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Are rigid sorting devices necessary to control size selectivity in demersal trawl fisheries?

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ABSTRACT

Diamond mesh codends are the most common size selectivity devices in trawls for releasing bycatch and undersized individuals. However, codend selectivity can vary due to the flexibility of the netting meshes, making discrimination by size between retained and released fish difficult to control. In some trawl fisheries, rigid sorting devices have been introduced to make size selection more controlled with sharper discrimination by size. However, the resulting size selectivity often does not show a sharp size selection. In the present study, we tested and compared the size selectivity performance of two “diamond-mesh codend designs” in the Barents Sea gadoid-trawl fishery: a four-panel codend, which was more rigid than a traditional two-panel codend design due to the additional selvedges, and a fully rigid codend design, that included a metal frame. The aim was to investigate the effect of added codend rigidness on the size selectivity of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and redfish (*Sebastes* spp.). In addition, the obtained results were compared to earlier research on size selectivity in this fishery including codends with different levels of rigidness and sorting grids. The results demonstrated that using a fully rigid codend did not result in a sharper size selectivity compared to a four-panel codend. Further, there was no indication that a rigid sorting grid makes size selectivity sharper than what can be obtained with a four-panel diamond mesh codend alone. There was also no proof that other codend stabilizing mechanisms such as shortened lastridge ropes could make the size selection sharper compared to the four-panel codend.

1. Introduction

In trawl fisheries, the codend is the aft part of the gear where the catch accumulates during the fishing process. The size selection of fish entering the trawl often takes place in the codend, with escapement of small individuals which are able to pass through the netting meshes, and retention of larger fish (Wileman et al., 1996; Herrmann, 2005a). The codends used in most trawl fisheries around the world are made of diamond mesh netting due to the simplicity in construction and ease of operation (Bak-Jensen et al., 2022). However, such codends can exhibit complex mechanical behaviors because diamond meshes are constructed of flexible twine, allowing variation in mesh openness in different parts of the codend during the fishing process (O’Neill and Kynoch, 1996; Herrmann and O’Neill, 2005). The variability in the openness of diamond meshes implies that fish of the same species and sizes are subjected to different escape opportunities in the codend as fish morphology and mesh geometry together are factors having major influence on the escape opportunities (Herrmann et al., 2009; Sistiaga et al., 2011; Tokaç et al., 2016; Tokaç et al., 2018; Cuende et al., 2020a; Cuende et al., 2022;). This depends on when during the fishing process they enter the codend and try to escape, as mesh openness can vary due to catch accumulation (Herrmann, 2005b). Therefore, the complex mechanical behavior of the codend may result in differences in retention probability for fish of the same species and sizes (Herrmann, 2005b; Herrmann and O’Neill, 2005; Herrmann et al., 2009).

The size-dependent retention probability for a species in a trawl is

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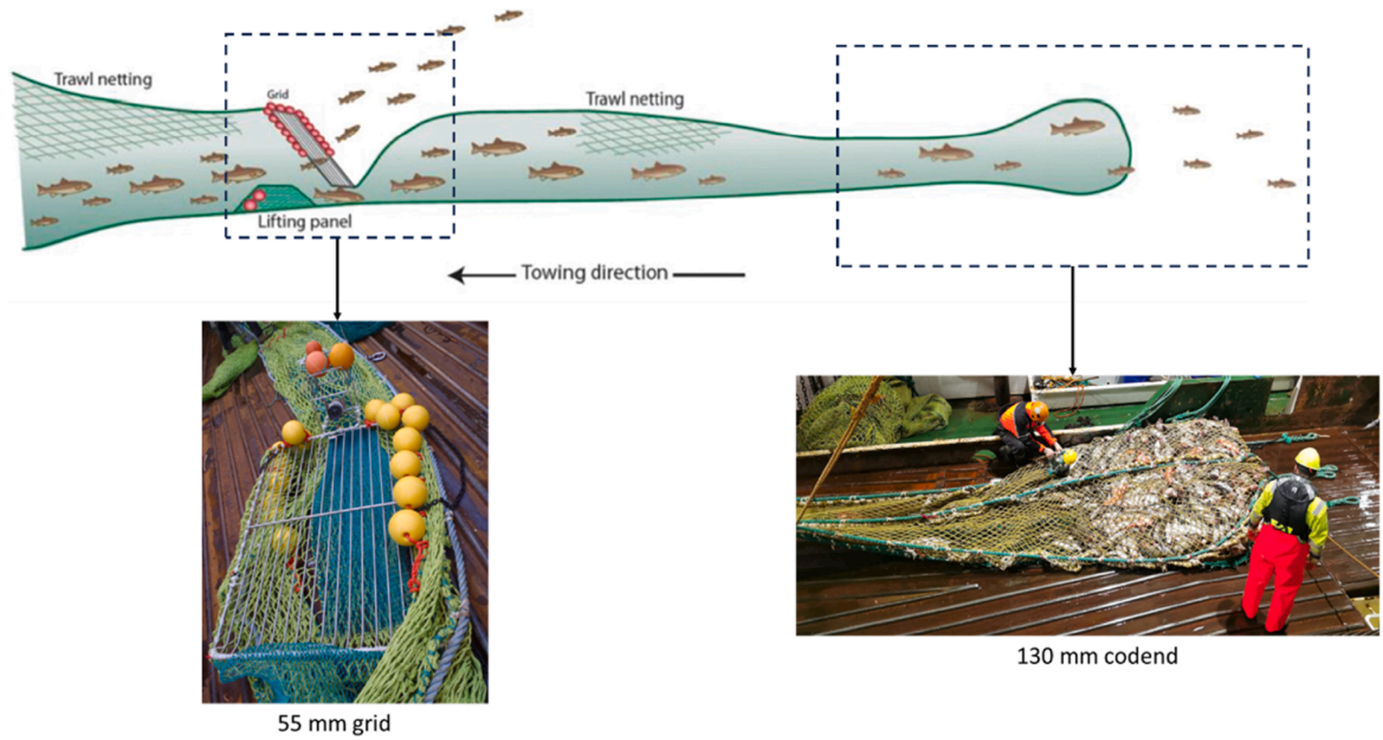

Fig. 1. Illustration of the grid and codend configuration mandatory in the Barents Sea demersal trawl gadoid fishery.

quantified by a size selection curve, which for a codend can be modelled by a s-shaped curve with increasing probability for retention with increasing fish size (Wileman et al., 1996). The sharpness of the selection curve defines how effective the codend can discriminate fish by size, i.e., which individuals will be retained or released, respectively. The mean transition point between the fish sizes that are released or retained depends on the fish species and the design characteristics of the codend, with factors such as mesh size and shape being among the most decisive (Wileman et al., 1996; O'Neill and Herrmann, 2007).

In fisheries which are regulated by minimum legal sizes (*MLS*), size selectivity devices such as codends that result in sharp selection curves are desirable because the fisheries management and industry objective is to minimize mortality of undersized individuals and maximize the catch of target size individuals. Specifically, such size selectivity devices in trawls should then be designed to have their mean transition point at the *MLS*, retaining most individuals above that specific length while releasing most individuals below. In practice, such sharp size selection is challenging to achieve due to several factors, including variation in the openness of the codend meshes during fishing. Thus, the potentially low discrimination efficiency due to mesh opening angle variability challenges the effectiveness of the technical selectivity measures like minimum codend mesh size to regulate fisheries (Bak-Jensen, 2022).

To improve codend size selection, several different technical measures have been applied (Kennelly and Broadhurst, 2021) including codend circumference (Sala et al., 2011, 2016, Reeves et al., 1992) or twine thickness (Sala et al., 2007; Graham et al., 2009, Herrmann et al., 2013a). Further, technical measures adding rigidness, i.e. making the codend structure and mesh shape less variable, have been applied including the use of shortened codend lastridge ropes (SL) (Isaksen and Valdemarsen, 1990; Lök et al., 1997; Ingólfsson and Brinkhof, 2020; Cuende et al., 2022), turning codend netting 90 degrees (T90) (Wienbeck et al., 2011; Cheng et al., 2020; Brinkhof et al., 2022a) or increasing the number of codend selvedges by constructing the codend by four panels (Cheng et al., 2019).

