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Is there a limit to the potential effects of shortening lastridge ropes on the size selectivity of diamond mesh codends?

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A R T I C L E I N F O

Handled by A.E. Punt

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A B S T R A C T

Shortening codend lastridge ropes can be an effective fishing gear modification to improve the size selection properties in diamond mesh codends. Lastridge ropes attached to codend selvedges withstand the longitudinal forces created by the catch building up and therefore, prevent the codend meshes from closing. However, the extent to which the lastridge ropes should be shortened to maximize the effect of this measure is unclear. Besides opening codend meshes, shortening lastridge ropes can also lead to net folding, which can potentially have negative consequences for size selectivity. In the present study, we tested the size selective properties of a 129 mm diamond mesh codend in three different configurations: 0 %, 15 % and 30 % shortened lastridge ropes. Selectivity data were collected for cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and redfish (*Sebastes* spp.) in the Barents Sea gadoid bottom trawl fishery. Shortening the lastridge ropes by 15 % had a significant effect on the release efficiency of haddock between 35 and 50 cm, whereas to obtain a similar result for cod, the lastridge ropes had to be shortened by 30 %. However, the use of shortened lastridge ropes significantly increased the retention of fish below 35 cm for both species, especially when the lastridge ropes were shortened from 15 % to 30 %. The effect on redfish size selectivity was in general limited. Exploitation pattern indicators showed that there was no added benefit from shortening them further from 15 % to 30 % for any of the three species. This study concludes that, while shortening lastridge ropes can contribute to improved size selection of diamond mesh codends, reducing them beyond 15 % is not recommended because it can substantially increase the retention of undersized fish, probably due to net folding.

1. Introduction

The size selective properties of trawl codends, i.e. the length-dependent escapement probabilities in fishing gears, are one of the most studied topics within fishing gear technology (Kennelly and Broadhurst, 2021). The codend collects fish gathered by the gear making it the most likely place for the size selection processes to occur (Beverton, 1963; Clark, 1963). Traditionally, trawl codends have been constructed of diamond meshes, and still today many fisheries have technical regulations with a minimum size in the diamond mesh codend (Brčić et al., 2018; Cheng et al., 2019, 2020; Petetta et al., 2020).

The size selection properties of diamond mesh codends can vary due to their flexible nature. Specifically, the accumulation of catch can make the shape of the codend and the meshes in it vary greatly throughout a trawl tow. As the catch accumulates, the longitudinal tension in the codend increases, which leads to the majority of the meshes in the

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codend closing thereby limiting the escape possibilities for fish (Robertson and Stewart, 1988; Herrmann, 2005a, 2005b; Herrmann and O'Neill, 2005; Herrmann et al., 2007; O'Neill and Herrmann, 2007).

Some of the modifications proposed to counteract the variability in the size selection properties of diamond mesh codends include the installation of additional sorting devices. For example, in the Barents Sea gadoid bottom trawl fishery, fishermen are obliged to use a size sorting grid with a minimum bar spacing of 55 mm installed in the extension piece preceding a codend with a minimum mesh size of 130 mm (Brinkhof et al., 2020). Moreover, in the Bay of Biscay multispecies demersal trawl fishery, fishermen are allowed to use a diamond mesh codend with 70 mm mesh size if a square mesh panel with 100 mm mesh size is installed in the extension piece (Alzorriz et al., 2016; Cuende et al., 2020a). However, the complexity added by inserting additional selection devices can lead to operational challenges e.g., gear maneuverability, extra costs, supplementary gear control, etc. (Sistiaga et al., 2016). Therefore, simpler modifications that can improve the size selection properties of diamond mesh codends are still sought. One such modification, which was proposed and tested in different fisheries during the 1990s, is the use of shortened codend lastridge ropes (SLR) (Isaksen and Valdemarsen, 1990; Lök et al., 1997). Lastridge ropes, also known as riblines in other regions, are attached to the selvedges (panel joints) of the codend with the purpose of withstanding the longitudinal forces created by the catch building up. The aim of shortening these ropes i.e. attaching shorter ropes to a given length of netting panels, is to prevent the codend meshes from closing due to the longitudinal forces during towing. These forces instead then become transferred to the lastridge ropes. Due to the relative simplicity of this measure, codends with SLR are again being considered as a potential measure to improve size selectivity in different fisheries today (Einarsson et al., 2021; Ingólfsson and Brinkhof, 2020; Sistiaga et al., 2021; Jacques et al., 2022).

