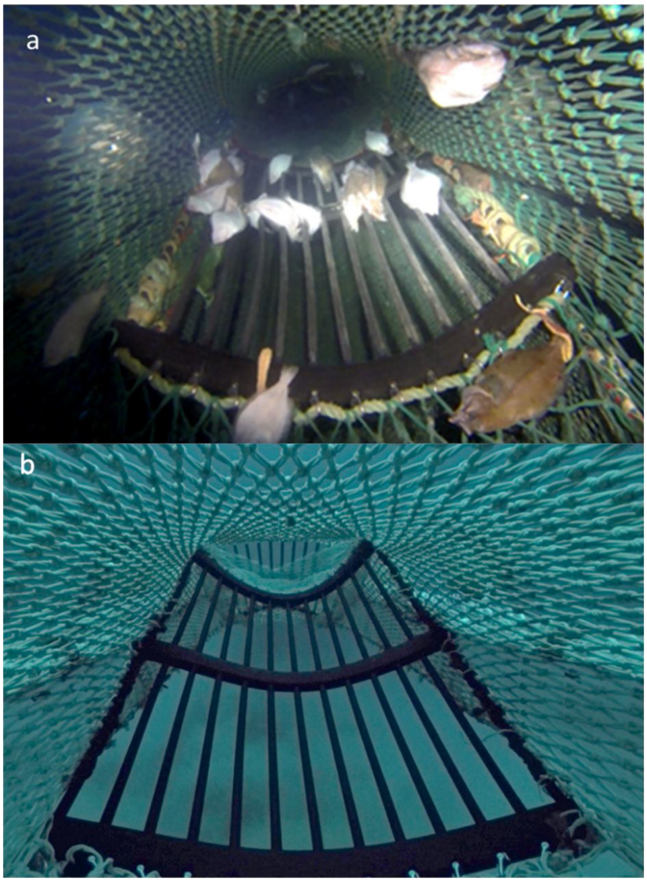

Fig. 6. Images illustrating the performance of the flexigrid section during the experiments conducted by Sistiaga et al. (2016) on a commercial vessel (a) and in the present study (b).

catching efficiency measured in this study implies negative impacts for both the fishing industry and the sustainability of the fishery. It should be noted that unlike selectivity parameter estimates, the indicator values depend on the size structure in the fishing area at the time experiments are conducted. Thus, our results could change if the structure of the fished population is altered. However, indicators are highly valuable because they provide a straightforward and insightful understanding of how gear performs in terms of the catch efficiency.

Several studies have concluded that cod and haddock exhibit distinct behavioral differences, where cod try to escape downward, whereas haddock tend to escape upward (Main and Sangster, 1981; Wardle, 1993; Beutel et al., 2008; Krag et al., 2010; Winger et al., 2010). However, our results indicated no differences in the grid contact of cod and haddock between the two grids. Similarly, Karlsen et al. (2018) and Melli et al. (2018, 2019) found no significant difference in the vertical distributions of cod and haddock in the aft of the trawl.

The present results clearly differed from the results obtained in a similar investigation (Sistiaga et al., 2016) of the size selectivity of a flexigrid system, although the previous study did not consider the codend selectivity. A comparison of the retention probabilities obtained for the flexigrid section in the present study and the results obtained by Sistiaga et al. (2016) indicates that the retention probabilities were significantly lower for both cod and haddock above the MRL in the present study. The results presented here also determined a significantly lower retention probability for fish below the MRL compared with Sistiaga et al. (2016). Both studies were conducted using the same method by collecting and measuring all of the escapees in the covers, and the same analysis methods were employed for estimating the size selectivity. However, the studies were conducted in different areas and seasons, and thus, differences in the water temperature, light conditions, depth, and the physiological condition of the fish could have potentially affected fish escapes (Engås and Ona, 1990; He, 1993; Michalsen et al., 1996; Krag et al., 2010). In addition, the catch density (entry rates) of fish, which is considered to influence fish escapes (Aglen et al., 1997; Godø et al., 1999), differed between the studies.

Factors such as unequal entry rates are confounding factors, and may have partially contributed to the different results obtained compared with previous studies, but the most likely explanation is the difference in the inclination angles of the grids between the two cruises. The visual comparison of the grid angles presented in the results showed that the angle of the grids was low in the cruise reported by Sistiaga et al. (2016) compared with the angle applied in the present study. Using higher grid angles made it increasingly difficult for fish to pass through the section by following a horizontal path and without hitting at least one of the grids. The difference between the grid sections in the two cruises is evident and it probably explains the higher grid contact values observed in the present study compared with that conducted by Sistiaga et al. (2016). This potential explanation for the difference in the size sorting efficiency between the flexigrid sections may also account for the differences in the size selection properties obtained with other types of sections when they are expected to be similar (i.e., the study by Larsen et al. (2018) compared with that by Sistiaga et al. (2010)). These results demonstrate that the grid inclination angles in grid sections such as the flexigrid system can differ considerably, which is of concern given the possible impacts of different grid angles on size selectivity. Thus, the development of methods to make the performance of grid sections less variable should be considered in future studies. Such an improvement could include applying chains or non-flexible Dyneema ropes to prevent the grid section to change geometry which may alter size selective performance after being subjected to rough handling and forces from large catches. Also, future studies should test different bar spacing in both the lower and upper grid in order to reduce the loss of fish above the MRL.

CRediT authorship contribution statement

Jesse Brinkhof: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft. **Roger B. Larsen:** Conceptualization, Data curation, Methodology, Writing - original draft. **Bent Herrmann:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing - original draft. **Manu Sistiaga:** Conceptualization, Data curation, Investigation, Methodology, Writing - original draft.

Declaration of Competing Interest

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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