However, in some specific fisheries, instead of changing the construction design of codends to reduce its size sorting variability, additional sorting devices that contribute to the overall size selectivity of the trawl have been introduced (He and Balzano, 2007; Cuende et al., 2020b). This is the case in the Barents Sea demersal trawl fishery targeting gadoid species. This fishery is regulated by *MLS*s, which for cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) are 44 cm and 40 cm, respectively. Apart from cod and haddock, which are the two main species in the fishery, the bycatch of redfish (*Sebastes* spp.) is also common in the fishery. The *MLS* for this species is 32 cm. In this fishery, the use of a rigid or semi-rigid sorting grid with a 55-mm bar spacing followed by a codend with a minimum mesh size of 130 mm is mandatory (Fig. 1) (Brinkhof et al., 2022a). The codends normally used are flexible and constructed of two panels (two-panel design) (Tveit et al., 2019; Hermann Pettersen, Norwegian Directorate of Fisheries, Personal Communication). A combined selective system like this allows bycatch and undersized fish to escape through, first, grid bar spacing or, second, codend netting meshes (Fig. 1), while the larger fish are being retained by the gear. The design and selectivity properties of such gear design have been tested and implemented in this fishery since the '90 s (for example, Larsen and Isaksen, 1993; Jørgensen et al., 2006; Sistiaga et al., 2016; Larsen et al., 2018a; Ingólfsson and Brinkhof, 2020; Brinkhof et al., 2022a, b).

Since the introduction of the mandatory grid and codend selectivity system almost 30 years ago, the use of the different types of grids has been discussed regarding their effectiveness. Specifically, according to fishermen and, to some extent, the scientific community, the additional costs and safety issues that follow the use of grids are not justified because there is no gain in the overall size selection performance of the gear by using a grid (Jørgensen et al., 2006; Grimaldo et al., 2008). The size selectivity of the grids has been assumed to be relatively sharp. However, the results of recent studies have shown that this is not necessarily true (Sistiaga et al., 2016). Therefore, the efforts to find codend constructions that alone would result in at least as sharp size selection curves as those obtained with the mandatory grid and codend configuration (Fig. 1), have increased in recent years (Brinkhof et al., 2022a, b; Sistiaga et al., 2022, 2023). Such codend constructions include, for example, T90 codends (Brinkhof et al., 2022a), four-panel

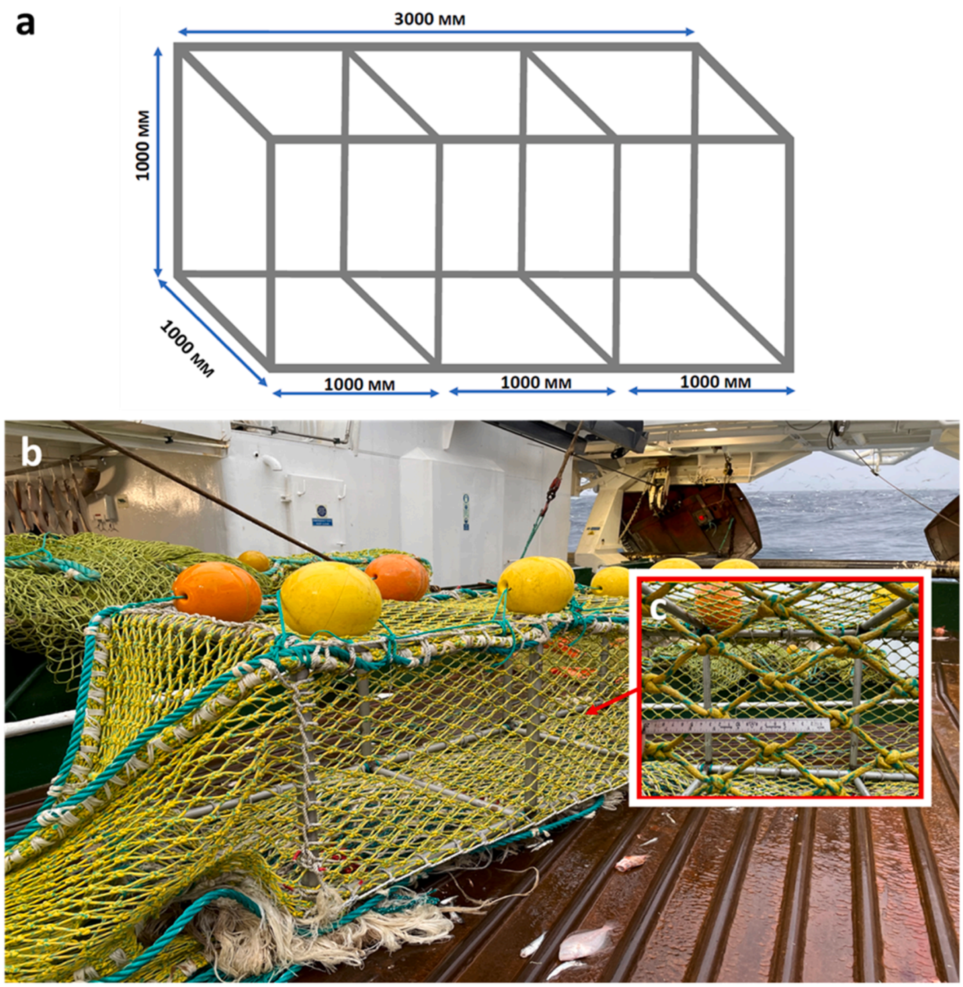

Fig. 2. a: schematical drawing of the dimensions of the frame used for testing fully rigid codend design. b: side view of the experimental fully rigid codend using the frame. c: zoomed lateral view of the netting in the fully rigid codend.

codends (four-panel design) (Sistiaga et al., 2023) and codends using SL (Brinkhof et al. 2022b; Sistiaga et al., 2022, 2023). The objective of the modifications made in these constructions is to add rigidness to the codend structure. This increased rigidness would lead to meshes with more uniform mesh openness along the codend throughout the whole fishing process compared to, for example, the traditional two-panel codends used in this fishery. More uniform mesh openness is believed to provide steeper selection curves as recently demonstrated for cod by Bak-Jensen et al. (2022) in the Baltic Sea demersal trawl fishery.

Encouraged by the positive results obtained with the codend constructions recently tested in the Barents Sea (Brinkhof et al., 2022a; Sistiaga et al., 2022, 2023) and the results obtained by Bak-Jensen et al. (2022) in the Baltic Sea fishery, the present study aimed at discerning how sharp and well-defined size selectivity can be achieved by increasing codend rigidness and controlling mesh openness during the fishing operation in the Barents Sea gadoid fishery. The research conducted included testing a four-panel codend and a fully rigid codend. Further, it compared the results to previously tested codends and the mandatory grid and codend configuration in this fishery.

2. Materials and methods

2.1. Fishing trials

Fishing trials were conducted onboard the research vessel Helmer Hanssen (63.9 m LOA and 4080 HP) along the coast of Norway (71°17.96–N - 71°40.30 N; 02°421.22–E - 02°656.95 E) between the 22nd of February and the 2nd of March 2023. The fishing gear used consisted of an Alfredo 3 trawl with a 19.2 m long fishing line and a 36.5 m long headline, and a pair of Injector Scorpion trawl doors (3100 kg and 8 m^2). The trawl was the same and rigged identical to Brinkhof et al. (2022a) and Sistiaga et al. (2023), with 60 m long sweeps, a 46 m long ground gear including an 18.9 m long rock-hopper gear in the middle. During the experiments, the geometry of the trawl was monitored by means of a set of trawl door sensors and a trawl height sensor (Marport).

