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Size matters for the efficiency of sorting grids in demersal trawls

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ABSTRACT

Size selectivity devices implemented in trawls are often strictly regulated and can remain unchanged over longer periods. This is the case for the Barents Sea gadoid trawl fishery, one of the most important and valuable demersal fisheries in the world, where since 1997 the compulsory gear has been composed of a sorting grid and a subsequent size selective codend. The upscaling and development of the trawl gear typically used in the area in the last three decades has contributed to capacity issues that can lead to inefficiencies in size selectivity and operational problems of grid sections. The present study investigates whether upscaling the mandatory grid by doubling its sorting area can improve the size selectivity in the fishery. A mandatory grid section and an upscaled grid section were directly compared in sea trials in a twin trawl configuration. The data were analyzed considering structural models, which resulted in a more logical representation of the relative performance of the two grid sections compared in the study than traditionally used empirical models. The upscaled grid significantly increased the sorting efficiency for undersized haddock (*Melanogrammus aeglefinus*), while the catch efficiency of commercial-sized cod (*Gadus morhua*) and haddock were equal. The additional sorting capacity exhibited by the upscaled grid is expected to play an important role in the future management of the fishery. Further, it demonstrates the importance of revising the efficiency of compulsory selectivity devices periodically and can point to the direction to adopt in other fisheries with similar issues. The upscaled grid did not imply any additional work or challenge for the crew during its operation.

1. Introduction

In many trawl fisheries, the regulations concerning selectivity comprise size sorting devices with specific construction characteristics and location in the trawl. Square mesh panels and sorting grids are examples of these types of devices (Kennelly and Broadhurst, 2021). Normally, these sorting devices are used independent of different characteristics of the trawl that have been demonstrated to affect the numbers and sizes of animals entering the trawl: e.g. mesh size, the size or type of trawl employed, length of the sweeps used, type of ground gear or other additional characteristics (Ingolfsson and Jørgensen, 2020; Sistiaga et al., 2015; Brinkhof et al., 2017). The aim of inserting size sorting devices in trawls is to achieve constant selectivity that discriminates the species and sizes of animals ultimately retained by the gear. Therefore, if there are changes in certain parts of the gear or operating conditions that jeopardize the ability for a specific sorting device to deliver constant selectivity, adaptations of the sorting device itself would be required.

For all fishing vessels participating in the Barents Sea demersal trawl fishery the use of a size sorting grid is mandatory. The sorting grid is placed in the extension piece of the trawl, a tapered or cylindrical netting section subsequent to the trawl belly, followed by a size selective codend (Fig. 1). The grids are strictly regulated and must have a minimum bar spacing of 55 mm, while codends are only regulated by mesh size, which needs to be at least 130 mm. In such a selectivity system, when the fish enters the extension piece of the trawl, they get a first chance to escape through the grid. The potential escape through the grid involves a behavioral and a mechanical component. Among those fish that contact the grid (behavioral component), those fish that can physically pass through the grid will escape the trawl (mechanical

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component), whereas those that do not contact the grid or can't physically pass between the bars in the grid will eventually drift back towards the codend, where they will get an additional chance to escape (Sistiaga et al., 2010). Since the introduction of the original steel-made Sort-X grid design in 1997 (Larsen and Isaksen, 1993), two other grid designs have been introduced in the fishery, the steel-made Sort-V and the Flexigrid, a dual grid system where the grids are made of rubber and plastic (Herrmann et al., 2012; Grimaldo et al., 2016). The latter was included in the regulation in 2002 and since then, except for some minor changes in the section netting designs (Sistiaga et al., 2023), the regulations and designs of the grids have remained practically unchanged to facilitate control by the authorities at sea. The construction of the sections as well as the size and material of the grids are strictly defined by the Directorate of Fisheries and cannot be altered. Thus, fishermen can freely choose their grid of choice and have a wider bar spacing than the established minimum of 55 mm if they wish, but each grid type needs to follow the size and construction specifications by the Directorate of Fisheries strictly and cannot be built larger or smaller than specified in the construction guidelines (See Grimaldo et al. 2016 for an overview of the three grid designs and Fiskeridirektoratet 2023 for further details and specifications).

Even though the design and size of the grids has remained the same, the size of the demersal trawls and capacity of the vessels participating in the fishery have increased substantially since the introduction of the grids. Further, large pelagic trawls designed to harvest demersal species like cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) have been tested in the fishery with the purpose of increasing catch efficiency and reducing the environmental impact of the fishery by partially substituting the use of the common demersal trawls (Sistiaga et al., 2016a). After some initial tests during the seventies, which resulted on the banning of such trawls in the fishery, pelagic trawls were further tested a decade ago (Sistiaga et al., 2016a) and are again considered these days because the reduction of the seabed impact of trawls has become a global concern for fisheries worldwide (Kaiser et al., 2016; McConnaughey et al., 2020; Hiddink et al., 2020). One of the challenges with implementing larger demersal trawls and pelagic trawls in this fishery is that the densities of fish entering the aft of the trawl can increase. Earlier studies carried out with sorting grids have identified capacity issues with the designs currently employed (e.g. Sistiaga et al., 2016b), meaning that at high fish entry densities grids can show reduced size sorting efficiency. In some cases, the capacity issues become acute leading to clogging of the grid, and in some cases complete blockage of the grid. Further, if due to blockage the catch starts accumulating in front of the grid, the whole grid section can burst resulting in loss of catch and serious gear damage (Sistiaga et al., 2016b).

In shrimp fisheries, the working principle of sorting grids used is based on the opposite sorting principle, i.e. animals that pass between the bars of the grid are retained whereas animals that cannot pass between the bars of the grid are released from the gear (Valdemarsen et al., 1993). In such fisheries, increasing the size of the grid has been shown to lead to an increase in the probability for animals to pass through the grid (Larsen et al., 2018a). Due to the increase in area, animals likely have more time and increased chance to orientate themselves towards the grid in a way that provides them with a length-dependent probability to pass through the grid (Sistiaga et al., 2010). Thus, it was speculated whether an increase in size could also be beneficial for size discrimination of key target species in fisheries like the Barents Sea demersal trawl fisheries.