In general, when a treatment results in a positive outcome, it can be reasonable to increase the dose of the treatment in order to maximize its effect on the subject investigated, which in this case would be shortening the lastridge ropes in the codend further. However, underwater observations of SLR codends show the risk that the netting in this type of codend can fold, resulting in wavy netting panels that in extreme cases can create "netting pockets" (Fig. 1). It can be speculated that the risk of creating these waves is caused by further shortening the lastridge ropes. This would lead to more open meshes in the transversal direction (Fig. 2a), which again increases the circumferential length of the meshes in the codend. If the lastridge ropes are shortened to a level where the circumferential length of the meshes exceeds the circumferential length of the codend based on its diameter, then the netting needs to fold to absorb the additional mesh length (Fig. 2b). Alternatively, if the meshes cannot open further in the transversal direction (due to stiffness in the codend material or other netting characteristics), and the lastridge ropes are shortened further, then the netting in the codend becomes too long and the panel needs to fold to absorb the excessive length in the longitudinal direction (Fig. 2c). These folding effects, which could also happen simultaneously, can have negative effects for the size selectivity of fish in the codend.

For a fish to be able to escape through the codend meshes, it first needs to contact the meshes, and then it needs to be physically able to pass through the meshes. The contact with a size sorting device in the gear, including codend meshes, can be defined as the fraction of fish that conditioned it enters the gear, is subjected to a size-dependent selection process by the device (Sistiaga et al., 2010). It can be hypothesized that the potential folding created in the codend by SLRs would limit, at least partially, the access to the meshes in the codend. This would limit contact and consequently the escape probability for fish.

The degree to which the ropes were shortened in the earlier studies (e.g., Isaksen and Valdemarsen, 1990; Lök et al., 1997; Ingólfsson and Brinkhof, 2020) varied between 12 % and 30 % of the original stretched length of the codend with only one degree of shortening tested in each study. This makes it difficult determine whether in each of these studies the optimal shortening percentage was reached or whether there was a potential unexploited gain of shortening the ropes further or their results already reflected the negative effects of folding due to having "over-shortened" the ropes. Thus, a systematic study comparing the results from different levels of SLR would help determine whether or where is the limit to the benefits of SLR in diamond mesh codends.

In the present study, we investigated the size selection properties of three different SLR codend configurations for diamond mesh codends in the Barents Sea gadoid trawl fishery, which is one of the most important demersal trawl fisheries in the world (Bergstad et al., 1987; Olsen et al., 2010). In this fishery, cod (*Gadus morhua*) and haddock (*Melanogramus aeglefinnus*) are the two main target species, whereas redfish (*Sebastes* spp.) is one of the main bycatch species. These three species have different Minimum Legal Sizes (*MLS*) of 44, 40 and 32 cm respectively, and important morphological and behavioral differences that can lead to

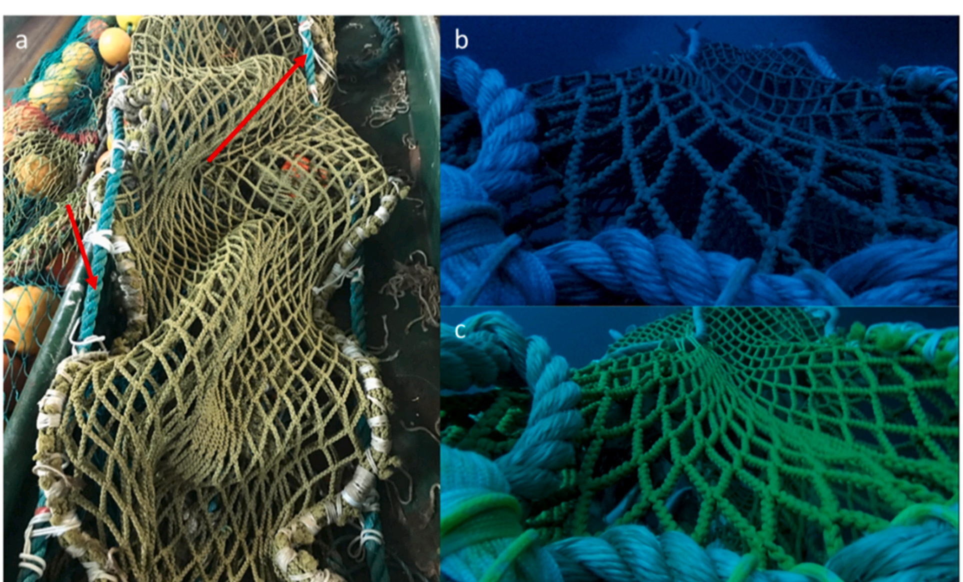

Fig. 1. a) a codend with SLR (lastridge ropes represented by red arrows) on deck. The SLR are 30 % shorter than the stretched length of the codend. b) and c) illustrate folding with SLR codends while fishing.