A 12 m long extension piece followed by a two- to four-panel transition piece were mounted before the codend. The codend was constructed of four identical diamond mesh panels. Each panel was 80 meshes long and 15 meshes wide built of 8 mm polyethylene (Hotmelt) twine and the mesh size was measured to be 132.80 $\pm$ 2.49 mm (mean $\pm$ SD). The meshes were measured with an OMEGA gauge and measuring two rows of 20 meshes. To test the fully rigid codend design, a 3 m long, 1 m wide and 1 m high frame built of thick steel tubes of Ø50 mm in diameter was used (Fig. 2a).

During the first half of the trials, this frame was fixed to the selvedges inside the codend, four meshes in front a choking rope inserted five meshes before the codline. The chocking rope ensured that all fish entering the codend was held in the frame and did not drift back to the last meshes before the codline, where the meshes were nearly closed. The selvedges and two meshes from each side of the panel were fixed to the frame so that each side of the frame was covered by netting panel with 11 meshes in height (Fig. 2b). Such fixed meshes had a resulting opening angle (OA) of $69.4 \pm 1.33°$, which is close to the optimal mesh OA for the escape of cod and haddock estimated in earlier studies (Herrmann et al., 2009; Sistiaga et al., 2011) (Fig. 2c). The mesh shape was digitized from a picture of the fully rigid codend taken on deck, and the OA estimated using the same method as in Sistiaga et al. (2011) and Bak-Jensen et al. (2022). Three meshes were selected at different points of the codend and a hexagonal shape fitted to them. The average opening angle of the hexagonal meshes fitted was then estimated as a rough average mesh OA in the fully rigid codend. During the second half of the trials, the frame as well as the choking rope were removed from the codend, so that the same codend netting was used when further testing the size selectivity of the less rigid four-panel codend configuration.

To collect potential escapees from the codend, we applied the covered-codend method as described in Wileman et al. (1996). The cover had the same design as the one used in Sistiaga et al. (2023), which ensured that no cod, haddock or redfish above 10 cm could escape through the cover meshes according to Sistiaga et al. (2011) and Herrmann et al. (2012). The cover had a diameter of 2.4 m, was 20 m long, and the mesh size was measured to be 41.63 ± 1.35 mm. To keep the cover off the codend, the cover was rigged with floats (top), six kites (sides) and 12 kg chains (bottom) at the entrance, and 12 kites around the circumference of the cover 2 m in front of the codline.

The catches in the codend and the cover were always kept separated and the total length of all cod, haddock, and redfish above 10 cm was measured to the nearest cm below.

2.2. Size selectivity data analysis

Codend size selection for fish is often described by a non-decreasing s-shaped curve that quantifies the retention probability as a function of length (Wileman et al., 1996). For a given species, the size selection properties of a codend are often quantified by two parameters: *L50* and selection range (*SR)*. *L50* is the length of fish that has 50% probability for being retained in codend conditioned it enters it. *SR* is the difference in length between fish with 75% retention probability and fish with 25% retention probability (Wileman et al., 1996). Therefore, the value of *SR* for a specific species and fishing gear can be used to quantify the sharpness of its size selection (Bak-Jensen et al., 2022). However, when size selection estimates are to be applied to quantify how well-controlled the specific codend can size discriminate between retained and released fish, the effect of between-haul variation in the size selection process needs to be considered (Frandsen et al., 2011; Sala et al., 2015). For example, even if the mean size selection curve is steep with a small *SR* value, if there is a considerable between-haul variation in *L50*, some hauls could hypothetically lead to the catch of many small fish while others could lead to the loss of large fish (Sala et al., 2015). One way to include the effect of between-haul variation into a single selection curve and, therefore, in the estimated *SR* value, is to estimate what Millar (1993) defined a "fishery selection curve" (Sistiaga et al., 2010; Herrmann et al., 2012). This can be obtained by pooling data over all hauls in the size selectivity analysis as described below.

In each haul, the data consisted of length class (l) count numbers of the fish of each species separately present in the codend and cover, respectively. The retention probability for each length class was then estimated from the number of fish in the codend and in the cover. The data in all hauls were analyzed pooled species by species to estimate the average size selectivity for the species and gear tested (Millar, 1993). The "average" retention probability $r(l)$ for each species was modelled using nine different parametric models that lead to non-decreasing size selectivity curves. These curves are asymptotically restricted to values between [0.0; 1.0].

The first four models applied are known as the *Logit, Probit*, *Gompertz*, and *Richards* models, and are described in detail in Wileman et al. (1996) and Bak-Jensen et al. (2022). The *Logit*, *Probit* and *Gompertz* models include the parameters *L50* and *SR*, whereas the *Richards* model requires an additional parameter (D), that gives more flexibility to the curve. When $D = 1.0$, the *Richards* curve becomes a *Logit* curve.

For each of the four traditional models, an equivalent model where only a fraction (C) of the fish entering the codend was subjected to a length-dependent probability of escape through the meshes in the codend was considered (Sistiaga et al., 2010; Herrmann et al., 2013a, Larsen et al., 2018a). These models are described in literature as *CLogit*, *CProbit*, *CGompertz*, and *CRichards* (further detail on the models can be found in Cuende et al., 2020b). In these models, if 25% of the fish would not contact the codend meshes, C acquired a value of 0.75, whereas if only half of the fish would contact the codend meshes C would be 0.5. The models with the parameter C were considered relevant because, especially in the hauls with the rigid codend, the potential increase in distance from the center of the codend to the netting panels could affect the contact of fish with the codend meshes.

In addition to the four traditional models and the corresponding four models including the contact parameter (C), a ninth model described as the *DLogit* model (Herrmann et al., 2016) was also considered. The *DLogit* model can describe a dual selection process assuming that a fraction of the fish entering the codend is subjected to one logistic size selection process whereas the remaining fraction is subjected to a different logistic size selection process.

Thus, nine models in total were considered for the codend size selection:

$$r(l,\boldsymbol{v}) = \begin{cases} Logit(l, L50, SR) \\ Probit(l, L50, SR) \\ Gompertz(l, L50, SR) \\ Richards(l, L50, SR, D) \\ CLogit(l, C, L50, SR) \\ CProbit(l, C, L50, SR) \\ CGompertz(l, C, L50, SR) \\ CRichards(l, C, L50, SR, D) \\ DLogit(l, C, L50_1, SR_1, L50_2, SR_2) \end{cases} \tag{1}$$

The selection curves and associated selectivity parameters $\boldsymbol{v}$ were estimated by means of a maximum likelihood function, which minimizes the negative of the log-likelihood function derived from the binomial probability mass function (Bak-Jensen, 2022):

$$LogLikelihood = -\sum_{i=1}^{m}\sum_{l}\{nr_{il} \times \ln(r(l,\boldsymbol{v})) + ne_{il} \times \ln(1.0 - r(l,\boldsymbol{v}))\} \tag{2}$$

where nr_{il} is the number of fish of length class l retained in the codend and ne_{il} is the number of fish of length class l that escaped from the codend into the cover in haul i. Among the nine candidate models the one with lowest AIC value (Akaike, 1974) was chosen to model the codend size selection for each species and codend individually. Once the specific model was identified for each species and codend configuration, the double bootstrap method implemented in the statistical analysis tool SELNET (Herrmann et al., 2012) was used to obtain the confidence intervals (CIs) for the size selection curve and the corresponding parameters. This bootstrapping approach is identical to the one described in Millar (1993) and takes into consideration both within-haul and between-haul variation for uncertainty estimation. For each species analyzed, 1000 bootstrap repetitions were conducted to obtain uncertainties for the size selection curve and associated model parameters in terms of Efron percentile 95% CIs (Efron, 1982; Herrmann et al. 2012).

2.3. Effect of codend mesh openness fixation

To estimate the potential effect of codend mesh fixation, the potential differences in size selectivity ($\Delta r(l)$) between the rigid codend configuration and the four-panel codend configuration were estimated by:

Table 1
Overview of the hauls conducted during the fishing trials with the rigid and four-panel codend configurations. In addition to the towing time and depth, the numbers (n) of cod, haddock, and redfish retained in the codend and codend cover in each haul are shown. *: no data.