Traditionally, direct comparisons between the performance of different fishing gears at sea (for example two different sorting grids) have been conducted by means of the catch comparison method (e.g., Krag et al., 2014; Herrmann et al., 2017; Ingolfsson et al., 2022). This method, which is thoroughly described in Herrmann et al. (2017) and Olsen et al. (2019) finally provides the size-dependent catch ratio between the gears (proportion caught with one gear with respect to the other one). The data from catch comparison studies in fisheries is normally modelled using flexible empirical models. However, this type of model can result in a less realistic representation of the ongoing capture processes in the gear, especially if for multiple length classes the number of individuals is low and the binominal noise high, i.e. in the tails of the model (see Fig. 2 in Sistiaga et al., 2024). Unlike flexible empirical models, structural models assume specific characteristics in the process (es) leading to the size selection in the gears (Wileman et al., 1996; Jacques et al., 2024). Thus, the model fitted to the collected data has a less flexible and pre-established structure. Structural models have not applied in catch comparison studies, and it is of interest to investigate whether these types of models can lead to better representation of catch comparison data in cases where the capture processes in the tested gears can be assumed to have certain characteristics.

The aim of the present study was to test whether an upscaled sorting grid can provide improved size selectivity results compared to an equivalent grid of standard size in fisheries like the Barents Sea demersal trawl fishery. If the upscaled grid would show improved performance, it would demonstrate the benefit of scaling sorting devices to cope with capacity changes in the rest of the gear. Furthermore, the ability of structural models to model catch comparison data was investigated.

2. Materials and methods

2.1. Fishing trials

Sea trials were conducted in the Barents Sea and more specifically in the fishing grounds around Bear Island (73° 48' 405" / 76° 00' 619" N – 15° 40' 766" / 22° 55' 537" E) between the 14th and 27th of November 2023. "M/Tr Ramoen" (75.1 m LOA, 3723 Gross Tonnage), a commercial trawler that operates with a twin-trawl configuration, was chartered for the experiments. It employs two Selstad 630# demersal trawls (headline height ca. 7 m), a pair of Thyborøn type 26 VFG doors (9 m, ∼4400 kg each), a central clump (Thyborøn 2700 mm, ∼6500 kg) and 100 m sweeps. The operational door distance is typically 220–250 m depending on the fishing depth.

Both demersal trawls were rigged identically to the belly of the trawl. In the aft of one of the trawls, we installed a standard single grid (i.e., Sort-V type) section built of 135 mm mesh size (nominal) netting with a steel standard-size grid. The steel grid was 1234 mm wide and 1750 mm high, and the bar spacing of the grid was measured to be 55.17 ± 0.36 mm (mean ± SD). It weighed ca. 45 kg in the water and was compensated by 17 8" floats (buoyancy 2650 g). This whole section, including the grid, which has an effective sorting area of 2.16 m, was identical to the one used by the commercial fleet today (Fig. 2a). In the

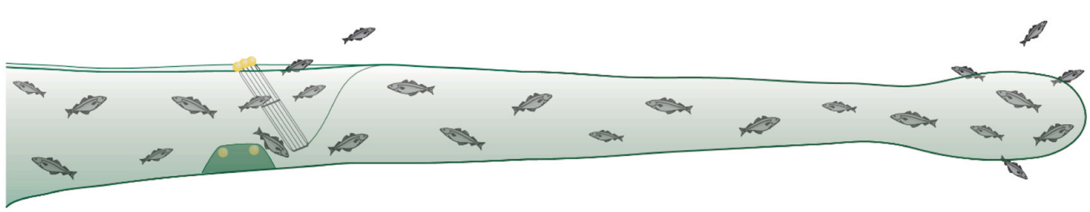

Fig. 1. Compulsory size selectivity gear in the Barents Sea bottom trawl fishery. It is a dual system composed by a grid with a minimum bar spacing of 55 mm inserted in the extension piece following the trawl belly, and a codend with a minimum mesh size of 130 mm.

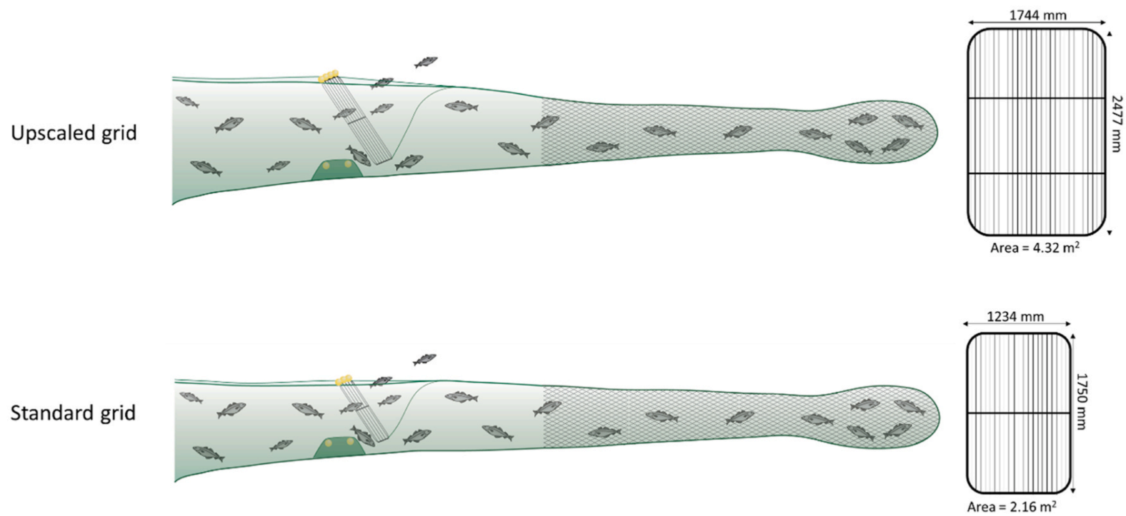

Fig. 2. Illustration of the gear configuration used during the trials with the upscaled and standard grids.

other trawl, we installed an upscaled version of the standard grid section currently used by the fleet, which was also built of 135 mm (nominal) mesh size netting. The steel grid was 1744 mm wide and 2477 mm high with an effective sorting area of 4.32 m in this case, double as large as that of the standard grid. It weighed ca. 74 kg in the water and was compensated by 28 8" floats. The bar spacing of the grid was measured to be 55.19 ± 0.67, which was practically the same as that of the standard grid with a somewhat larger variation in the measurements (Fig. 2b). For structural reasons, the upscaled grid had two transversal steel bars compared to the single transversal steel bar in the standard grid. The length and height of the netting section were upscaled accordingly so that the grid could be installed in the section with the same angle as in the standard section (approx. 25° leaning forward (Larsen and Isaksen, 1993)). This resulted in the section of the upscaled grid being 25.5 meshes longer and with 22 more meshes around than the standard grid section (Supplementary material, S1).