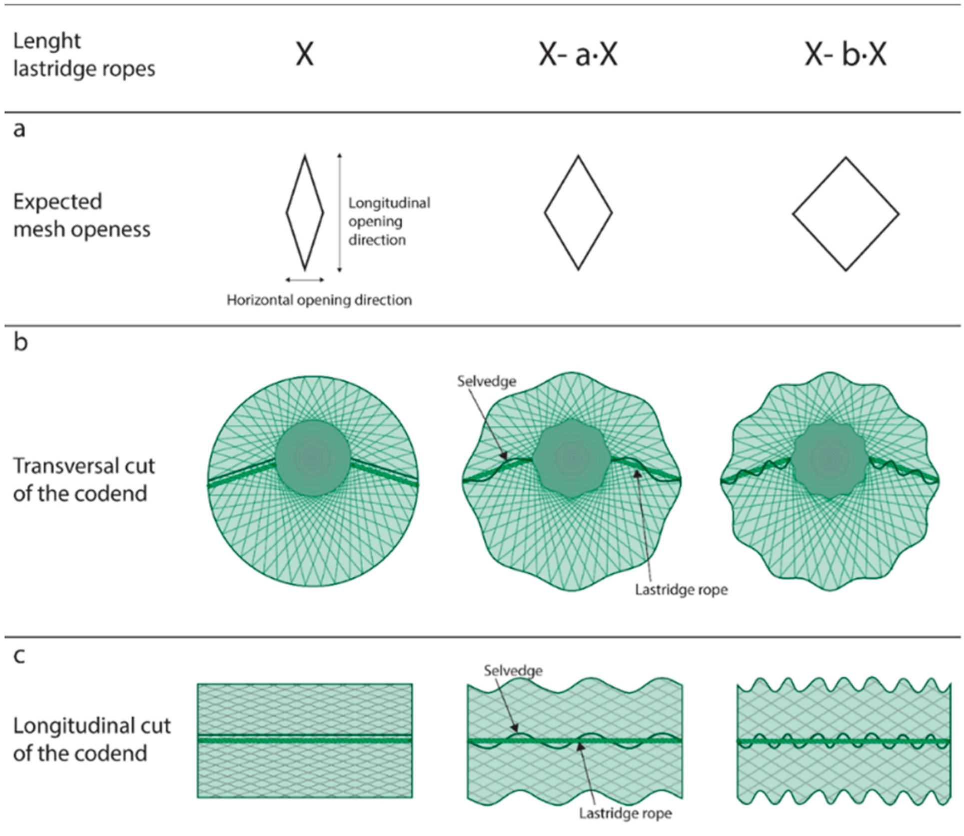

Fig. 2. Schematic illustration of the effect of shortening lastridge ropes by two different percentages (a and b, where a < b) of the original stretched length (X) of the codend.

varying selectivity results and management implications depending on the properties of the codend configuration applied (Sistiaga et al., 2011; Herrmann et al., 2012; Larsen et al., 2016). Further, there is an established maximum discard ratio in numbers of 15 % per species and haul in the fishery. As fishermen aim to maximize the revenue from their limited quotas, they are often only interested in catching cod and haddock well over the *MLS*, which is priced higher.

The main objective of this study was to investigate the potential benefits of shortening diamond mesh codend lastridge ropes for size selectivity purposes. Specifically, we aimed at answering the following research questions:

- How do the size selectivity properties of diamond mesh codends vary when lastridge ropes are shortened to different levels?
- Do the selectivity results indicate any potential negative consequences of reducing the lastridge rope length?
- Is it possible to explain the selectivity results obtained for cod, haddock, and redfish with the different SLR codend configurations?
- What is the optimal SLR codend configuration for the Barents Sea gadoid fishery considering the management objectives?