Date	Haul number	Time (UTC)	Towing time (min)	Codend configuration	Depth (m)	Cod (n)		Haddock (n)		Redfish (n)	
						Codend	Cover	Codend	Cover	Codend	Cover
24.02.2023	1	03:47	61	Rigid	294.75	113	0	36	247	6	2
24.02.2023	2	05:46	90	Rigid	293.86	250	3	33	232	*	*
24.02.2023	3	12:06	121	Rigid	267.17	206	21	161	214	82	56
24.02.2023	4	15:30	120	Rigid	249.16	108	17	93	135	54	64
24.02.2023	5	18:19	121	Rigid	266.9	226	30	268	238	101	121
25.02.2023	6	00:33	120	Rigid	233.89	141	18	34	48	87	97
25.02.2023	7	03:40	121	Rigid	271.12	268	47	189	306	124	117
25.02.2023	8	07:33	120	Rigid	242.8	201	20	52	173	126	212
25.02.2023	9	12:14	122	Rigid	256.45	124	12	68	227	241	194
25.02.2023	10	15:07	125	Rigid	264.68	115	25	61	155	159	144
25.02.2023	11	17:51	122	Rigid	257.31	145	30	69	461	41	34
25.02.2023	12	22:00	118	Rigid	285.75	60	6	16	367	12	7
26.02.2023	13	01:22	120	Rigid	287.49	156	5	10	126	10	6
26.02.2023	14	04:09	216	Rigid	*	565	17	57	289	10	9
26.02.2023	15	11:17	123	Four-panel	292.33	112	16	30	306	18	14
26.02.2023	16	14:10	122	Four-panel	301.05	149	6	57	655	13	9
26.02.2023	17	17:00	120	Four-panel	287.56	404	4	114	27	8	5
26.02.2023	18	19:56	114	Four-panel	276.5	360	16	74	80	12	10
26.02.2023	19	22:35	82	Four-panel	289.86	535	17	21	29	11	11
01.03.2023	20	01:25	120	Four-panel	292.75	705	72	94	165	26	11
01.03.2023	21	04:10	135	Four-panel	289.02	619	32	197	264	31	10
01.03.2023	22	09:22	119	Four-panel	292.61	956	43	172	342	83	11
01.03.2023	23	14:40	120	Four-panel	289.51	347	13	71	48	28	12
01.03.2023	24	17:22	120	Four-panel	291.99	617	69	49	94	28	8
01.03.2023	25	20:08	121	Four-panel	289.19	361	22	44	70	19	15
02.03.2023	26	00:17	120	Four-panel	291.64	383	37	28	140	12	8
02.03.2023	27	03:00	121	Four-panel	287.21	251	13	11	167	9	11
02.03.2023	28	05:55	119	Four-panel	294.5	384	37	41	618	36	15
02.03.2023	29	08:45	156	Four-panel	300.86	446	73	60	1003	48	23
02.03.2023	30	11:57	151	Four-panel	290.99	148	12	26	562	48	13

$$\Delta r(l) = r_{rigid\quad codend}(l) - r_{four-panel\quad codend}(l) \tag{3}$$

To obtain the 95% CIs for $\Delta r(l)$, the bootstrap population results for $r_{four\text{-}panel\ codend}(l)$ and

$r_{rigid\ codend}(l)$ were used. As they were obtained independently of each other, a new bootstrap population of results for $\Delta r(l)$ was created following a procedure widely applied in literature (Larsen et al., 2018b; Cheng et al., 2019; Einarsson et al., 2021; Petetta et al., 2021; Sistiaga et al., 2023). The same approach (Eq. 3) was applied to obtain estimates for differences *ΔL50* and *ΔSR* in selection parameters by codend mesh fixation.

2.4. Comparison to earlier studies

To quantify how well-controlled and sharp size selection can be obtained by using the specific sorting device and to what extent different gear configurations can provide controlled and sharp size selection, we compared the *SR* values of the gears tested in this study to those obtained with different gear configurations in earlier studies in this fishery. We also compared the *L50* values between the studies as it provides an estimate of the size at which the mean length for the discrimination between retained and released fish is located. However, contrary to *SR*, the *L50* of a specific gear can be more easily controlled by, for example, changing mesh size or bar spacing (Sistiaga et al., 2011).

We compared the parameters *L50* and *SR* found in the literature for the selectivity devices including the mandatory grid and codend configuration, four-panel codends with and without SL, two-panel codends with and without SL and T90 codends. The studies included in the comparison were selected by the following set of criteria: (1) the study had to be conducted in demersal trawl fisheries within the same geographical area and targeting the same species as the present study; (2) the size selectivity results for *L50* and *SR* had to be provided with 95% CIs; (3) in studies including sorting grids, the codend selectivity had to be estimated conditional on that the fish entered the codend; and (4) the study had to be conducted using codend with mesh sizes ± 10 mm of the codend mesh size measured in the present study (132.80 ± 2.49 mm). In addition to the four criteria considered here, additional

Table 2
AIC values for the three species included in the trials with the rigid codend and the four-panel codend configurations. Values in bold highlight the models that resulted in the lowest AIC value.

	Cod		Haddock		Redfish	
Model	Rigid codend	Four-panel codend	Rigid codend	Four-panel codend	Rigid codend	Four-panel codend
Logit	675.34	1669.42	**1382.58**	1364.97	1234.5	**239.61**
Probit	673.92	**1659.09**	1384.76	1416.83	1240.42	291.48
Gompertz	736.47	1695.78	1457.19	1617.95	1340.65	300.91
Richards	**666.45**	1669.57	1383.09	1349.22	**1200.4**	294.74
DLogit	670.15	1660.76	1382.77	**1344.79**	1204.24	294.64
CLogit	668.08	1671.8	1428.4	1374.5	1224.9	296.9
CProbit	667.47	1661.76	1424.41	1368.44	1220.9	294.9
CGompertz	675.06	1683.83	1449.21	1379.88	1253.28	303.76
CRichards	668.23	1672.35	1430.4	1375.53	1206.42	298.12