Both grid sections had a 58-mesh long extension piece in front, and 35-mesh long extension piece behind the grid and in front of the codend, all built of 135 mm nominal mesh size netting. However, while the circumference of the extension piece in front of the grid section was maintained at #74 meshes when the upscaled grid was used, it was reduced from #80 meshes to #52 meshes when the standard grid was used. This reduction in the circumference of the extension piece in front of the grid section was necessary when the standard grid section was used because it was smaller than the upscaled grid section (Supplementary material, S1). The codends in each of the trawls were built of knotless netting and were #90 meshes long with a circumference of #80 open meshes around. Both codends were blinded with liners built of netting with 32.90 ± 0.74 mm mesh size. The liners had 300 meshes around and therefore kept a low opening angle, which together with the small mesh size ensured that no cod or haddock > 20 cm would be able to escape from the codend (Sistiaga et al., 2011).

The sections with the upscaled grid and the section with the standard grid were swapped halfway through the trials to avoid any influence due to potential differences in the fishing power of the two trawls employed (Fig. 2; Table 1). The catches from both trawls were kept in separate bins onboard. All cod and haddock above 20 cm were measured to the nearest cm below except for those hauls where for practical issues the

Table 1
Overview of the hauls conducted during the experimental sea trials with the upscaled grid (*U*) and the standard grid (*S*). *nU* is the number of fish measured in the trawl with the upscaled grid, and *S (n)* is the number of fish measured in the trawl with the standard grid. Data for cod and haddock. *qU* and *qS* are the subsampling fractions applied to each compartment, respectively. * = no catches.

Haul Nr	Time start (hh:mm)	Towtime (hh:mm)	Depth (m)	Side U	Cod				Haddock				Total Catch (kg)
					nU	*qU*	*nS*	*qS*	*nU*	*qU*	*nS*	*qS*	
1	04:00	03:56	232	Port	826	1.000	662	1.000	186	1.000	153	1.000	2735
2	09:30	05:04	221	Port	927	1.000	1170	1.000	278	1.000	44	1.000	4063
3	15:37	05:24	201	Port	636	1.000	533	1.000	294	1.000	292	1.000	3396
4	21:30	04:52	216	Port	537	1.000	607	1.000	552	1.000	653	1.000	4600
5	03:23	05:09	227	Port	680	1.000	774	1.000	369	1.000	414	1.000	4530
6	09:45	05:23	228	Port	959	1.000	938	1.000	238	1.000	205	1.000	3463
7	15:41	05:10	230	Port	722	0.600	677	0.557	256	1.000	276	1.000	5000
8	21:26	02:16	270	Port	245	1.000	255	1.000	532	1.000	631	1.000	3011
9	03:14	04:34	240	Port	478	1.000	493	1.000	276	1.000	582	1.000	3429
10	09:02	05:02	203	Port	256	1.000	293	1.000	167	1.000	433	1.000	1168
11	20:56	03:39	300	Port	328	1.000	392	1.000	354	1.000	593	1.000	2509
13	04:41	05:07	266	STB	541	1.000	506	1.000	328	1.000	326	1.000	3437
14	10:33	04:44	355	STB	522	0.776	500	0.809	387	0.774	495	0.780	3747
15	16:29	04:40	259	STB	651	0.538	524	0.463	546	0.595	478	0.608	9579
16	21:26	04:46	305	STB	567	0.572	626	0.752	385	0.595	390	0.716	5079
17	03:14	04:53	274	STB	534	0.743	499	0.713	389	0.741	394	0.649	4267
18	09:02	02:21	290	STB	142	1.000	95	1.000	292	1.000	332	1.000	1844
19	20:56	01:42	216	STB	678	0.333	533	0.264	*	*	*	*	7201
20	23:31	04:18	235	STB	700	0.284	794	0.322	*	*	*	*	9752
23	16:29	04:49	234	STB	585	0.185	641	0.195	*	*	*	*	10056
24	22:13	04:51	244	STB	667	0.205	691	0.198	*	*	*	*	12825

catch had to be subsampled. In the hauls where the catch was subsampled, all fish in the fraction that was not measured were counted and the subsampling factor calculated (Table 1). To ensure that the fish included in the data analysis were not exposed to a size selection process in the blinded codend, only cod and haddock > 20 cm were included in the size selection analysis and estimation of the exploitation pattern indicators.

2.2. Catch comparison and catch ratio analysis

The data acquired during the sea trials could be analyzed paired because they were collected with a twin trawl configuration. We carried out a catch comparison (*CC*) and catch ratio (*CR*) analysis to quantify the potential length-dependent differences in the catch efficiency between the upscaled grid (*U*) and the standard grid (*S*) averaged over hauls following the procedure described in Herrmann et al. (2017) and Olsen et al. (2019):

$$CC_l = \frac{\sum_{j=1}^{h}\left\{\frac{nU_{lj}}{qU1_j}\right\}}{\sum_{j=1}^{h}\left\{\frac{nU_{lj}}{qU1_j} + \frac{nS_{lj}}{qS_j}\right\}} \tag{1}$$

$nU1_{lj}$ and nS_{lj} are the individuals caught in the trawl with the upscaled grid and the trawl with the standard grid, respectively for haul *j*. *h* is the number of hauls carried out, while for each specific haul *j*, qU_j and qS_j are the subsampling factors.