2. Materials and methods

2.1. Sea trials and data collection

The sea trials were carried out onboard the research vessel Helmer Hanssen (63.9 m long and 4080 HP (3000 kW)) from December 8–14th, 2021. The fishing grounds were located around Bear Island in the central Barents Sea (73°50`N–74°42`N, 17°23`E–16°02`E). The fishing operations were conducted with an Alfredo No. 3 trawl, which has a 19.2 m long fishing line, 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 trawl used by Brinkhof et al. (2022) and was rigged identically; with 60 m long sweeps, a 46 m long ground gear, and an 18.9 m long rock-hopper gear. During the whole trial period, the performance of the trawl was monitored by a set of trawl door sensors and a trawl height sensor.

An extension piece followed by a two- to four-panel transition piece was mounted before the codend. The codend was constructed of 4 identical #80 × #15 knotless (braided Ø 6 mm PE twine) diamond mesh panels. The stretched mesh size was measured to be 129.33 ± 2.07 mm (mean ± SD) based on 2 × 20 measurements following to Wileman et al. (1996). The four-panel codend was chosen instead of a more traditional two-panel construction because this configuration allows for the application of two additional lastridge ropes and consequently a potentially larger effect by shortening them. Each selvedge contained three meshes, meaning that the codend had 60 free meshes in circumference.

The following three SLR configurations were tested in the diamond mesh codend:

- 0 % SLR configuration: lastridge ropes with the same length as the codend selvedges.
- 15 % SLR configuration: lastridge ropes in the last 6 m of the codend closest to the codline shortened by 15 %, i.e. having a length of 5.1 m.
- 30 % SLR configuration: lastridge ropes in the last 6 m of the codend closest to the codline shortened by 30 %, i.e. having a length of 4.2 m.

In this study, we applied the covered codend method (Wileman et al., 1996). The cover used had a diameter of 2.4 m and was 20 m long, covering the entire length of the codend to retain potential escapees. The cover mesh size of 51.13 ± 1.30 mm ensured the retention of all cod, haddock and redfish above 10 cm. This was tested by simulation in FISHSELECT based on morphometric data for the three species from Sistiaga et al. (2011) and Herrmann et al. (2012). To keep the cover off the test 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 ca. 2 m in front of the codline.

In all hauls, the catch in the codend was kept separate from the catch in the cover, and the length of all cod, haddock and redfish above 10 cm were measured to the nearest cm below.

2.2. Estimation of size selection of the different codend configurations

In each haul, all fish over 10 cm were either retained in the test codend or in the codend cover and therefore, the data could be analyzed as binominal catch data. For each of the SLR configurations and species separately, the catch data for all hauls were pooled together for analysis because we were only interested in the length-dependent codend retention probability ($\boldsymbol{r}_{codend}(l)$) for the different length classes of each species averaged over hauls. The analysis was carried out using the maximum likelihood estimation method and following the same procedure used by Sistiaga et al. (2021), where different parametric models of the form $\boldsymbol{r}_{codend}(l, \boldsymbol{v}_{codend})$ were tested to model codend size selection. In Sistiaga et al. (2021), four basic models were considered, *Logit*, *Probit*, *Gompertz*, and *Richard* (further model information in Lomeli, 2019). The *Logit*, *Probit* and *Gompertz* models are fully described by the parameters *L50* and selection range (*SR*). *L50* is defined as the length (*l*) at which a fish has a 50 % probability of being retained by the gear and the *SR* is the difference in length between fish with 75 % and 25 % probabilities of being retained. The *Richard* model requires the estimation of an additional parameter, the asymmetry parameter (*D*). In the present study, we also tested these models. In addition, we considered for each of these models a scenario 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 (Sistiaga et al., 2010): *CLogit*, *CProbit*, *CGompertz*, and *CRichard* (see Cuende et al., 2020a for further information on these models). These models were considered relevant because it was hypothesized that the potential folding in the codend netting created by shortening the lastridge ropes could be reflected in the lack of contact with the codend meshes for a specific fraction of fish. In these models, for example, if 80 % of the fish entering the codend contact the codend meshes, *C* would acquire a value of 0.8, whereas if only half of the fish entering the codend contacted the codend meshes, *C* would be equal to 0.5. It could be expected that the higher the extent of folding, the lower the escape chance for fish through the codend meshes, which would be reflected in a lower value of *C*. Finally, a ninth model, which in the literature is referred to as *DLogit* (Herrmann et al., 2016) was also considered. The *DLogit* is able to describe a dual selection process and assumes that a fraction of the fish entering the codend (*C*) will be subjected to one logistic size selection process while the remaining fraction (1.0 – *C*) will be subjected to a different logistic size selection process. Thus, nine models were considered in total for $\boldsymbol{r}_{codend}$ $(l, \boldsymbol{v}_{codend})$:

$$\boldsymbol{r}_{codend}(l, \boldsymbol{v}_{codend}) = \left\{ \begin{array}{c} Logit(l, L50, SR) \\ Probit(l, L50, SR) \\ Gompertz(l, L50, SR) \\ Richard(l, L50, SR, D) \\ CLogit(l, C, L50, SR) \\ CProbit(l, C, L50, SR) \\ CGompertz(l, C, L50, SR) \\ CRichard(l, C, L50, SR, D) \\ DLogit(l, C, L50_1, SR_1, L50_2, SR_2) \end{array} \right\} \quad (1)$$