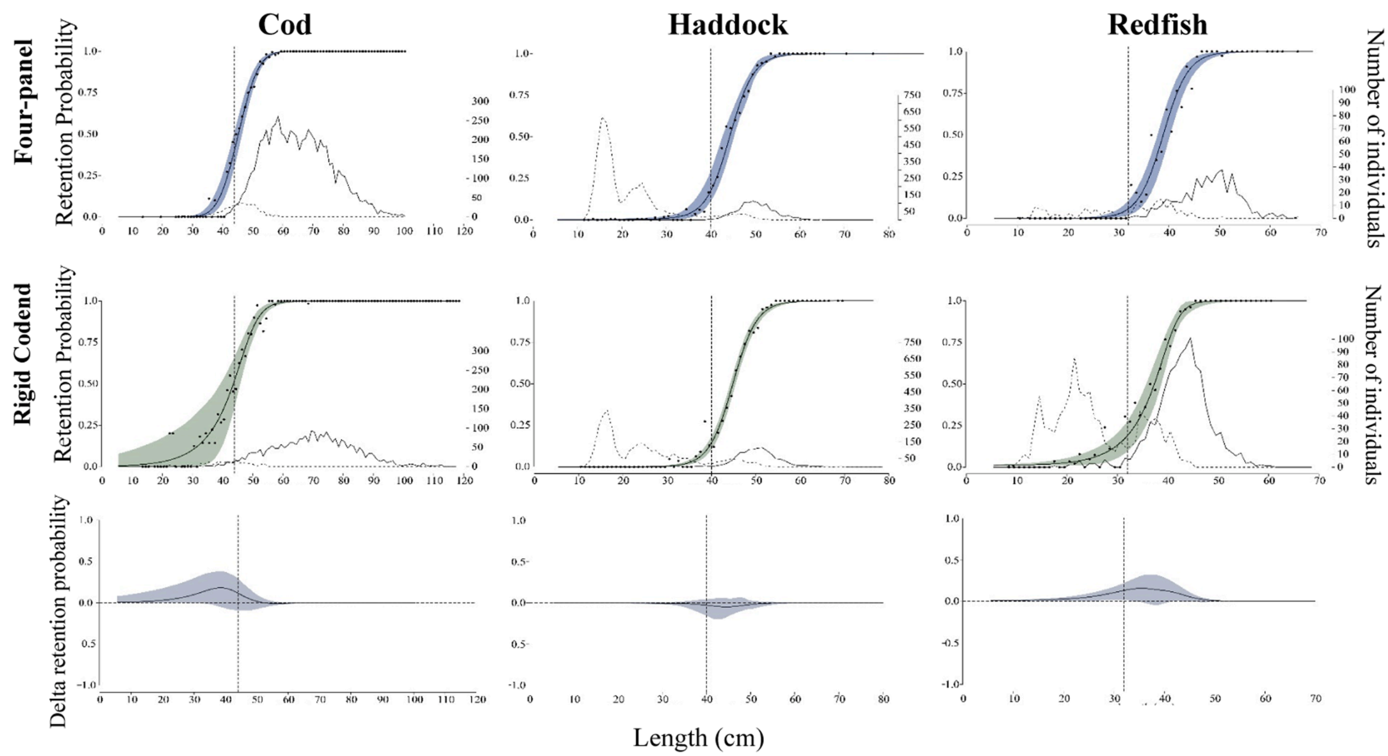

Fig. 3. The two upper rows show length-dependent retention probabilities for cod, haddock, and redfish with the four-panel codend and the rigid codend. In each plot, the circles represent the experimental observations, the solid curve represents the models fitted to the data, and the shaded areas represent the 95% CIs (for four-panel codend (blue) and rigid codend (green)). The black dashed line in the bottom represents the population of fish in the cover whereas the full black line represents the population of fish in the codend. The lower row shows *Δr(l)* plots for the comparison between the four-panel codend (baseline) and the rigid codend. The shaded areas show 95% confidence intervals. The vertical stippled lines show the *MLS* for each species (44, 40 and 32 cm for cod, haddock and redfish, respectively).

Table 3
Fit statistics and size selectivity parameters obtained for cod, haddock and redfish with the rigid codend and the four-panel codend configurations. Values in brackets are 95% confidence intervals.

	Cod		Haddock		Redfish	
	Rigid codend	Four-panel codend	Rigid codend	Four-panel codend	Rigid codend	Four-panel codend
Model	*Richard*	*Probit*	*Logit*	*DLogit*	*Richard*	*Logit*
L50 **(cm)**	43.60 (39.33: 45.89)	45.26 (43.78: 46.63)	44.81 (44.21: 45.45)	44.26 (42.62: 45.25)	37.34 (35.72: 38.71)	38.86 (37.73: 40.22)
SR **(cm)**	10.65 (6.39: 20.76)	7.10 (6.30: 7.90)	5.92 (5.20: 6.70)	5.95 (5.22: 8.62)	6.56 (4.85: 8.18)	5.39 (4.20: 6.37)
***p*-value**	>0.999	>0.999	0.931	0.962	0.224	0.999
Deviance	43.31	39.12	42.01	35.42	56.17	22.99
DOF	104	88	57	52	49	49

codend construction characteristics other than mesh size could have been considered. However, increasing the number of criteria would have reduced the number of comparable studies available and therefore, only those that were considered most relevant were applied here.

Table 4
Values for potential differences in size selectivity (*ΔSR* and *ΔL50*) - between the four panel (four-panel) codend (baseline) and the rigid codend (test) for cod, haddock and redfish. Values in brackets represent 95% confidence intervals.

	Cod	Haddock	Redfish
ΔSR **(cm)**	3.55 (−0.92: 13.43)	-0.03 (−2.74: 1.00)	1.17 (−0.88: 3.20)
ΔL50 **(cm)**	-1.66 (−5.92: 1.30)	0.55 (−0.59: 2.26)	-1.52 (−3.62: 0.42)

3. Results

During the fishing trials, we conducted a total of 30 hauls, where 14 hauls tested the fully rigid codend configuration (Fig. 2) and 16 hauls were carried out using the four-panel codend configuration. Cod, haddock and redfish were captured in sufficient numbers to be included in the size selectivity analysis for both designs tested. In the 30 hauls conducted, a total of 10,188 cod, 10,024 haddock and 2732 redfish were captured and length measured (Table 1).

3.1. Selectivity analysis and model fit statistics

The results obtained with the different models showed that all fish entering the codend were subjected to a size selection process through the codend meshes independent on whether the frame (rigid codend design) was used or not. This is demonstrated by the AIC values (Table 2), which show that neither the *CLogit*, the *Cprobit*, the *CGompertz*, nor the *CRichards* model resulted in the lowest AIC value in any of the six cases (three species and two gear configurations) included in this study. For all cases except for the data for haddock with the four-panel codend, which was best represented by a *DLogit* model, the models with the lowest AIC value were those from the traditional family of models being the *Logit*, *Probit*, *Gompertz*, and *Richards* models.

A visual inspection of the size selectivity curves showed that the models chosen in each case represented the trend in the experimental data well (Fig. 3). This is supported by the fit statistics for the selected models with *p*-value, which exceeded 0.05 in every case (Table 3), meaning that the differences between the data and the modelled curves could well be coincidental.

Table 5
Fishing gear characteristics and selectivity results (*L50* and *SR*) for earlier results of research conducted with different types of sorting devices in the Barents Sea demersal trawl gadoid fishery. The selectivity systems include the mandatory grid and codend combination in the specific fishery, different number of codend panels (two-panel and four-panel codends), two-panel codends with shortened lastridge ropes (SL) and four-panel codends with SL. SL15 and SL30 represent codend where the lastridge ropes were shortened by 15 and 30%, respectively. Values in brackets represent 95% confidence intervals. In the case of the mandatory system (grid and codend combined), L50 and SR are values for the combined system. *: none.

