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Effect of grid section design on trawl size selectivity

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A B S T R A C T

Sorting grids are introduced in trawl fisheries to improve size selectivity and reduce the variability of results obtained with sorting devices constructed of netting e.g., codends. Grids are rigid or semi-rigid structures where the bar spacing defines the sizes of fish that can pass through. However, for size selection to occur, fish need to be oriented towards the grid in specific ways, which may depend on the netting construction where the grid is installed. In the Barents Sea gadoid trawl fishery, fishermen are allowed to use different netting configurations within the same type of grid, but it is unclear to which degree the performance of sorting grids depends on the construction characteristics of the netting section where they are installed. This study compares the size selective properties of a steel grid mounted in three different netting section configurations: 2-panel section, 4-panel section, and 4-panel section with a modified lifting panel. Overall, the results of the study demonstrate that the 2-panel configuration performs better than the two 4-panel configurations tested. The differences were smaller when the 2-panel and the 4-panel section with a modified lifting panel were compared. Specifically, the grid contact probability for haddock with the 2-panel configuration was 0.92 (0.90 – 0.95) and significantly higher than for the 4-panel configuration, which was estimated to be 0.82 (0.77 – 0.89). For cod, the grid contact probability between the different configurations did not vary more than 6% and the differences were not significant. The 4-panel configuration led to significantly higher retention of cod between 40 to 60 cm and haddock between 20 and 54 cm than the 2-panel configuration. The results also show that despite having been assumed to provide constant size selectivity, the performance of sorting grids is sensitive to relatively small design changes in the section where they are mounted.

1. Introduction

Trawls are very diverse and represent one of the most important fishing gears worldwide (Valdemarsen, 2001; Watson and Tidd, 2018). Their popularity arises from the fact that they are very adaptable, robust and efficient. However, the application of this gear is not exempt of challenges and controversy. In addition to issues related to energy consumption and seabed disturbance (Tyedmers, 2001; Schau et al., 2009; Eigaard et al., 2017), trawls have often been criticized for their poor and unpredictable size selective properties (e.g., Lucchetti et al., 2021).

Selectivity in trawls has been widely studied in the last four decades and most of the research carried out has focused on the intermediate section of the trawl or the codend (Kennelly and Broadhurst, 2021). Codend size selectivity has been demonstrated to vary because as the catch builds up, the increasing longitudinal forces in the meshes in the codend change their shape and consequently their selective properties as well (Herrmann, 2005a,b; Herrmann and O'Neill, 2005). Therefore, in the pursuit of more constant selectivity results i.e., equal selectivity performance of the gear independent of varying factors like fish entry density in the gear or catch size, the authorities of different countries have considered, and in some cases implemented, codend mesh geometries different to diamond meshes (e.g. Wienbeck et al., 2011) and additional devices to supplement codend size selectivity (e.g. Herrmann et al., 2015; Cuende et al., 2020; Sistiaga et al., 2008; Brinkhof et al., 2020).

Norway and Russia implemented the compulsory use of sorting grids in the Barents Sea gadoid fishery in 1997 (Larsen and Isaksen, 1993; Larsen et al., 2018). Today, fishermen participating in this fishery can use three different types of grids, the Sort-X, Sort-V and flexigrid (Herrmann et al., 2013a), all installed in the extension piece in front of the codend. Fishermen can

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choose freely between the different types of grids and a recent questionary handed out to fishermen in this fishery showed that the flexigrid is the preferred grid type with >90% of the fishermen using it at least at times during the year. The Sort-V grid is the next most used alternative as the Sort-X is practically not used today. Sorting grids are rigid or semi-rigid structures expected to provide constant size selection as bar spacing in principle defines whether each individual entering the trawl can or cannot escape. However, the fish need to interact with the grid with a certain orientation, which will be influenced by the construction characteristics of the netting panels in which the grid is located. In Norway, grids can be mounted in netting sections constructed of 2- or 4-panels, but most of the fleet uses the more traditional 2-panel construction (Personal communication, Hermann Pettersen, Norwegian Directorate of Fisheries). While the regulations are strict regarding specifications like the size of the grid, grid angle or minimum bar spacing, fishermen can choose between different netting section designs to mount the grid. It is unclear how sensible the performance of the grid section is to the design of the netting section where it is mounted and if fish are presented to the grid in the same way with the different designs. Therefore, the current study compares the size selection of a specific sorting grid but installed in different section designs.

Most fisheries around the world are managed by regulations that include minimum legal sizes (*MLS*) for the target species and potential bycatch species i.e., for each particular species, the regulations allow capture of animals over its *MLS*, whereas animals below *MLS* should be released. When a size sorting device is sensitive to changes in its construction or the surrounding conditions and cannot produce constant size selectivity results, it becomes challenging to comply with management objectives, especially when these are based on *MLS*. Cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) are the main species targeted in the gadoid trawl fishery in the Barents Sea with *MLS*s of 44 and 40 cm, respectively. Different fish species can act differently when they are surrounded by the trawl netting, and these two species have earlier been reported to enter the trawl at different positions in the gear and behave differently in the aft of the trawl (Main and Sangster, 1981, 1982; Valdemarsen et al., 1985; Engås et al., 1998; Sistiaga et al., 2016). Therefore, it is likely that changes in grid section construction can influence the selectivity of different species differently.

Earlier studies have stated the importance of the lifting panel to ensure a high level of interaction between fish and the grid (Grimaldo et al., 2015) and differences between similar grid constructions built of 2- and 4-panels (Sistiaga et al., 2016). In studies carried out with the flexigrid, Sistiaga et al. (2016) reported that a 4-panel construction provided better size selectivity results than a 2-panel construction, whereas Brinkhof et al. (2020) reported that the size selectivity performance of a 2-panel is better than that of a 4-panel section. This demonstrates that it is unclear which of the two construction types should be selected. However, controlled experiments to evaluate how these types of changes simultaneously applied to a sorting grid section can potentially affect its size selectivity have not been carried out. In 2016, the Norwegian regulations incorporated the use of a 4-panel Sort-V section as a legal alternative to the original 2-panel Sort-V version for the Barents Sea gadoid fishery (Fig. 1) because the increased water flow in 4-panel sections compared to 2-panel sections was believed could improve the performance of the grid (Gjøsund et al., 2013; Grimaldo et al., 2015). The 4-panel Sort-V construction was not prior to this point tested at sea nor directly compared to the original 2-panel version. Using this change in the regulation as base, the aim of the present study was to investigate the sensitivity of grid sections to changes in construction. The research carried out aimed at answering the following questions:

- Does a Sort-V grid section result in constant size selectivity independent of the netting being constructed of 2- or 4-panels?
- Do additional changes in the lifting panel contribute to making size selectivity results more constant?
- How do the different constructions tested perform considering the management objectives in the fishery?