The ability of the different models to describe the data was evaluated based on the *p*-value and residual inspection following Wileman et al. (1996). Model selection for each of the codend configurations tested and species included was done based on AIC (Akaike, 1974). Thus, the model with the lowest AIC value was chosen in each case to represent the data.

The Efron 95 % percentile confidence intervals (CIs; Efron, 1982) for the model selected for each configuration and each species were estimated by bootstrapping following the procedure described in Millar (1993), which takes both within-haul and between-haul variation into consideration. The bootstrap procedure applied was identical to that applied in Sistiaga et al. (2021) and was based on 1000 bootstrap repetitions. The analyses described in this subsection and all following subsections were conducted using the software tool SELNET (Herrmann et al., 2012).

2.3. Effect of shortening lastridge ropes

To estimate the potential differences in $\boldsymbol{r}_{codend}$ $(l, \boldsymbol{v}_{codend})$ between the different codend configurations tested and to measure the potential effect of shortening the lastridge ropes, Eq. (2) was applied:

$$\Delta r(l, \boldsymbol{v}_1, \boldsymbol{v}_2) = r_1(l, \boldsymbol{v}_1) - r_2(l, \boldsymbol{v}_2) \quad (2)$$

The CIs for $\Delta \boldsymbol{r}(l, \boldsymbol{v}_1, \boldsymbol{v}_2)$ were obtained by creating a new bootstrap population with 1000 repetitions from the bootstrap population results obtained for $\boldsymbol{r}_1(l, \boldsymbol{v}_1)$ and $\boldsymbol{r}_2(l, \boldsymbol{v}_2)$. This procedure has been applied in several studies to compare the size selectivity performance of two different gears (e.g. Larsen et al., 2018; Cheng et al., 2019; Einarsson et al., 2021; Petetta et al., 2021; Sistiaga et al., 2021).

2.4. Explanation of retention probability using fish morphology and codend mesh geometry

We investigated whether the size selectivity curves obtained for cod, haddock and redfish with each of the three codend configurations tested in the sea trials could be replicated by simulation considering the morphological characteristics of the different species and the characteristics of the netting in the experimental codend. The simulations were all conducted using the software FISHSELECT; a framework of methods, tools and software developed to determine if a fish can penetrate a certain mesh shape and size in fishing gear (Herrmann et al., 2009). The morphological measurements used in the simulations were those presented in Sistiaga et al. (2011) for cod and haddock, and Herrmann et al. (2012) for redfish. These simulations were conducted for diamond meshes with a stretched mesh opening of 129 mm, which was the mean mesh size for the experimental codend in the sea trials, with opening angles (OAs) varying between 10° and 90° with intervals of 5°. The objective with the different OAs was to determine the dependency of the size selection curves established for each codend configuration on the different mesh OAs. In addition to the meshes with different OAs, slack meshes and semi-slack meshes (i.e. meshes can potentially be deformed by the effort of the fish while trying to escape) with 25 %, 50 % and 75 % "slackness" were considered as potential contributors. The semi-slack meshes were obtained by linear interpolation between the 90° OA mesh curve and the slack mesh curve. To account for the potential variability in the codend mesh sizes and that fish in the catch accumulation zone may have multiple escape attempts involving meshes of different sizes (Herrmann, 2005a), diamond meshes of 133 mm mesh size (mean mesh size + 2 times the standard deviation, which was 2.07 mm) were also considered in the simulations. The simulation procedure to determine the combinations of contributions needed from the different meshes and OAs to reproduce the different experimental curves obtained for the different cases in the study, was identical to the one presented more in detail in Herrmann et al., (2013, 2016) or Cuende et al. (2020b).