The experimental CC_l rate is modelled through maximum likelihood estimation often by using *a* flexible empirical function (Herrmann et al., 2017; Olsen et al., 2019):

$$CC(l, \boldsymbol{v}) = \frac{\exp(f(\boldsymbol{w}, v_0, \ldots, v_s))}{1 + \exp(f(\boldsymbol{w}, v_0, \ldots, v_s))} \tag{2}$$

In Eq. (2) *f* is a polynomial of order *s* with coefficients v_0 to v_s, and *s* was considered with an order up to 4 (Herrmann et al., 2017). With an empirical model like model (2) no assumptions are made regarding the functional form of the individual processes that leads to the length dependent catch comparison rate. Here, besides (2), we also considered so-called structural models as candidates to describe the catch comparison rate. The type of structural models considered are based on assuming a specific functional form for the individual processes determining the catch comparison rate (Jacques et al., 2024; Santos et al., 2016). In this specific case, the individual processes determining the catch comparison rate are the size selection in the two grids, which leads to the following functional form for *CC(l, v)*:

$$CC(l, \boldsymbol{v}) = \frac{SP \times ru(l, \boldsymbol{vu})}{SP \times ru(l, \boldsymbol{vu}) + (1.0 - SP) \times rs(l, \boldsymbol{vs})} \quad \textit{where} \quad \boldsymbol{v} = (\boldsymbol{vu}, \boldsymbol{vs}, SP) \tag{3}$$

where $ru(l, \boldsymbol{vu})$ models the size selection process in the upscaled grid with parameters $\boldsymbol{vu}$ and $rs(l, \boldsymbol{vs})$ the size selection process in the standard grid with parameters $\boldsymbol{vs}$. *SP* is the split parameter that quantifies the fraction of fish that enters the trawl with the upscaled grid, conditioned they enter one of the trawls. Often the size selection in grid sections like the ones used here is modelled by models that consider that a length-independent fraction of the fish does not contact the grid to be size sorted by it (Sistiaga et al., 2010):

$$r(l, \boldsymbol{v}) = 1.0 - C \times (1.0 - rc(l, \boldsymbol{vc})) \quad \textit{where} \quad \boldsymbol{v} = (C, \boldsymbol{vc}) \tag{4}$$

where *C* quantifies the fraction of the fish that contacts the grid and $rc(l, \boldsymbol{vc})$ models the size selection in the grid for the fraction of fish that contacts it. For $rc(l, \boldsymbol{vc})$ we considered the 4 basic S-shaped size selection models (Wileman et al., 1996): *Logit*, *Probit*, *Gompertz* and *Richards*. In addition, we considered a case with no size selection through any of the grids. Thus $ru(l, \boldsymbol{vu})$ and $rs(l, \boldsymbol{vs})$ were modelled by:

$$r(l, \boldsymbol{v}) = \begin{cases} CLogit(l, \boldsymbol{vc}, C) = 1.0 - C \times (1.0 - Logit(l, \boldsymbol{vc})) \\ CProbit(l, \boldsymbol{vc}, C) = 1.0 - C \times (1.0 - Probit(l, \boldsymbol{vc})) \\ CGompertz(l, \boldsymbol{vc}, C) = 1.0 - C \times (1.0 - Gompertz(l, \boldsymbol{vc})) \\ CRichards(l, \boldsymbol{vc}, C) = 1.0 - C \times (1.0 - Richards(l, \boldsymbol{vc})) \\ 1.0 \end{cases} \tag{5}$$

Model fit was evaluated based on the *p*-value, which should not be < 0.05 for the combined model to describe the experimental data sufficiently well, except for cases where the data were subjected to overdispersion (Herrmann et al., 2017; Wileman et al., 1996). The model with the lowest AIC among the 18 considered was selected to model experimental CC_l data (Akaike, 1974). Specifically, this was done for each bootstrap iterations conducted to obtain the confidence intervals (CIs) for the average *CC(l, v)*. Thereby, the uncertainty in model selection is taken into account in the estimation of the CIs following the BMS procedure described by Jacques et al. (2024). Based on the 1000 bootstrap iterations conducted for each case, the Efron percentile 95 % CIs were estimated (Efron, 1982; Herrmann et al., 2012).

Based on *CC(l, v)*, the relative catch efficiency between the two compared gears known as catch ratio *CR(l, v)* was estimated following Herrmann et al. (2017) and Olsen et al. (2019).

2.3. Assessment of the effect of considering empirical and structural models

Since the analysis in the present study considered both empirical and structural models as candidate models for *CC(l, v)*, it was of interest to investigate potential differences between the traditional modelling only considering empirical models and the modelling approach presented here, which also considered structural models. Further, the case where *CC(l, v)* only considered structural models was evaluated.

2.4. Exploitation pattern indicators

Indicators in the form of size-integrated average values for the catch ratio ($CR_{average}$) below and above *MLS* as well as discard ratios for the upscaled grid and standard grid (*nDiscard ratio*) were estimated directly from the experimental catch data as in Sistiaga et al. (2024). The *MLS* for cod in the Barents Sea is 44 cm whereas for haddock it is 40 cm. Note that discards are not allowed in the Barents Sea and that fish under *MLS* captured must be processed onboard.

The statistical software SELNET (Herrmann et al., 2012, 2017) was used to conduct all analysis in Sections 2.2 – 2.4.

3. Results

In a total of 21 hauls the gear showed no sign of malfunction and were included in the data analysis (Table 1). In these 21 hauls, a total of 24,384 cod and 12,520 haddock were length-measured. Towing time varied between 5:24 (hh:mm) and 1:42 but due to that the gears were fished in a paired gear configuration and exposed to the same fishing conditions, this variarion did not have any effect on the assessment of the relative performance of the two gears compared.

3.1. CC and CR analysis

All 16 structural models, the model for no escape and the empirical 4th order polynomial model presented in materials and methods were tested on the data for each species. The *CC* analysis carried out showed that for cod and haddock, the models that best represented the mean experimental data and resulted in the lowest AIC were the *CProbit-CRichards* model and *CRichards-CGompertz* model, respectively (Table 2). The results of the *CC* analysis for cod show that despite the low *p*-value ($p < 0.05$) in the fit statistics, the model represented the trends in the data well. Therefore, it was assumed that the low *p*-value observed for cod was a result of overdispersion in the data (Table 2; Fig. 3). For haddock, the *p*-value was > 0.05 meaning that it can not be ruled out that the dicrepancy between the model and the experimental data can be coincidental. Visual inspection of the model fit showed that in this case as well the model represented the experimental data well.