2. Materials and methods

2.1. Experimental design and data collection

The Norwegian trawler fleet operating in the Barents Sea is composed by 36 vessels between 40 and 80 m targeting mainly cod and haddock. Other important bycatch species would be saithe (*Pollachius virens*), redfish (*Sebastes* spp.) and Greenland halibut (*Reinhardtius hippoglossoides*). According to the legislation, all vessels participating in this fishery are obliged to use a sorting grid with a minimum bar spacing of 55 mm in the extension piece of the trawl and a codend with a minimum mesh size of 130 mm, which is normally constructed of diamond meshes.

Experimental fishing was conducted onboard the R/V "Helmer Hanssen". We used an Alfredo 3 trawl built of two panels with 420 meshes in circumference. The netting used was made of 4 mm polyethylene (PE) twine and the nominal size of the meshes in the trawl was 155 mm. In addition to the trawl, we employed a set of Injector Scorpion otter boards (weighing 3100 kg, and an area of 8 m^2 each) connected by 60 m long sweeps with 3 m long backstraps followed by 7 m long connector wire. To protect the sweeps from excessive abrasion a Ø53 cm steel bobbin was inserted in the middle of the sweeps. The ground gear used was 46 m long and comprised of 18.9 m long rock-hopper gear (Ø53 cm) in the middle and a 14 m long (Ø19 mm) chain with three equally spaced steel bobbins (Ø53 cm) in each of the sides. The rock-hopper gear was attached to the 19.2 m long fishing line in the trawl. The headline of the trawl was 36.5 m long.

During the trials we tested a Sort-V sorting grid in three different netting configurations: a 2-panel section, which is the configuration mostly used by the fleet and was identical to the one described in the legislation (Fig. 1); a 4-panel section identical to the one described in the legislation (Fig. 2); and a 4-panel section with a modified lifting panel (Fig. 3). The reason for testing this third configuration was that the lifting panel has substantial differences between the 2- and 4-panel configurations, and it was speculated in advance that this could be a potential source for differences between the 2- and 4-panel configurations. The section and grid used for the last two configurations was the same i.e., only the lifting panel was modified in the section. The grids in the two sections tested were identical in size (1650 × 1234 mm) and the bar spacings in them were measured to be 54.8 ± 1.1 mm (mean ± SD) and 55.4 ± 1.2 mm for the 2-panel section and 4-panel section (with and without the modified lifting panel), respectively. Due to that the trawl and codend we used were identical through the trials and constructed in 2-panels, a 2-to 4-panel transition section and a 4- to 2-panel transition section were applied in front and behind the grid section when the 4-panel grid section was employed (Figs. 2 and 3). When the 2-panel section was applied, extension pieces were used both in front and behind the grid section (Fig. 1) so that the length of the gear was as similar as possible in both cases.

After the grid section and the extension piece we attached a codend, which was 12 m long and had 60 meshes in circumference. The codend was built of single braided Ø8 mm hotmelt PE twine, with a mesh size of 133.8 ± 2.2 mm.

The experimental design followed the covered-gear method (Grimaldo et al., 2016). Thus, in all three configurations tested a

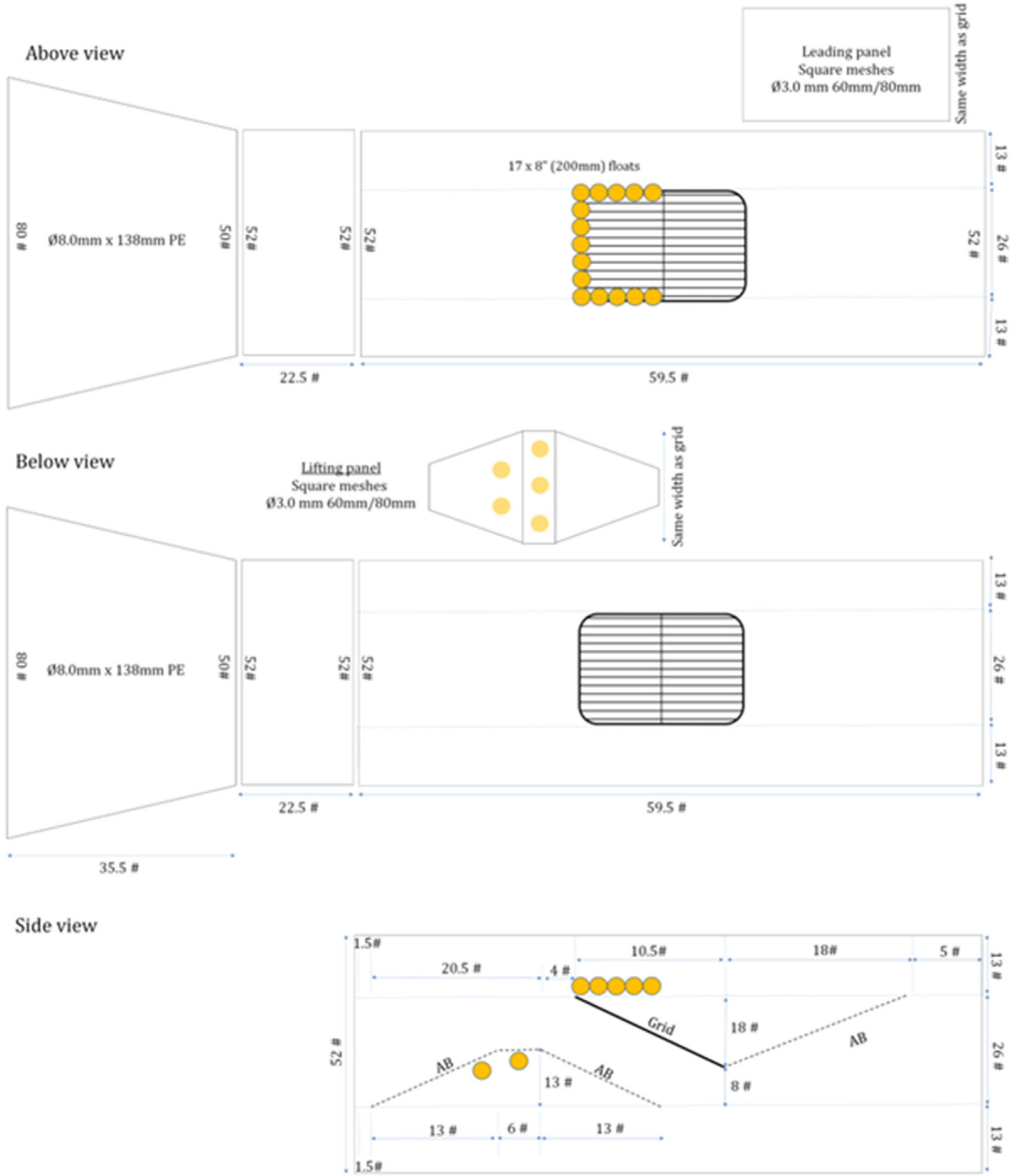

Fig. 1. Construction details of the 2-panel grid section.

cover was mounted over the grid to catch the escapees. The cover had an inner mesh size of 45.8 ± 1.5 mm and was reinforced with a large mesh netting to lower the risk of breakage. To keep the cover clear from the grid and avoid blockage seven floats were installed along the cover. Due to that only the selectivity of the sorting grid was relevant in the present study, the codend was blinded with an inner-net with a nominal mesh size of 40 mm and low hanging of approximately 0.2.