Index	Gear category	Source	Species	Grid bar spacing (mm)	Codend type	Construction	Codend mesh size (mm)	*L50*(cm)	*SR*(cm)
1	Mandatory	Brinkhof et al., 2022b	Cod	55	Diamond mesh	Two-panel	130	52.7 (51.7–53.8)	8.1 (7.3–9.0)
2	Mandatory	Brinkhof et al., 2020	Cod	55	Diamond mesh	Two-panel	133	53.7 (52.3–55.7)	10.3 (9.2–11.2)
3	Mandatory	Sistiaga et al., 2010	Cod	55	Diamond mesh	Two-panel	135	52.9 (51.6–54.5)	8.3 (7.0–10.2)
4	Mandatory	Sistiaga et al., 2010	Cod	55	Diamond mesh	Two-panel	141	54.2 (53.0–55.9)	6.89 (5.5–8.8)
5	Two-panel	Sistiaga et al., 2022	Cod	*	Diamond mesh	Two-panel	128	41.2 (381–43.4)	8.75 (5.6–13.0)
6	Two-panel	Brinkhof et al., 2020	Cod	*	Diamond mesh	Two-panel	133	39.8 (31.1–44.9)	14.5 (10.2–20.7)
7	Two-panel	Sistiaga et al., 2010	Cod	*	Diamond mesh	Two-panel	135	45.8 (42.3–48.3)	8.8 (6.7–11.3)
8	Two-panel	Sistiaga et al., 2022	Cod	*	Diamond mesh	Two-panel	137	44.3 (41.3–47.1)	12.3 (8.4–16.6)
9	Two-panel	Sistiaga et al., 2010	Cod	*	Diamond mesh	Two-panel	141	49.3 (46.4–51.1)	7.3 (5.2–10.0)
10	Four-panel	Sistiaga et al., 2023	Cod	*	Diamond mesh	Four-panel	129	48.2 (47.2–49.1)	8.8 (7.9–10.0)
11	Two-panel SL	Sistiaga et al., 2022	Cod	*	Diamond mesh SL15	Two-panel	128	41.8 (39.5–43.8)	9.6 (8.0–11.2)
12	Two-panel SL	Sistiaga et al., 2022	Cod	*	Diamond mesh SL15	Two-panel	137	49.1 (48.2–49.9)	6.1 (5.3–7.0)
13	Four-panel SL	Sistiaga et al., 2023	Cod	*	Diamond mesh SL15	Four-panel	129	48.4 (46.8–49.8)	6.4 (5.0–7.8)
14	Four-panel SL	Sistiaga et al., 2023	Cod	*	Diamond mesh SL30	Four-panel	129	52.2 (50.6–53.5)	5.9 (4.6–7.3)
15	Four-panel T90	Brinkhof et al., 2022a	Cod	*	T90	Four-panel	136	50.2 (48.6–51.8)	9.7 (8.9–10.5)
1	Mandatory	Brinkhof et al., 2022b	Haddock	55	Diamond mesh	Two-panel	130	51.9 (50.4–54.5)	9.2 (6.7–9.4)
2	Mandatory	Brinkhof et al., 2020	Haddock	55	Diamond mesh	Two-panel	133	55.0 (53.9–56.4)	7.6 (5.2–9.8)
3	Mandatory	Sistiaga et al., 2010	Haddock	55	Diamond mesh	Two-panel	135	51.9 (50.7–53.3)	6.9 (5.2–8.8)
4	Mandatory	Sistiaga et al., 2010	Haddock	55	Diamond mesh	Two-panel	141	53.4 (52.0–54.8)	6.6 (5.0–8.4)
5	Two-panel	Sistiaga et al., 2022	Haddock	*	Diamond mesh	Two-panel	128	39.2 (38.5–39.9)	7.1 (6.0–8.3)
6	Two-panel	Brinkhof et al., 2020	Haddock	*	Diamond mesh	Two-panel	133	46.3 (44.7–48.9)	10.3 (6.4–16.2)
7	Two-panel	Sistiaga et al., 2010	Haddock	*	Diamond mesh	Two-panel	135	43.4 (40.6–45.5)	7.3 (5.3–9.5)
8	Two-panel	Sistiaga et al., 2022	Haddock	*	Diamond mesh	Two-panel	137	41.1 (39.6–42.3)	6.8 (5.0–7.9)
9	Two-panel	Sistiaga et al., 2010	Haddock	*	Diamond mesh	Two-panel	141	45.3 (41.5–47.9)	8.2 (5.1–11.7)
10	Four-panel	Sistiaga et al., 2023	Haddock	*	Diamond mesh	Four-panel	129	37.8 (36.4–39.5)	6.8 (5.6–8.4)
11	Two-panel SL	Sistiaga et al., 2022	Haddock	*	Diamond mesh SL15	Two-panel	128	40.5 (39.8–41.2)	6.8 (6.2–7.3)
12	Two-panel SL	Sistiaga et al., 2022	Haddock	*	Diamond mesh SL15	Two-panel	137	45.1 (44.5–45.7)	6.3 (5.8–69)
13	Four-panel SL	Sistiaga et al., 2023	Haddock	*	Diamond mesh SL15	Four-panel	129	44.0 (42.8–45.1)	5.6 (5.0–6.1)
14	Four-panel SL	Sistiaga et al., 2023	Haddock	*	Diamond mesh SL30	Four-panel	129	46.0 (44.9–46.8)	6.1 (5.0–7.6)
15	Four-panel T90	Brinkhof et al., 2022a	Haddock	*	T90	Four-panel	136	49.0 (47.6–50.1)	8.8 (7.6–10.0)
16	Mandatory	Herrmann et al., 2013b	Redfish	55	Diamond mesh	Two-panel	135	44.5 (42.0–48.9)	8.1 (5.5–11.1)
17	Mandatory	Herrmann et al., 2013b	Redfish	55	Diamond mesh	Two-panel	141	45.6 (42.8–49.4)	8.4 (4.4–14.3)
5	Two-panel	Sistiaga et al., 2022	Redfish	*	Diamond mesh	Two-panel	128	32.8 (31.4–34.9)	6.4 (4.2–8.5)
18	Two-panel	Herrmann et al., 2012	Redfish	*	Diamond mesh	Two-panel	135	39.5 (34.5–42.3)	6.7 (4.0–11.1)

(*continued on next page*)

Table 5 (*continued*)

Index	Gear category	Source	Species	Grid bar spacing (mm)	Codend type	Construction	Codend mesh size (mm)	*L50*(cm)	*SR*(cm)
19	Two-panel	Herrmann et al., 2013b	Redfish	*	Diamond mesh	Two-panel	135	39.5 (34.2–42.7)	6.7 (3.8–11.5)
8	Two-panel	Sistiaga et al., 2022	Redfish	*	Diamond mesh	Two-panel	137	35.2 (32.5–38.6)	9.05 (6.04–12.50)
20	Two-panel	Herrmann et al., 2013b	Redfish	*	Diamond mesh	Two-panel	141	38.8 (0.1–42.6)	5.6 (0.1–33.1)
10	Four-panel	Sistiaga et al., 2023	Redfish	*	Diamond mesh	Four-panel	129	36.0 (34.7–37.6)	9.5(6.3–12.2)
11	Two-panel SL	Sistiaga et al., 2022	Redfish	*	Diamond mesh SL15	Two-panel	128	38.6 (37.2–39.6)	7.6 (5.6–10.1)
12	Two-panel SL	Sistiaga et al., 2022	Redfish	*	Diamond mesh SL15	Two-panel	137	42.5 (41.4–43.5)	6.5 (4.8–8.5)
13	Four-panel SL	Sistiaga et al., 2023	Redfish	*	Diamond mesh SL15	Four-panel	129	38.5 (36.5–40.1)	6.9 (5.1–9.2)
14	Four-panel SL	Sistiaga et al., 2023	Redfish	*	Diamond mesh SL30	Four-panel	129	38.6 (37.6–397)	8.5 (6.3–11.6)

3.2. Effect of using a rigid codend design for size selectivity

For cod and haddock, the selectivity results obtained did not prove any difference in size selection between the rigid codend and the four-panel codend as neither *SR* nor *L50* values were significantly different. Further, the delta analysis showed that *ΔSR, ΔL50* and *Δr*(*l*) contained 0.0 in the 95% CIs (Table 4; Fig. 3). For redfish, neither *ΔSR* nor *ΔL50* were different from 0.0, but the *Δr*(*l*) curve was slightly above 0.0 between 20 and 35 cm, meaning that the rigid codend retained significantly more redfish of those sizes than the four-panel codend (Table 4; Fig. 3). Thus, our results showed that using a rigid codend did not improve the capability to control size selection on any of the species investigated compared to what can be obtained with a four-panel codend.

3.3. Comparison with earlier tested size sorting devices

The comparison of the size selectivity results obtained in the present study with those from earlier experiments conducted in the same area and for the same species show that selectivity varies between codend constructions and can differ significantly from the compulsory grid and codend gear configuration in the Barents Sea (Table 5).

3.3.1. Comparison of sharpness in size selection (SR)

The SR obtained for cod with the rigid codend configuration was inconclusive due to wide CIs (6.39: 20.76 cm), which resulted in that the SR for this configuration did not differ significantly from any of the earlier results included in the comparison. Regarding the four-panel codend, none of the earlier studies had significantly lower SR. However, comparing with the four-panel codend tested here, the gear tested in several studies resulted in significantly higher SR for cod: Brinkhof et al. (2020) with the mandatory gear grid and codend gear and a 133 mm two-panel codend alone, Sistiaga et al. (2022) with a 137 mm two-panel codend, Sistiaga et al. (2022) with a 128 mm two-panel codend with SL and Brinkhof et al. (2022a) with a 136 mm T90. The only earlier reference with a four-panel codend (Sistiaga et al., 2023) also resulted in a significantly higher SR than the one obtained here (Fig. 4; Table 5).

The SR results obtained for haddock with the two codend configurations tested in this study were well in line with those earlier obtained in this fishery with other size sorting devices (Table 5). The SR obtained with the rigid codend in these experiments differed only from one study (Brinkhof et al. 2022a) testing a 136 mm T90 codend resulting in a significantly larger than SR value. The rest of the comparisons revealed no significant differences (Fig. 4; Table 5).