For cod, the *CC* analysis using the BMS approach also showed that in the 1000 bootstrap repetitions conducted the *CRichards-CGompertz* was the model that most often resulted in the lowest *AIC* among the models tested. This model resulted in the lowest *AIC* in 169 out of the 1000 bootstrap repetitions conducted, which contrasts with the model that resulted in the lowest AIC for the mean experimental data i.e., *CProbit-CRichards*. The *CProbit-CRichards* model resulted in the lowest AIC in 53 out of the 1000 repetitions. In addition to the *CRichards-CGompertz* and *CProbit-CRichards* models, eight other models resulted in the lowest *AIC* in at least 50 ocassions (>5 % of the cases) (Fig. 3).

For haddock, the *CRichards-CGompertz* model resulted in the lowest AIC in 385 out of the 1000 bootstrap repetitions. This was also the model that resulted in the lowest AIC for the mean experimental data. Although the *CRichards-CGompertz* model was clearly the one that most often resulted in the lowest *AIC*, i.e., 38.5 % of the 1000 repetitions, five other models resulted in the lowest *AIC* in > 5 % of the bootstrap repetitions (Fig. 3).

The results of the *CC* and *CR* analysis show that the trawl with the upscaled grid captured less undersized cod (< 44 cm) than the trawl with the standard grid configuration. However, these differences were not significant for any of the length classes included in the analysis, i.e. fish > 20 cm. Further, the catch efficiency of both gears tested showed to be practically equal for cod > 60 cm, which would make sense considering that the upper size sorting limit for a 55 mm grid is reached at ca. 60 cm (Sistiaga et al., 2011) (Fig. 4).

For haddock, the trawl equiped with the upscaled grid captured significantly less undersized fish than the trawl with the standard grid section. However, there was no significant difference between the trawls for the catches of commercial-sized haddock (> 40 cm). For haddock > 55 cm, the *CC* and *CR* curves showed equal catches, which is again well in agreement with the upper size sorting limit for this species with a 55 mm grid bar spacing (Sistiaga et al., 2011) (Fig. 4).

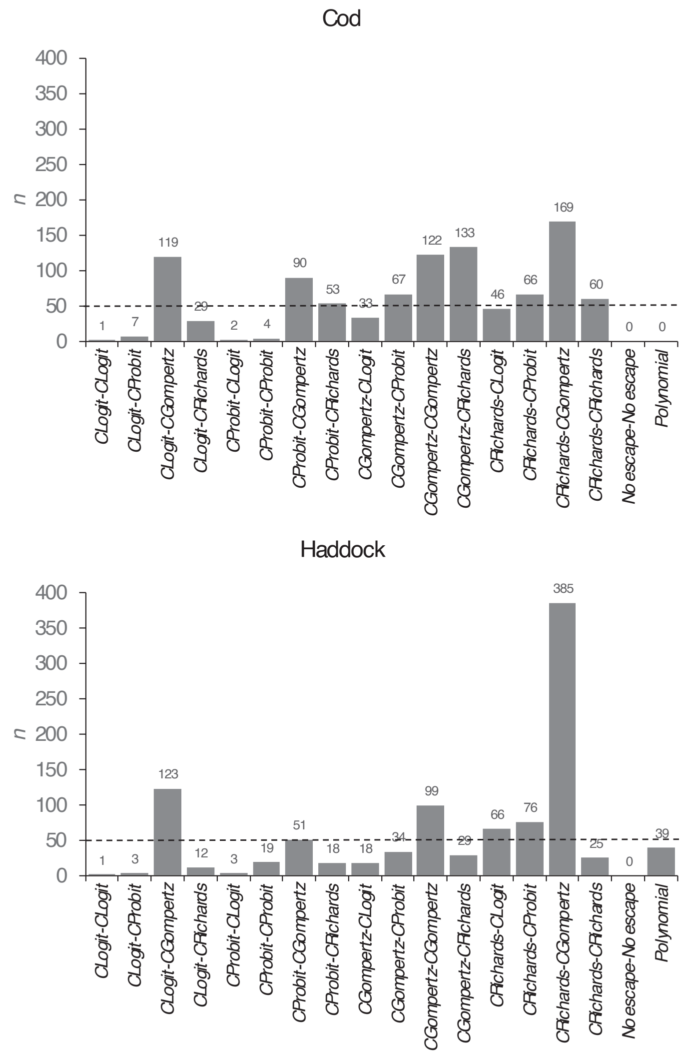

Fig. 3. Count bar plot for the 18 different models considered in the BMS analysis approach. The horizontal dashed line shows edge for the models that were selected at least 50 times out of the 1000 bootstrap resamples, i.e., at least 5 %.

Table 2
AIC values and fit statistics for the different models tested in the *CC* analysis. Rows in grey show the cases with lowest AIC value for cod and haddock, respectively. DOF = Degrees of Freedom.