The trawl was monitored by acoustic sensors measuring door spread, trawl height, and catch volume. The latter was installed so that it would warn when the catch exceeded approximately 1.5 tons. The total length of all cod and haddock above 20 cm retained in either the codend or any of the covers was measured to the nearest centimeter below.

2.2. Data analysis

The size selection in the grid sections was modelled based on the *CLogit* model (Herrmann et al., 2013b), which accounted for that not necessary all fish entering the grid section contacted the grid:

$$CLogit\left(l, C_{grid}, L50_{grid}, SR_{grid}\right) = 1.0 - \frac{C_{grid}}{1.0 + exp\left(\frac{ln(2.0)}{SR_{grid}} \times \left(l - L50_{grid}\right)\right)} \quad (1)$$

Only the fish contacting the grid is subjected to a size-dependent probability for escaping through it. In the *CLogit* model, l denotes fish length and parameter C_{grid} quantifies the assumed fish length-independent probability for a fish entering the grid zone to

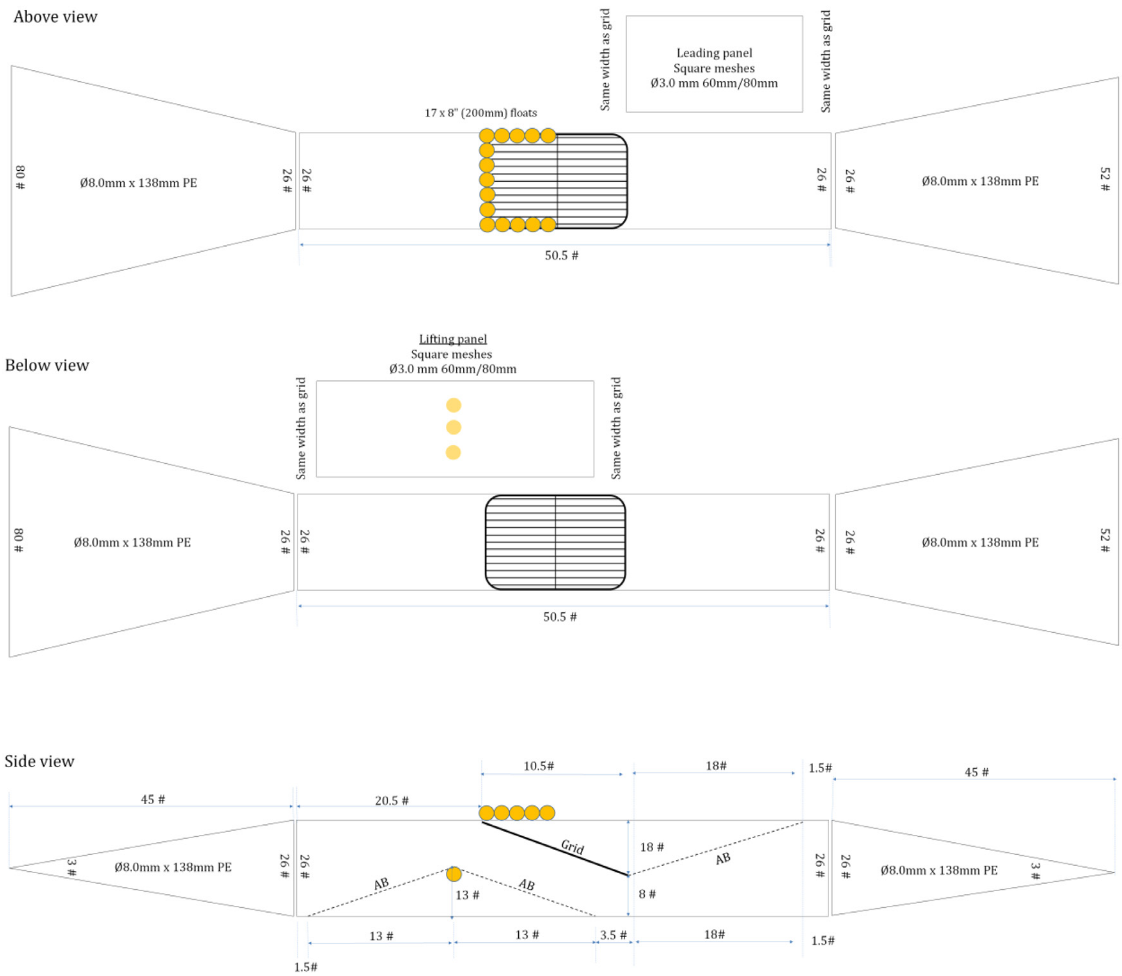

Fig. 2. Construction details of the 4-panel grid section.