For redfish, the two codend configurations tested in the present study showed an indication of lower SR compared to those earlier obtained in this fishery with other size sorting devices (Table 5). This was especially the case for the four-panel codend. However, the SR obtained for neither the four-panel codend nor the rigid codend differed significantly from any of the earlier results obtained results with other selectivity configurations in this fishery (Fig. 4; Table 5).

3.3.2. Comparison of L50

For cod, the *L50s* obtained with the two codend configurations tested in the present study were significantly lower than the ones obtained for the mandatory grid and codend configuration in four earlier studies. Regarding the comparison with other earlier tested codend configurations, the two-panel codends from earlier studies showed selectivity properties similar to those of the two codend configurations tested here. Only the *L50* for the 141 mm two-panel codend tested in Sistiaga et al. (2010) was significantly higher than the *L50* for the rigid codend configuration tested here. In general, the *L50* values obtained in earlier studies with SL codends for cod were significantly higher than the results obtained here with exception of results described in Sistiaga et al. (2022) testing the 128 mm SL codend. Finally, the 136 mm T90 codend tested in Brinkhof et al. (2022a) showed a significantly higher *L50* compared to the present study (Fig. 5; Table 5).

The mandatory grid and codend configurations tested in earlier studies resulted in higher *L50* values for haddock than the two codend configurations tested here. The comparison with two-panel codends earlier tested in this fishery showed variable results. While some studies (Sistiaga et al.,2010; Brinkhof et al.,2020) reported results that were similar to those obtained with the rigid and four-panel codends, Sistiaga et al. (2022) reported significantly lower *L50* values for 128 and 137 mm mesh size codends, respectively. Contrary to cod, the four-panel codend in Sistiaga et al. (2023) showed a significantly lower *L50* than the different results obtained with the codends tested here. Regarding SL codends, none of the earlier tested codends resulted in higher *L50* values, and the two-panel SL codend in Sistiaga et al. (2022) resulted in a significantly lower *L50*. The T90 codend tested in Brinkhof et al. (2022a) resulted in a significantly higher *L50* than any of the two codend configurations in the present study (Fig. 5; Table 5).

For redfish, the *L50*s obtained with the rigid codend and the four-panel codend were significantly lower than those obtained with the mandatory grid and codend gear as showed in Herrmann et al. (2013). Regarding earlier studies using two-panel codends, only the result presented by Sistiaga et al. (2022) for a 128 mm codend resulted in a significantly lower *L50* than the ones for the two codends tested here, while the *L50*s in the other four included studies were similar. This was also the case for the four-panel codend (Sistiaga et al., 2023), which resulted in a *L50* that did neither differ from the rigid codend nor the four-panel codend tested here. Compared to the SL codend results, only the 137 mm SL codend in Sistiaga et al. (2022) resulted in a significantly higher *L50* than the ones obtained for the codend configurations tested

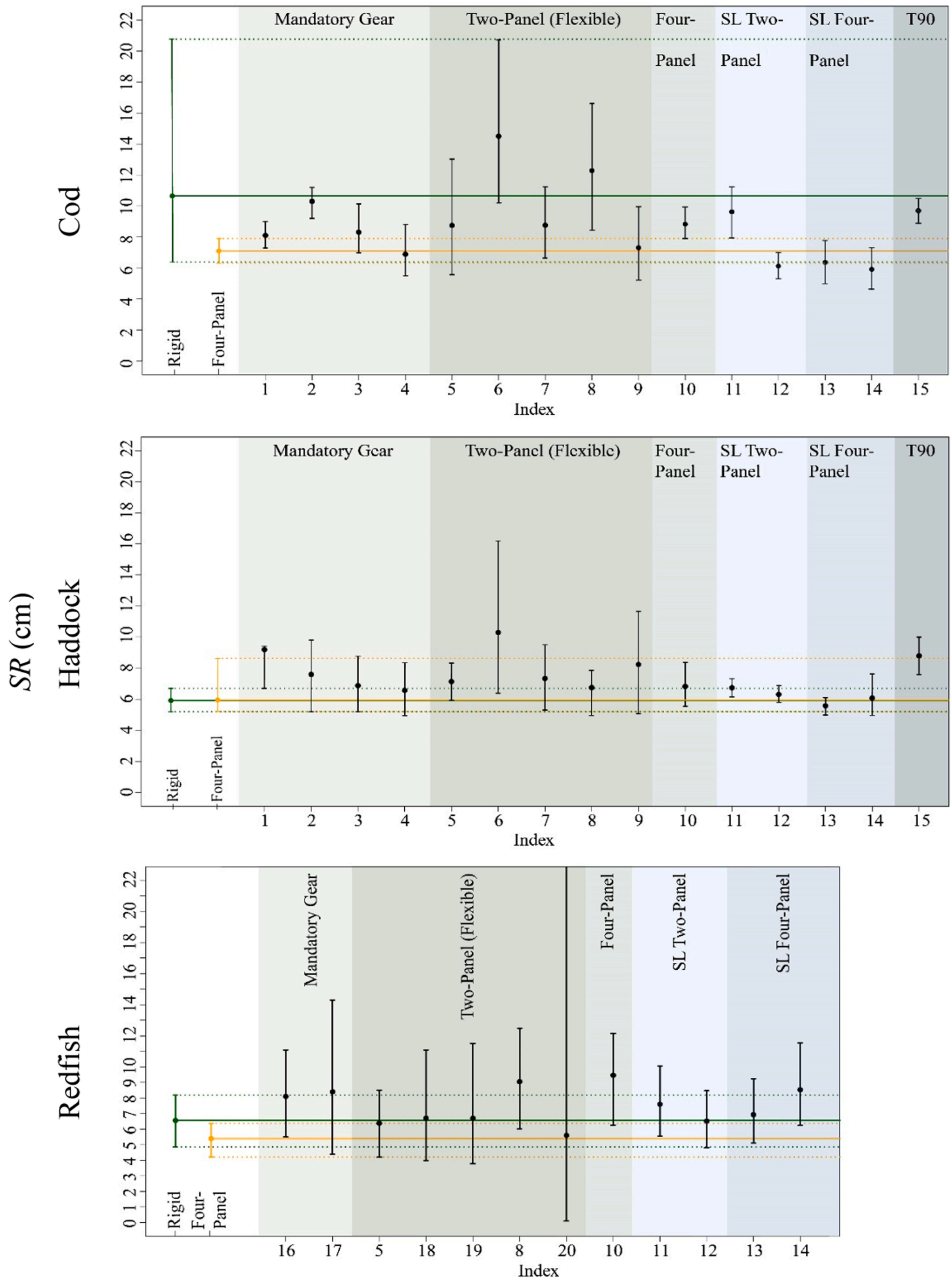

Fig. 4. Comparison of the *SR* results obtained in the present study for the rigid codend (green solid line) and the four-panel codend (yellow solid line) with historical results obtained for different size sorting devices tested in the Barents Sea demersal trawl fishery. Results are provided for cod, haddock and redfish. The stippled lines show the 95% confidence intervals for the rigid codend (green) and four-panel codend (yellow), respectively. The historical data obtained with the mandatory grid and codend gear, two-panel codends with and without shortened lastridge ropes (SL), four-panel codends with and without SL and turned mesh (T90) codends, are indexed based on the data shown in Table 5. For the historical data, the 95% confidence intervals are provided as error bars.