		Cod						Haddock			
Model Test1	Model Test2	AIC	*p* - value	Deviance	DOF	Model Test1	Model Test2	AIC	*p* - value	Deviance	DOF
CLogit	*CLogit*	62008.91	0.002	136.04	92	*CLogit*	*CLogit*	19358.16	0.0496	75.68	57
CLogit	*CProbit*	62008.99	0.002	136.03	92	*CLogit*	*CProbit*	19358.07	0.0514	75.45	57
CLogit	*CGompertz*	62004.57	0.001	141.46	92	*CLogit*	*CGompertz*	19357.78	0.0529	75.27	57
CLogit	*CRichards*	62005.53	0.001	140.39	91	*CLogit*	*CRichards*	19359.79	0.0438	75.27	56
CProbit	*CLogit*	62008.98	0.002	136.25	92	*CProbit*	*CLogit*	19358.40	0.0449	76.28	57
CProbit	*CProbit*	62009.07	0.002	136.24	92	*CProbit*	*CProbit*	19358.31	0.0468	76.04	57
CProbit	*CGompertz*	62008.80	0.002	135.90	92	*CProbit*	*CGompertz*	19358.03	0.0479	75.89	57
CProbit	*CRichards*	62002.31	< 0.001	143.94	91	*CProbit*	*CRichards*	19360.04	0.0396	75.89	56
CGompertz	*CLogit*	62006.52	< 0.001	159.28	92	*CGompertz*	*CLogit*	19363.01	0.0238	80.02	57
CGompertz	*CProbit*	62006.52	< 0.001	159.89	92	*CGompertz*	*CProbit*	19362.93	0.0248	79.80	57
CGompertz	*CGompertz*	62007.93	0.003	134.25	92	*CGompertz*	*CGompertz*	19362.66	0.0253	79.67	57
CGompertz	*CRichards*	62008.15	< 0.001	159.75	91	*CGompertz*	*CRichards*	19364.67	0.0205	79.68	56
CRichards	*CLogit*	62008.93	0.001	136.97	91	*CRichards*	*CLogit*	19355.81	0.0725	72.10	56
CRichards	*CProbit*	62009.04	0.001	136.74	91	*CRichards*	*CProbit*	19355.77	0.0715	72.19	56
CRichards	*CGompertz*	62008.70	0.001	139.81	91	*CRichards*	*CGompertz*	19355.03	0.0965	70.17	56
CRichards	*CRichards*	62010.18	< 0.001	159.73	90	*CRichards*	*CRichards*	19357.05	0.0804	70.27	55
No escape	*No escape*	62129.05	< 0.001	175.09	98	*No escape*	*No escape*	19632.70	0	320.03	63
Polynomial		62047.08	< 0.001	164.61	94	*Polynomial*		19361.77	0.1133	72.37	59

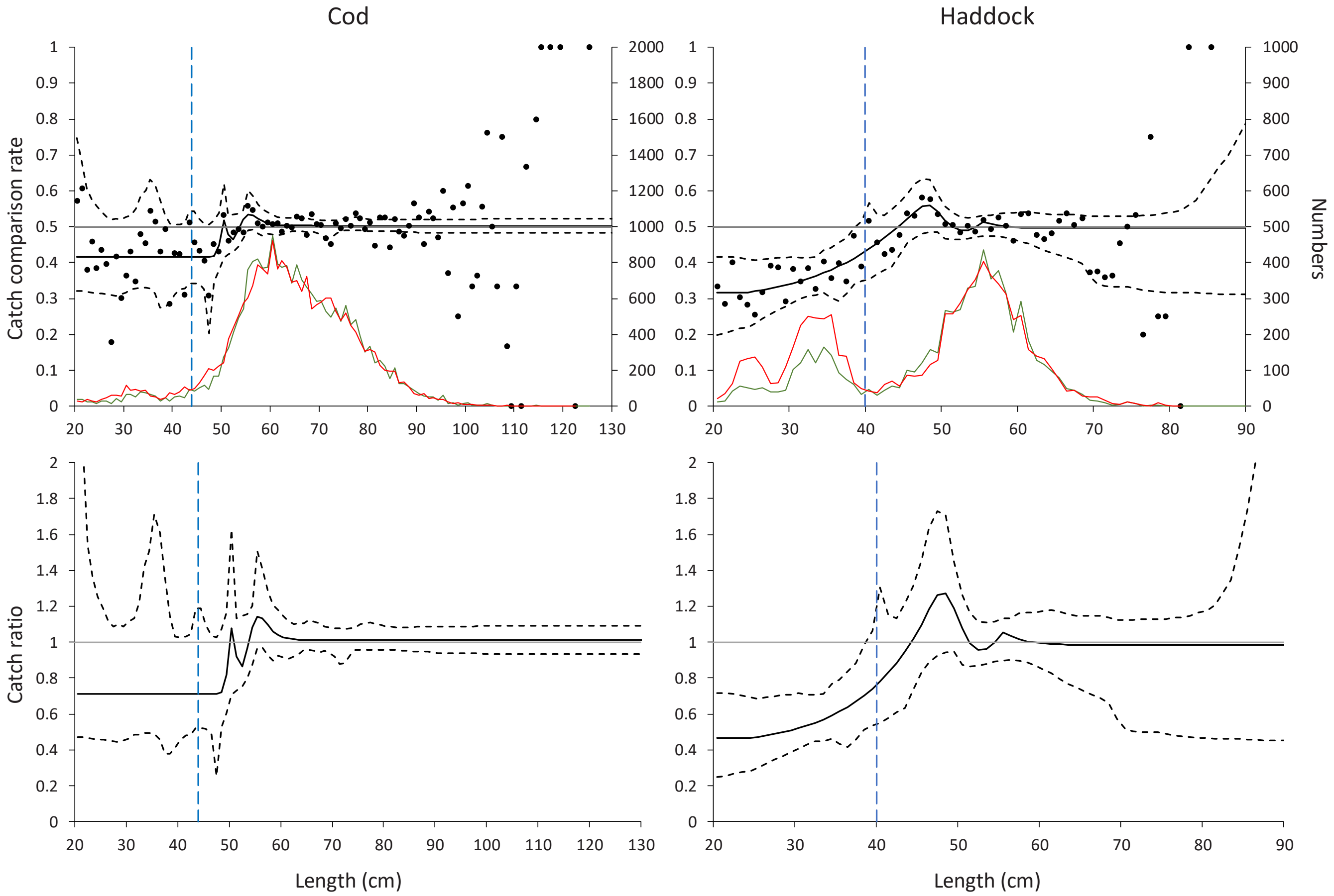

Fig. 4. Catch comparison rate (top row) and catch ratio (lower row) for the trawl configuration with the upscaled grid versus the standard sorting grid. In the catch comparison plots the circles show the experimental catch comparison ratios, whereas the solid line and the stippled lines show the modelled catch comparison ratio and the corresponding 95 % confidence intervals. The green lines show the catch distribution in the upscaled grid configuration gear whereas the red lines show the catch distribution in the standard grid configuration gears, both with scale in the right axis. In the catch ratio plots the solid black curve is the catch ratio curve, and the stippled curves are the corresponding 95 % confidence intervals. The horizontal grey lines represent the line for equal catch efficiency in each of the comparisons, whereas the vertical stippled blue lines represents the *MLS* in every case.