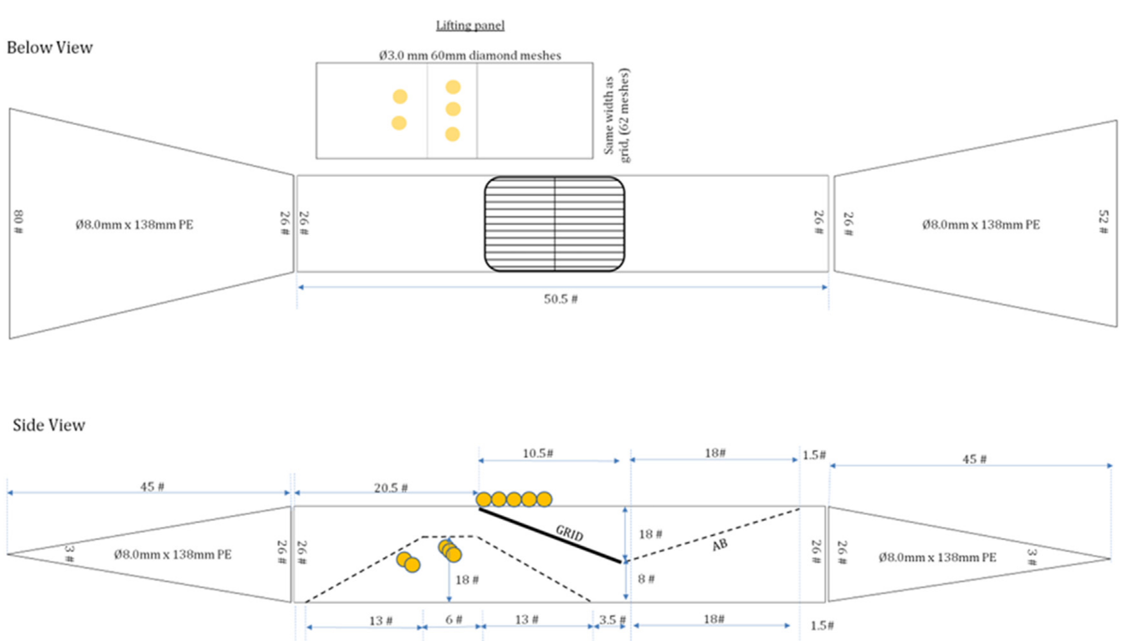

Fig. 3. Construction details of the modified 4-panel grid section.

also contact it in a way that provides it with a length-dependent probability for escaping through the grid. The parameter C_{grid} undertakes a value between 0.0 and 1.0, where a value at 1.0 would mean that every fish entering the grid zone would contact the grid. A value at 0.3 on the other hand would mean that only 30% of the fish entering the grid zone would contact it. For the fish contacting the grid the *CLogit* model assumes a traditional *Logit* size selection model (Wileman et al., 1996) defined by the parameters $L50_{grid}$ (length of fish with 50% probability to escape through the grid conditioned it makes contact) and SR_{grid} (= $L75$–$L25$).

The *CLogit* model was applied separately for each species in each grid section to model the size selection in the section. The values for the model parameters (C_{grid}, $L50_{grid}$, SR_{grid}) were obtained using Maximum Likelihood (ML) estimation based on the experimental data pooled over hauls i (1 to h) by minimizing:

$$-\sum_{i=1}^{h}\sum_{l}\left\{nE_{il}\times ln\left(\frac{C_{grid}}{1.0+exp\left(\frac{ln(2.0)}{SR_{grid}}\times\left(l-L50_{grid}\right)\right)}\right)\right.$$
$$\left.+nR_{il}\times ln\left(1.0-\frac{C_{grid}}{1.0+exp\left(\frac{ln(2.0)}{SR_{grid}}\times\left(l-L50_{grid}\right)\right)}\right)\right\} \quad (2)$$

Where nE_{li}, and nR_{li} are the number of individuals belonging to length class l in haul i that escaped in the grid section and got retained by it, respectively.

The goodness of fit diagnosis of the *CLogit* model to describe the experimental data was based on the p-value, model deviance vs. degrees of freedom, and inspection of the model curve's ability to reflect the trends in the data (Wileman et al., 1996). The ML estimation using Eqs. (1) and (2) requires aggregation of the experimental data over hauls. This results in stronger data to estimate the average size selectivity, but it does not explicitly consider between-haul variation in selectivity (Fryer, 1991). To account for the effect of between-haul variation in the estimation of uncertainty in size selection and for the uncertainty in individual hauls due to sample sizes, we used a double bootstrap method (Millar, 1993; Herrmann et al., 2012). Based on the bootstrap results we estimated the Efron percentile confidence intervals (CIs) (Efron, 1982) for both the estimated parameters in Eq. (2) and the resulting size selection curve (1). We used the software tool SELNET (Herrmann et al., 2012) for the analysis and applied 1000 bootstrap iterations to estimate CIs.

2.3. Comparing size selection between grid sections

The difference in the size selection performance between the different grid sections were species-wise obtained by estimating the delta in size selection ($\Delta r\,(l) = r_1\,(l) - r_2\,(l)$). Where $r_1\,(l)$ and $r_2\,(l)$ represent the grid section size selection modelled by (1) for two different sections compared. The 95% CIs for $\Delta r\,(l)$ was obtained based on the groups of bootstrap results for the individual sections by the method described in Larsen et al. (2018).

2.4. Exploitation pattern indicators

To evaluate how each of the three grid sections systems performed in the specific fishery, three exploitation pattern indicators were estimated separately for each species: nP^-, nP^+, and *nDiscard*. nP^- and nP^+ quantified the retention efficiency in the grid section for fish below and above the *MLS* (as percentages), respectively, whereas *nDiscard* represented the discard ratio in numbers and denoted the percentage of undersized fish in the codend catch. It is important to note that discards are not allowed in the Barents Sea and that while illegally caught, fish under *MLS* must be processed onboard. The naming here is only justified by the terminology earlier used for this parameter in literature (Wienbeck et al., 2014; Melli et al., 2020).

The indicators nP^-, nP^+, and *nDiscard* can be used to summarize the catch patterns for specific gear configurations 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). Ideally, for a target species, nP^- and *nDiscard* should be low (close to 0%), whereas nP^+ should be high (close to 100%), that is, retain all individuals over the *MLS* that enter the codend. The indicator values are estimated directly from the catch data by:

$$nP^- = 100\times\frac{\sum_{l<MLS}\{r_{codend}\,(l,\,v_{codend})\times nPop_l\}}{\sum_{l<MLS}\{nPop_l\}},$$
$$nP^+ = 100\times\frac{\sum_{l\geq MLS}\{r_{codend}\,(l,\,v_{codend})\times nPop_l\}}{\sum_{l\geq MLS}\{nPop_l\}}, \quad (3)$$
$$nDiscard = 100\times\frac{\sum_{l<MLS}\{r_{codend}\,(l,\,v_{codend})\times nPop_l\}}{\sum_{l} r_{codend}\,(l,\,v_{codend})\times nPop_l}$$

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

3.1. Overview of experimental data

We carried out a total of 32 hauls between the 20th of February and 5th of March 2021 in the southern part of the Barents Sea (7118.03 – 7132.34 N/02432.56 – 02551.97 E). During this experimental data collection period, a total of 14706 cod and 10358 haddock were caught and length-measured, and later included in the size selectivity analyses (Table 1).

3.2. Model fit and fit statistics

The results show that the *Clogit* model represented the selectivity data well in all cases for all three gears tested and the two species included in the study (Fig. 4). In every case the p-value is >0.05, meaning that we cannot rule out that the difference between the model and the experimental observations is coincidental (Table 2).

For cod, C_{grid} did not vary much between the three grid sections tested, and although it was approximately 5% lower for the 4-panel grid configuration than for the 2-panel configuration and the 4-panel configuration with the modified lifting panel, the differences were not significant in any case. For haddock also, the 4-panel grid section resulted on a lower contact than the other two sections, but in this case the difference was approximately 10% and significant when the 2-panel and 4-panel grid sections were compared. For both species $L50_{grid}$ was considerably higher for the 2-panel grid section than the two different 4-panel sections tested and for both cod and haddock these differences were significant (Table 2). For haddock SR_{grid} was significantly lower for the 2-panel configuration compared to the two 4-panel configurations (Table 2).