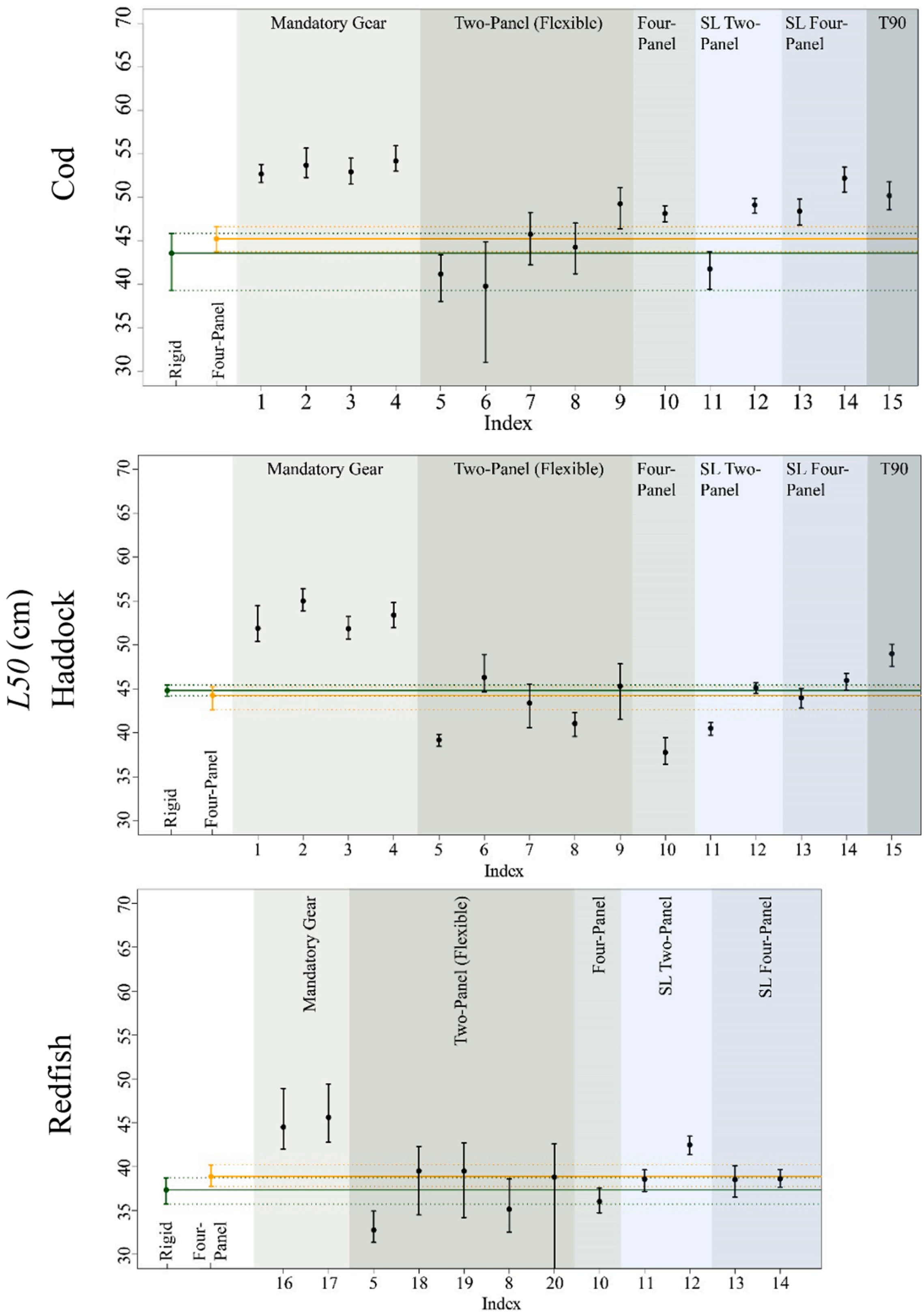

Fig. 5. Comparison of the *L50* results obtained in the present study for the rigid codend (green solid line) and the four-panel codend (yellow solid line) with historical results obtained for different size sorting devices tested in the Barents Sea demersal trawl fishery. Results are provided for cod, haddock and redfish. The stippled lines show the 95% confidence intervals for the rigid codend (green) and four-panel codend (yellow), respectively. The historical data obtained with the mandatory grid and codend gear, two-panel codends with and without shortened lastridge ropes (SL), four-panel codends with and without SL and turned mesh (T90) codends, are indexed based on the data shown in Table 4. For the historical data, the 95% confidence intervals are provided as error bars.

here, while the rest of the *L50*s were similar (Fig. 5c; Table 4).

4. Discussion

The results obtained in the present study showed that for cod, haddock, and redfish, a fully rigid codend did not result in sharper size selection compared to a four-panel codend (Table 4). However, the comparison of results obtained here with results from earlier trials testing two-panel codends, demonstrate that controlling the mesh openness of the codend by means of additional selvedges as obtained with a four-panel codend, shortening lastridge ropes, or as in this study, a rigid frame, can be an effective measure to sharpen size selectivity (Fig. 4).

Bak-Jensen et al. (2022) demonstrated that a fully rigid codend can have significantly sharper size selection than a flexible two-panel codend. These results are in line with the present study since it showed that adding rigidness to a two-panel codend can result in sharper size selection (Fig. 4). However, the added rigidness obtained with a four-panel instead of the two-panel codend may be just as efficient at reducing this variability. Further, comparing the four-panel codend /tested here to other types of codend modifications with added rigidness tested earlier in this fishery like codends with SL or T90 codends (Brinkhof et al., 2022a; Sistiaga et al., 2022, 2023), showed that none of these two alternative designs resulted in significantly lower *SR* than those obtained with the four-panel design tested here (Fig. 4, Table 5).

Comparison of the codend selectivity results between the two configurations tested here and earlier studies with the mandatory grid and codend configuration, revealed that the use of a sorting grid does not result in sharper size selection compared to the selection that can be obtained by applying the codend size selection alone (Fig. 4, Table 5). Specifically, our results suggest that if the mesh size of a four-panel codend would be adjusted to result in a similar *L50* as a 55 mm sorting grid, the former would result in at least as sharp and controlled size selectivity results. Therefore, our results suggest that the mandatory sorting system in the Barents Sea can be simplified without risking making size selection less well-defined if the codend meshes are stabilized using a four-panel construction.

The codends used in the Barents Sea gadoid fishery are mostly two-panel codends that follow a two-panel sorting grid section (Tveit et al., 2019; Hermann Pettersen, Norwegian Directorate of Fisheries, Personal Communication). There is controversy as to whether the two- or four-panel grid sections perform best regarding the size selectivity, which according to literature, also depends on the type of sorting grid used in the gear. Specifically, while Sistiaga et al. (2016) reported that for cod and haddock a four-panel flexigrid section results in sharper size selectivity curves compared to a two-panel flexigrid section, Sistiaga et al. (2023) recently reported that a two-panel Sort-V grid section can result in significantly sharper size selection than a four-panel Sort-V section for the same species. A two-panel grid section can be combined with a four-panel codend adding a two- to four-panel transition piece of the trawl between the grid and the codend. Thus, independent of whether the sorting grid continues to be compulsory in the fishery in this area and the type of grid chosen by fishermen, the results of the present study show that a four-panel codend design is to be preferred in detriment of a two-panel design to obtain sharper size selectivity and increase control over the exploitation pattern of the trawler fleet.

Trawls are one of the most relevant fishing gears worldwide (Van Anrooy et al., 2021; FAO, 2023) and the codend is an essential part of the trawl because it accumulates the catch, and most of the size selection of the fish entering the trawl often takes place here (Wileman et al., 1996; Herrmann, 2005a). Therefore, the results obtained here can be of interest for many different trawl fleets and should encourage researchers and managers from other regions to test codends with increased rigidness, especially codends built in four-panel configurations. This simple measure may lead to achieving sharper size selection and better control over the exploitation pattern in different fisheries.

CRediT authorship contribution statement

bent herrmann: Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Morteza Eighani:** Writing – original draft, Data curation. **Kristine Cerbule:** Writing – original draft, Investigation, Data curation. **Enis N Kostak:** Writing – original draft, Data curation. **Roger B. Larsen:** Investigation, Data curation. **Eduardo Grimaldo:** Writing – original draft, Investigation, Data curation. **Manu Sistiaga:** Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jesse Brinkhof:** Writing – original draft, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **zita Bak-Jensen:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, 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.

Data Availability

Data will be made available on request.

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