3.2. *Empirical models vs structural models*

In the present study, we applied structural models to model *CC/CR* data for the first time and the results show that these types of models can be better suited to describe *CC* data than empirical models (Table 2; Fig. 3). Further, because they comprise constraints related to the nature of the data, structural models showed to be more appropriate to model the data, especially at the tails, where the data are usually weaker (Fig. 5). Here, the ratio expected in the comparison would be 1.0 because, independent of the grid used, both trawls would be expected to

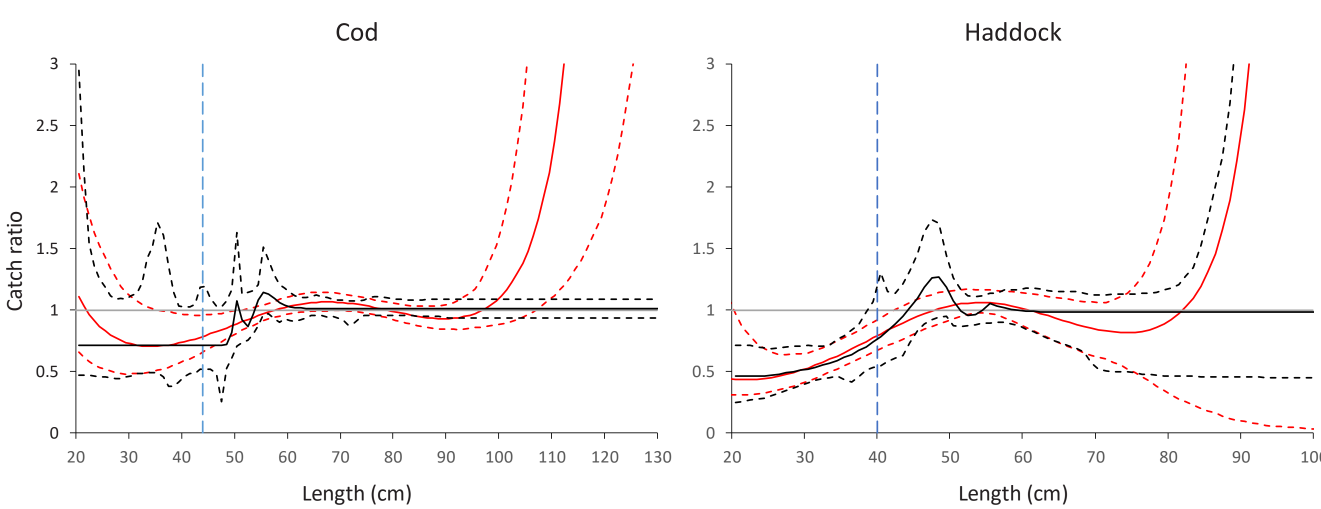

Fig. 5. Comparison of the structural model (black) and the empirical model (red) applied to the data collected for cod (left) and haddock (right).

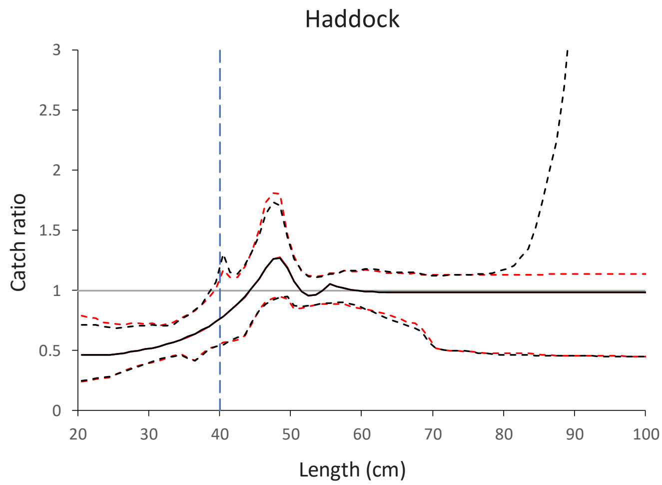

Fig. 6. Comparison of the structural that considers a 4th order polynomial model in the BMS approach (black) and a structural model that does not consider a 4th order polynomial model in the BMS approach.

retain the fish above the sorting range of the 55 mm bar spacing in the grids equally efficiently.

The BMS approach applied in the data analysis (Jacques et al., 2024) showed that for cod, the polynomial model was not the model of choice in any of the 1000 repetitions conducted, meaning that in all cases structural models were the model of choice. For haddock on the other hand, the polynomial model was the most suitable model in 39 out of the 1000 bootstrap repetitions conducted. These 39 cases, which is less than 5 % probability that this would be the model of choice (Fig. 3), led to the upper CI for the largest length classes following an increasing trend that is not consistent with what one would expect from the model at this point (Fig. 6). This particularity does not appear when only structural models are considered in the BMS approach.

3.3. Exploitation pattern indicators

The size-integrated exploitation pattern indicators showed that for cod, the capture probability for fish under *MLS* with the upscaled grid with respect to the standard grid ($CR_{average-}$) was 73.3 %. However, this value was not significantly different from 100 %, meaning that the difference between the gears for this indicator was not significant. For haddock, $CR_{average-}$ was 55.33 % and significantly different from 100 %, showing that the trawl with the upscaled grid captured significantly less undersized haddock than the trawl with the standard grid section (Table 3). For both cod and haddock, the estimated capture probability for fish above *MLS* was very close to 100 % meaning that both grids tested were equally efficient at retaining commercial-sized fish of the two species (Table 3). The discard ratio for the upscaled grid was lower than for the standard grid for both cod and haddock, but was not significantly different between the grids for any of the species. The discard ratio was significantly higher for haddock than for cod for both grid configurations tested (Table 3).

Table 3
Exploitation pattern indicators for the trials comparing the upscaled grid configuration (*U*) and the standard grid configuration (*S*).