Table 1
Overview of the hauls carried out with the three different grid sections tested during the experimental sea trials. The numbers of cod and haddock retained in the codend, cover over the grid (Cover I) and cover over the codend (Cover II) in each haul are provided.

Haul nr	Gear	Time (hr:min)	Trawl time (min)	Depth (m)	Cod			Haddock		
					Codend	Cover I	Cover II	Codend	Cover I	Cover II
1	2-panel grid	20:08	45	292.49	583	101	1	50	145	1
2	2-panel grid	00:09	50	290.97	1352	36	3	82	109	2
3	2-panel grid	18:45	47	291.65	1751	99	9	116	247	5
4	2-panel grid	09:49	44	298.41	431	71	4	66	298	23
5	2-panel grid	21:59	48	293.22	648	64	1	33	129	3
6	2-panel grid	03:28	31	305.90	457	67	3	52	141	3
7	2-panel grid	03:15	47	292.68	574	52	2	56	179	6
8	2-panel grid	06:24	35	296.9	355	56	1	63	188	10
9	2-panel grid	22:56	57	293.74	337	39	3	68	312	4
10	2-panel grid	02:39	40	294.14	167	16	3	69	230	2
11	4-panel grid	14:13	60	291.56	680	24	*	219	175	*
12	4-panel grid	17:53	37	289.76	423	16	*	90	175	*
13	4-panel grid	22:21	51	288.92	579	23	*	96	146	*
14	4-panel grid	02:25	44	284.55	394	11	*	117	158	*
15	4-panel grid	03:45	20	285.65	47	12	*	23	47	*
16	4-panel grid	04:49	41	287.15	120	11	*	48	132	*
17	4-panel grid	07:47	40	282.46	162	49	*	100	168	*
18	4-panel grid	09:53	59	283.51	157	36	*	141	194	*
19	4-panel grid	12:48	47	283.79	204	41	*	154	185	*
20	4-panel grid	14:20	60	286.29	62	26	*	109	161	*
21	4-panel grid mod.	05:18	60	284.31	570	58	*	207	225	*
22	4-panel grid mod.	09:26	36	286.19	587	66	*	272	257	*
23	4-panel grid mod.	13:44	41	289.59	96	12	*	206	146	*
24	4-panel grid mod.	16:05	32	285.91	106	14	*	103	105	*
25	4-panel grid mod.	18:08	54	285.87	363	38	*	203	305	*
26	4-panel grid mod.	22:04	61	286.56	418	28	*	161	194	*
27	4-panel grid mod.	01:52	60	289.05	351	22	*	131	193	*
28	4-panel grid mod.	05:14	59	285.04	632	82	*	307	321	*
29	4-panel grid mod.	09:27	61	287.75	276	22	*	151	167	*
30	4-panel grid mod.	13:35	60	283.73	176	25	*	156	211	*
31	4-panel grid mod.	16:45	80	288.00	255	18	*	153	235	*
32	4-panel grid mod.	18:47	92	287.07	111	17	*	255	364	*

Table 2
Selection model, selectivity parameters and fit statistics for cod and haddock and the three grid section configurations tested during the sea trials.

Species	Grid section	C_{grid}	$L50_{grid}$	SR_{grid}	Deviance	DOF	P-Value
	2-panel	0.79 (0.71 – 0.88)	53.15 (51.91 – 54.83)	6.70 (5.48 – 7.91)	62.64	97	0.9974
Cod	4-panel	0.74 (0.61 – 0.95)	48.29 (44.88 – 51.13)	7.93 (5.77 – 10.78)	74.48	98	0.9632
	4-panel modified	0.80 (0.66 – 0.90)	48.67 (46.97 – 50.41)	7.57 (6.17 – 8.87)	51.49	93	0.9999
	2-panel	0.92 (0.90 – 0.95)	51.36 (50.57 – 52.22)	5.15 (4.26 – 6.22)	38.18	53	0.9376
Haddock	4-panel	0.82 (0.77 – 0.89)	47.27 (46.11 – 48.16)	8.63 (7.07 – 10.67)	41.93	46	0.6434
	4-panel modified	0.91 (0.87 – 0.95)	47.32 (46.58 – 47.95)	8.98 (7.62 – 10.66)	37.91	55	0.9618

3.3. Comparison of selectivity curves and delta plots

The results show that the 4-panel grid configuration leads to significantly higher retention rates of both cod and haddock than the 2-panel grid configuration (Fig. 5a, c). This is also clearly illustrated by the delta plots (Fig. 5b, d), which show that the 4-panel configuration leads to significantly higher retention of cod between 40 to 60 cm and significantly higher retention of haddock for all length classes between 20 and 54 cm than the 2-panel configuration. The difference between the sections is also length dependent as the difference for larger cod and haddock is bigger than for the smaller fish (Fig. 5).

The comparison between the modified 4-panel configuration and the 2-panel configuration shows similar trends to the comparison between the 4-panel configuration and the 2-panel configuration. However, the differences in this case were slightly lower. The modified 4-panel grid configuration retained significantly more cod between 43 and 60 cm and more haddock between 35 and 53 cm than the 2-panel configuration. As for the comparison between the 2-panel and 4-panel configurations, the difference in this case is also length-dependent as it is larger for the bigger cod and haddock (Fig. 6).

The results of the comparison between the 4-panel grid and the 4-panel grid with the modified lifting panel show that the former retains on average more cod and haddock between 20 and 55 cm. However, these differences were not significant for cod and only significant for undersized haddock (Fig. 7).

3.4. Exploitation pattern indicators

The indicators for cod showed that although the retention probability for undersized fish (nP^{-}) was lower for the 2-panel configuration than for the two 4-panel configurations, the differences observed were not significant. However, the retention probability of cod above *MLS* (nP^{+}) for the two 4-panel configurations was ca. 5% higher than for the 2-panel configuration, which was a significant difference. Discard ratio (*nDiscard*) was 1.15% for the 4-panel configuration, whereas for the 2-panel and modified 4-panel configurations were 0.81% and 0.91% respectively, but the differences between the configurations were not significant in any case (Fig. 8).