	$CR_{average-}$ (%)	$CR_{average+}$ (%)	*nDiscard ratioU* (%)	*nDiscard ratioS* (%)
Cod	73.31 (51.68 - 105.92)	100.83 (96.56 - 106.24)	4.90 (3.58 - 6.49)	6.62 (4.62 - 8.34)
Haddock	55.33 (45.23 - 69.01)	101.98 (93.37 - 111.02)	22.27 (13.81 - 34.56)	3456. (21.76 - 49.74)

4. Discussion

In the past three decades, the size and capacity of the vessels and the demersal trawls commonly used in the Barents Sea demersal trawl fishery have increased substantially (Riksrevisjonen, 2020; Standal and Asche, 2018). However, the compulsory grid sections used by the fleet have remained the same size since they were implemented in 1997 (Fiskeridirektoratet, 2023) and therefore, there was a need to investigate the potential benefits of applying an upscaled grid with a larger sorting area. The main reason for the strict regulations in the grid construction guidelines and the fishing vessels not to be allowed to use many different grids including grids with larger sorting areas can be attributed to control reasons. The demersal resources in this region are share between Norway and Russia and there are also vessels from several third countries that have smaller quota rights in the area. Thus, standardization and strict regulations in the grid section construction for all participating vessels makes it easier for the authorities to control that fishing vessels comply with the grid regulation in force.

The changes in the size of the sorting grid and the grid section tested in the present study probably lead to changes in fish behavior in the section and consequently the length-dependent contact probability at the grid. Thus, the increase in space between the lifting panel and the grid resulting from the upscaling of the netting section could in principle contribute to fish passing through the grid without contacting the grid. On the other hand, increasing the size sorting area of the grid will likely spread the area at which the fish entering the grid section contacts the grid, increasing the probability for them to orientate with a length-dependent probability to be size sorted on it.

The improved size sorting efficiency demonstrated for the upscaled sorting grid tested here can be an especially valuable example for both demersal and pelagic trawl fisheries that can benefit from using sorting grids and have implicit risk for high fish entry densities. Further, this improved sorting ability could be of value in other fisheries where the species involved have limited ability to contact the grid. A fish can potentially pass through the grid section without contacting the grid and getting a chance to escape because it can pass over the lifting panel and below the grid. Fish with poor swimming ability that fail to orientate themselves towards the grid with an orientation that provides them with the chance to pass through the grid would be especially susceptible to this. With a larger grid, it is likely that fish with poor swimming ability increase their chance to meet the grid with an orientation that provides them with a length-dependent probability to be size sorted by the grid. This could be the reason that in shrimp fisheries, larger grids have been demonstrated to provide more efficient size sorting of shrimp and undersized fish (Larsen et al., 2018a).

Haddock have previously been reported to increase their number of escape attempts from a trawl at lower densities (Jones et al., 2008). Although similar studies are not conducted for cod, it is likely that lower fish densities also have a positive effect on the number of escape attempts for cod. However, haddock is a more active species than cod in the trawl with a higher ability to contact the grid to be size sorted (Sistiaga et al., 2010; Krag et al., 2014; Larsen et al., 2018b). Thus, it is possible that haddock can take more advantage than cod of the increase in grid area in the upscaled grid, increasing its chances for escape when it can physically pass between the bars in the grid. Moreover, earlier studies have shown that compared to cod, haddock swim higher up in the trawl body (Main and Sangster, 1981, 1982; Engås et al., 1998), which will make more unlikely that haddock swims through the upscaled grid section without contacting the grid, despite the increased space between the lifting panel and the grid. It could be speculated that the selectivity for other relevant fish species in the fishery would also benefit from increasing grid sorting area. Saithe and redfish have been reported to behave very actively in the trawl and seek outlet from it more actively than cod (Tschernij and Suuronen, 2002; Krag et al., 2014; Grimaldo et al., 2018), whereas for Greenland halibut, whose orientation towards the grid is critical for escape (Herrmann et al., 2013), an upscaled grid would likely only increase the probability for size selection. However, further tests with large trawls and upscaled grids on these species are needed to make a complete scientific evaluation of the consequences of implementing an upscaled grid.

The industry would benefit from the possibility of using an upscaled grid that matches large demersal trawls better. Further, the upscaled grid could be applied with smaller trawls if the fish densities in the fishing area are high. Due to its improved sorting ability, the upscaled grid tested here retained less undersized fish with respect to commercial-sized fish than the standard grid. This would be largely beneficial for the fishing industry as it would contribute to maximizing the value of their quotas and at the same time would reduce the environmental impact and inconveniences linked to catching fish under *MLS*. The use of the upscaled sorting grid did not imply any additional work or maneuverability challenge for the crew compared to the standard sorting grid. But, due to its size, the risk for the bars in the upscaled grid to bend is higher than that of the standard grid and therefore, the grid needs to be tested over longer periods, and its structural strength may have to be further improved.

Catch comparison data like those collected in the present study to compare the size sorting efficiency of the standard and upscale grids tested, have traditionally been analysed using empirical models. The main reason for choosing this type of modelling is that the flexibility of empirical models can often represent the trends in the data well. However, this flexibility can also lead to features in the resulting models that do not concord with what one could logically expect from the nature of the comparison. Thus, contrary to structural models that imply pre-established constraints based on logic assumptions, empirical models can result on models which are partially an artifact of the approach used, especially in cases of poorly represented length classes. This is well illustrated by the empirical model fitted to the *CR* data in this study, which showed a steep increase for the largest length classes of cod and haddock. This increase is simply a consequence of the binominal noise in the data due to the lack of fish for those length classes. This particularity does not appear when only structural models are considered in the BMS approach, illustrating the advantages of only considering structural models when some of the characteristics of the expected model are known with certainty in advance.

In conclusion, the findings in the present study show the need for upscaling size selectivity devices applied in trawls to cope with the increase in capacity and catch efficiency of modern fishing vessels. Further, the study illustrates the advantages of applying structural models to *CC* data and why such an approach can be more adequate than the typically used empirical models to analyze data comparing the performance of different fishing gear.

CRediT authorship contribution statement

Dagfinn Lilleng: Writing – original draft, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Liz Kvalvik:** Writing – original draft, Investigation, Data curation. **Jostein Saltskår:** Writing – original draft, Investigation, Data curation. **Kristian L. Skaar:** Writing – original draft, Investigation, Data curation. **Manu Sistiaga:** Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Bent Herrmann:** Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Formal analysis, Conceptualization. **Jesse Brinkhof:** Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Hermann Pettersen:** Writing – original draft, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2025.107430.

Data availability

Data will be made available on request.

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