For haddock, nP^{-} for the 2-panel configuration was 7.82%, which was 13.48% lower and significantly different from the 4-panel configuration tested. nP^{-} was also 8.11% lower for the modified 4-panel configuration than for the standard 4-panel

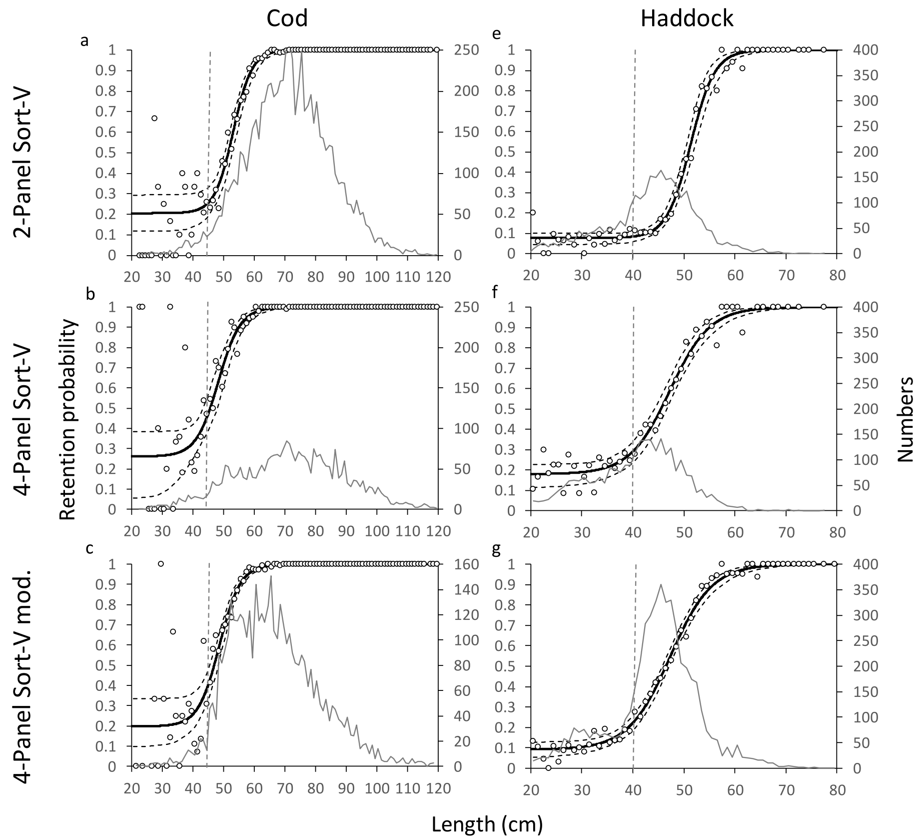

Fig. 4. Length-dependent retention probabilities for cod and haddock with three different grid systems tested during the trials. The circles in each plot represent the experimental observations. The solid curve represents the models fitted to the data. The stippled curves represent the 95% CI's. The grey line represents the population fished by the gear (codend + cover (s)). The stippled vertical grey lines show the *MLS* for cod (44 cm) and haddock (40 cm).

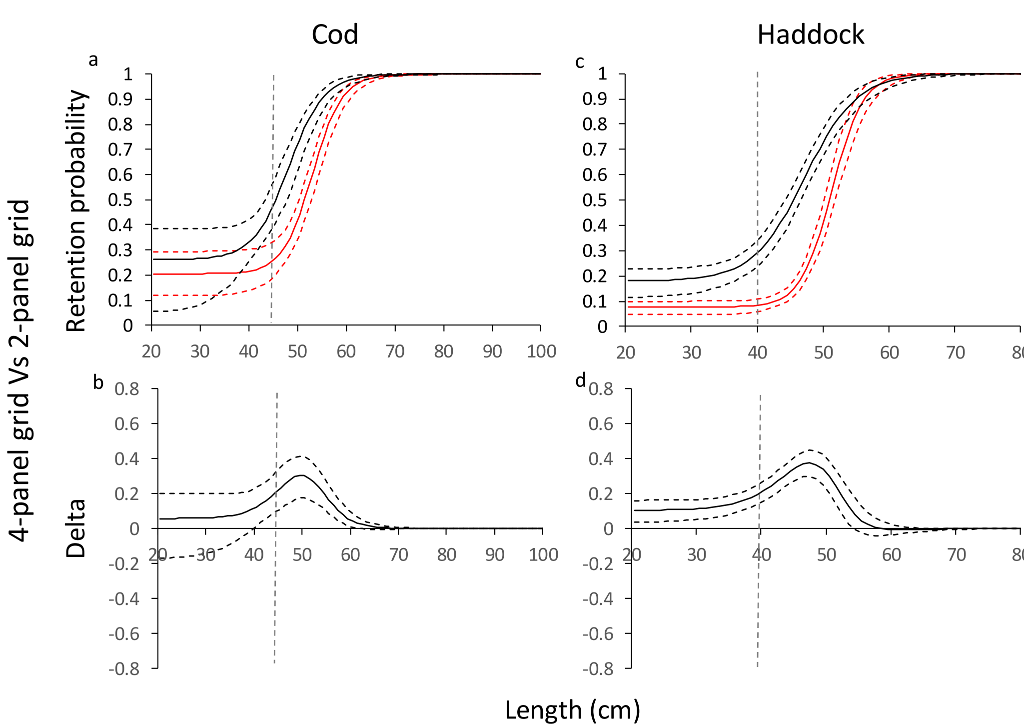

Fig. 5. Comparison of the retention probability for the 4-panel (black) and 2-panel (red, baseline) grid sections. Delta plots of the comparisons for the two species are shown in plots b, and d. The stippled curves represent the 95% CIs in each case and the stippled vertical grey lines show the *MLS* for cod (44 cm) and haddock (40 cm). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

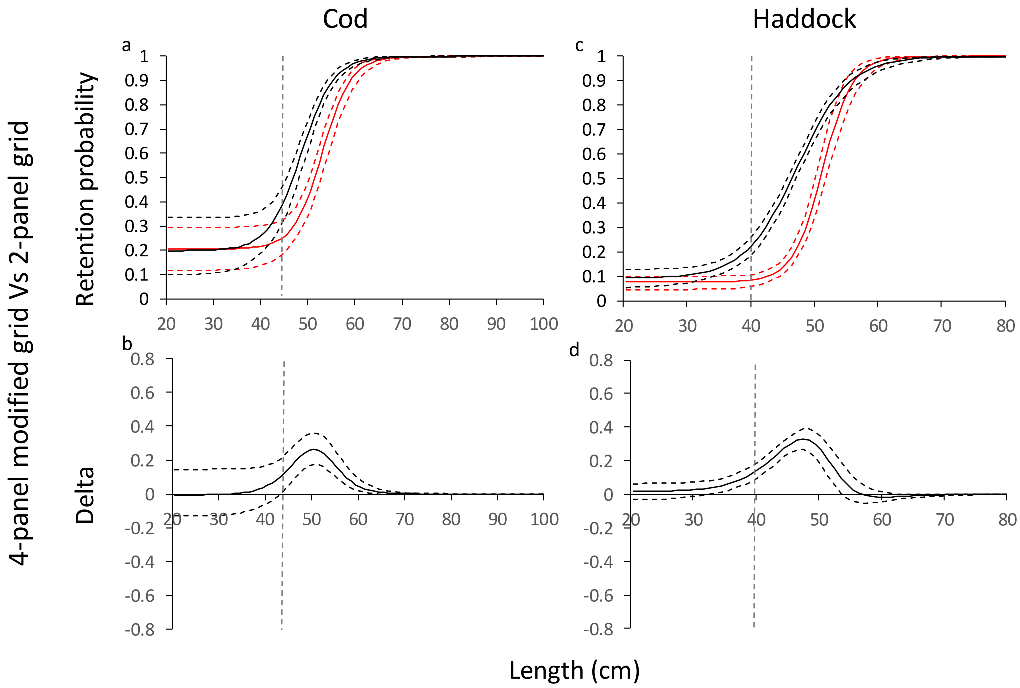

Fig. 6. Comparison of the retention probability for the 4-panel grid section with the modified lifting panel (black) and the 2-panel grid (red, baseline) sections. Delta plots of the comparisons for the two species are shown in plots b and d. The stippled curves represent the 95% CIs in each case and the stippled vertical grey lines show the *MLS* for cod (44 cm) and haddock (40 cm). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

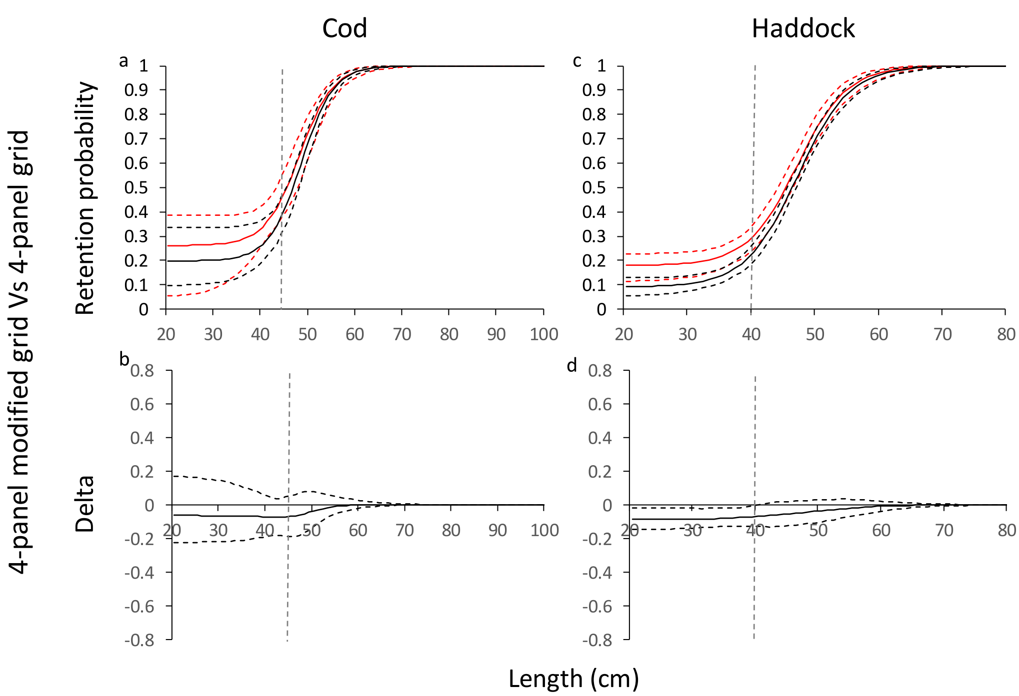

Fig. 7. Comparison of the retention probability for the 4-panel grid section with the modified lifting panel (black) and the 4-panel grid (red, baseline) sections. Delta plots of the comparisons for the two species are shown in plots b and d. The stippled curves represent the 95% CIs in each case and the stippled vertical grey lines show the *MLS* for cod (44 cm) and haddock (40 cm). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

configuration, but the confidence limits in this case overlapped slightly. nP^+ values for the 4-panel and 4-panel modified configurations were 59.14 and 54.61% respectively. Both values were significantly higher than nP^+ for the 2-panel configuration, which was estimated to be 32.10%. *nDiscard* was highest for the 4-panels configuration and ca. 3.8% higher than for the 2-panel and 4-panel modified configurations tested. However, the differences estimated were not significant (Fig. 8).

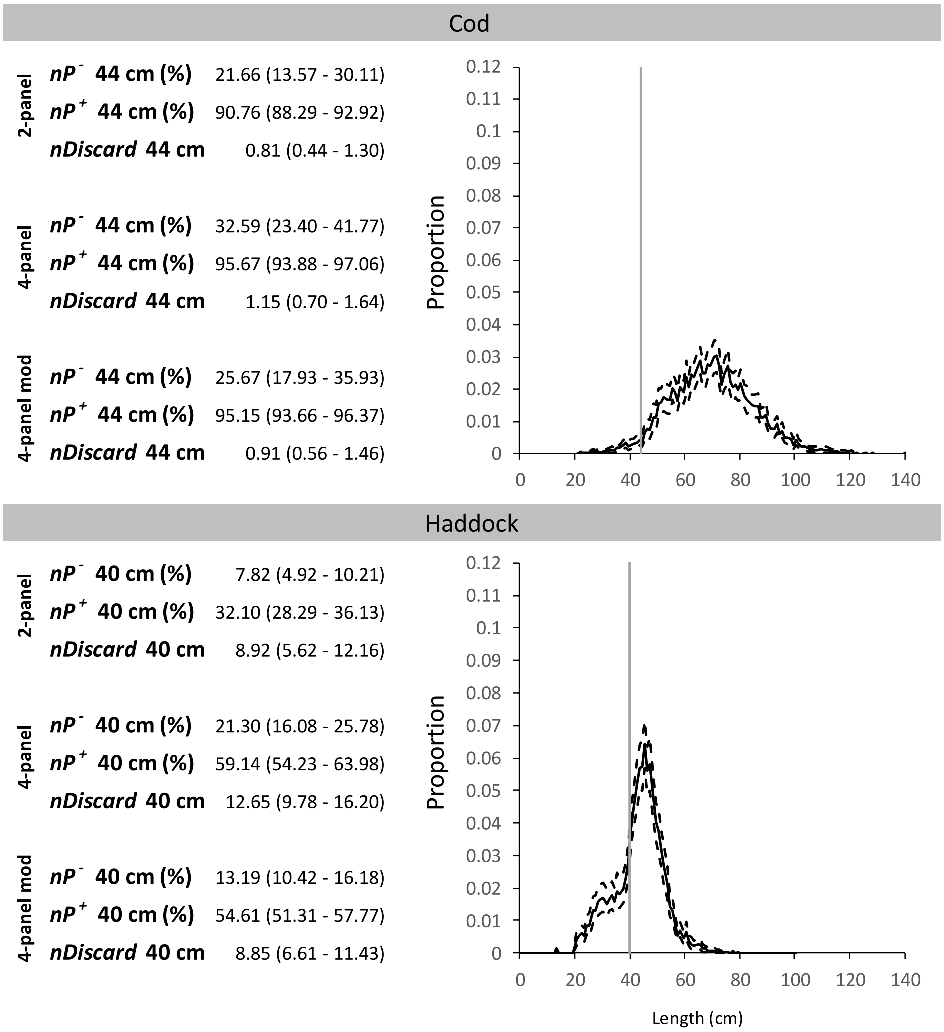

Fig. 8. Exploitation pattern indicators for cod (*MLS* = 44 cm) and haddock (*MLS* = 40 cm) with the three gear configurations tested during the trials and the population of fish encountered for each species during the whole trial period. In the plots, the black lines represent the normalized population, and the dashed lines show the 95% confidence intervals for each species during the whole cruise. The vertical grey lines show the *MLS* for each species.

4. Discussion

The results of the present study show that changing the netting construction around a sorting grid can significantly change the size selection performance of the grid, despite the grid itself remaining unchanged. Grids have often been looked at as robust size sorting devices with rather stable size selection properties because they are rigid or semi-rigid and the bar spacing is not as deformable as, for example, the meshes in a codend (Robertson and Stewart, 1988; Herrmann, 2005a,b; O'Neill and Herrmann, 2007). However, the results obtained here, as well as other earlier studies, show that grid sections can be more sensitive than expected to construction changes e.g., changes in lifting panel (Grimaldo et al., 2015); changes in grid angle (Grimaldo, 2006) or changes in the overall construction of the grid section (Sistiaga et al., 2016).

Here, the size selection curves showed that the 2-panel grid section resulted in higher contact than the 4-panel grid section with regular lifting panel, meaning that conditioned they enter the gear, more fish were subjected to a length-dependent sorting process at the grid when this configuration was applied. This result was the same for cod and haddock, although haddock showed higher contact probability than cod independent of the grid section configuration applied. The higher ability of haddock to contact sorting grids has earlier been documented in the literature (Sistiaga et al., 2010; Larsen et al., 2018) and explained as a consequence of the more active behaviour of haddock inside towed fishing gears when compared to cod (Tschernij and Suuronen, 2002; Rosen et al., 2012). For both species, the difference in contact observed between the configurations was reduced when the lifting panel in the 4-panel section was raised, as the change most likely increased the number of fish that were directed towards the grid with better orientation to attempt escape. This illustrates the importance of the netting construction around the grid, and shows again (Grimaldo et al., 2015) the importance of the lifting panel in these types of grid sections. However, despite the reduction in contact difference observed when modifying the lifting panel, it was clear from the selectivity curves that the lifting panel was not the only source for the difference observed between the different configurations because the 2-panel configuration still resulted in sharper selectivity curves. The reduction in sharpness when moving from the 2-panel to 4-panel configuration, which was characterized by an increase in SR, must originate from additional problems for fish to contact the grid in the 4-panel sections. The size, bar spacing and angle of attack of the grids in the sections tested were practically identical, meaning that if fish were equally capable of contacting the grid in all configurations tested, the size selection curves would be the same for all three cases.

Grid sections exhibit a substantial reduction in waterflow from the inlet to the outlet (Gjøsund et al., 2013), but it has earlier been suggested that 4-panel grid sections allow better water flow through than 2-panel grid sections (Grimaldo et al., 2015). Increased water flow can be an advantage in grid sections because it can prevent clogging, which is a known problem with sorting grids at high fish entry densities (Sistiaga et al., 2016; Eigaard et al., 2021). However, the option of increasing water flow in the grid section poses a dilemma because while it reduces the risk for clogging, it also reduces the time for fish to orientate themselves correctly towards the grid and attempt escape. We did not have the necessary equipment to measure waterflow in the grid sections during the present trials, but if it was higher for the 4-panel sections than for the 2-panel section, that may have been the source for the differences in the steepness of the size selection curves observed here. In earlier studies carried out with the flexigrid, Sistiaga et al. (2016) observed that a 4-panel construction provided steeper size selection curves and lower risk for clogging than a 2-panel construction, which conflicts with the argumentation given above and the results from Brinkhof et al. (2020), who found the 2-panel flexigrid to perform substantially better than in 4-panel section in Sistiaga et al. (2016). These results add uncertainty as to which of the two grid section construction types performs better, but it corroborates that grids do not provide as constant size selection properties as earlier believed and that relatively small design changes can result in substantial size selectivity performance differences.

The exploitation pattern indicators showed that for both species the 2-panel Sort-V grid configuration was the most efficient configuration to release fish below *MLS*, but at the cost of an additional loss of fish above *MLS*. The 4-panel configuration with the regular lifting panel for both species, as well as the 4-panel configuration with the modified lifting panel for cod, had a probability to catch fish below *MLS* that was significantly higher than the maximum of 15% allowed by legislation. Further, the results for haddock showed that as earlier illustrated by Brinkhof et al. (2020) for the flexigrid, the efficiency of grids with a bar spacing of 55 mm to catch haddock over its *MLS* is too low. This has not only implications for the fishing industry but also for more fundamental aspects like fish welfare, as specific individuals in the fishing grounds may be subjected to multiple catch and release processes. In fisheries regulated by *MLS*, grid section designs that provide sharp size selection curves are preferred because they can easier comply with the management regulations and adapt to potential changes by changing grid bar spacing. When the performance of a grid section has flaws and results in flatter size selection curves as observed for the 4-panel grid sections in the present study, it is not possible to adjust selectivity with bar spacing.

The present study shows the importance of accounting for design changes other than simply the grid when evaluating the performance of a sorting grid system i.e., it demonstrates that considering changes to the construction of the section is key and can affect the overall selectivity performance of sorting grids. Further, it shows that similar design changes can produce opposite results on different types of grids and especially, that the performance of this type of device can be sensitive to relatively small design changes and imply potentially large consequences for size selection.

Based on the results obtained here, fishermen should use the 2-panel Sort-V grid configuration rather than the 4-panel Sort-V configuration in the Barents Sea gadoid fishery, at least until the 4-panel configuration of this grid is modified and its size selective performance improved. Further research is also recommended to better understand the implications of using 2- vs. 4-panel gear constructions, not only for grids but for other size selection devices as well.

CRediT authorship contribution statement

Manu Sistiaga: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Bent Herrmann:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jesse Brinkhof:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft. **Roger B. Larsen:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft.

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.

Data availability

Data will be made available on request.

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