2.5. Exploitation pattern indicators

Exploitation pattern indicators provide a measure on how a particular gear configuration performs in a specific fishery situation. Unlike the size selectivity curves, indicators depend on the length structure of the population encountered by the gear at the time the trials were carried out. They enhance the understanding of the performance of the gear configuration investigated and therefore, are often used in fishing gear selectivity studies (Santos et al., 2016; Cheng et al., 2019; Kalogirou et al., 2019; Melli et al., 2020; Cuende et al., 2022).

In this study, we estimated three different exploitation pattern indicators, *nP*⁻ (percentage of individuals retained for individuals below *MLS*), nP^{+} (percentage of individuals retained for individuals above *MLS*) and *nDiscard* (Discard ratio) (Eq. (3)), and their corresponding 95 % CIs following the procedure described in Sistiaga et al. (2021). As in Sistiaga et al. (2021), the size selection curve estimated for each species and gear configuration was applied to the population for each species which was obtained by summing all fish in the cover and codend and in all hauls conducted during the trials independently for each species.

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

In Eq. (3), $nPop_l$ is the number of fish in length class (*l*) of the population entering the codend, i.e. the sum of the catches in the codend and codend cover. The indicators were estimated considering the current *MLS* of 44, 40 and 32 cm for cod, haddock and redfish, respectively. However, it was of interest also to consider a more realistic fisheries scenario for the Barents Sea where fishermen are interested in the capture of cod and haddock well above their *MLS* due to economic reasons, i.e., larger fish acquire a higher price per kilo. Therefore, indicators were also estimated for a *MLS* of 50 cm for cod and 45 cm for haddock. All exploitation pattern indicator estimations were carried out in SELNET (Herrmann et al., 2012), with the 95 % CIs estimated using the bootstrap method described above.

3. Results

During the experimental fishing trials, we conducted a total of 29 hauls: nine with the 0 % SLR configuration, ten with the 15 % SLR configuration and ten with the 30 % SLR configuration. In total, 7044 cod, 18,582 haddock and 3447 redfish were measured and included in the size selectivity analyses (See Table S1 in the supplementary material for further information on the hauls conducted during the experimental period.).

3.1. Size selectivity analysis and model fit

The *Probit* (cod) and *DLogit* (haddock and redfish) were the most adequate models to fit the data when the codend lastridge ropes were not shortened (0 % SLR configuration). For the rest of the cases except for the redfish with the 30 % SLR codend, models that considered a *C* < 1.0 provided the best fit (Table 1). The fit statistics show that the models chosen represented the data well for all nine cases. The *p*-values were > 0.05 in all cases meaning that the difference between the modelled selectivity curve and the obtained experimental retention rates could be coincidental (Table 1). A visual inspection of the model fit to the data also shows that the models follow the trend of the data well and that there are no patterns in the differences between the data and the curves (Fig. 3).

The estimated parameter values obtained for cod, haddock and redfish showed that *L50* in general increased when lastridge ropes were shortened, which is similar to the expected effect of by increasing the mesh size. This increase was significant for all three species when the configurations of 0 % and 30 % SLR were compared, but not when the 0 % and 15 % SLR codends were compared. The pattern for the *SR* was

Table 1
Parameter values and fit statistics for the models chosen to represent the selectivity data for cod, haddock and redfish and the three gear configurations tested. Values in brackets represent 95 % confidence intervals.

		Model	*L50*	*SR*	*D*	*L501*	*SR1*	*L502*	*SR2*	Contact (*C*)	Deviance	DOF	*p*-Value
Cod	0 % SLR	*Probit*	48.17 (47.22–49.06)	8.83 (7.91–9.95)	–	–	–	–	–	–	31.23	95	1.000
	15 % SLR	*CLogit*	48.43 (48.80–49.81)	6.37 (5.00–7.77)	–	48.57 (46.86–50.11)	6.17 (4.66–7.63)	–	–	0.98 (0.92–0.99)	46.97	93	1.000
	30 % SLR	*CProbit*	52.21 (50.62–53.52)	5.92 (4.64–7.30)		52.60 (50.99–53.76)	5.38 (4.30–6.65)	–	–	0.93 (0.87–0.98)	49.72	94	1.000
Haddock	0 % SLR	*DLogit*	37.77 (36.41–39.48)	6.83 (5.55–8.37)	–	43.05 (41.01–48.03)	4.69 (1.84–6.55)	36.34 (34.64–39.04)	1.19 (0.60–6.35)	0.51 (0.14–0.76)	28.36	58	1.000
	15 % SLR	*CLogit*	43.98 (42.83–45.07)	5.58 (4.99–6.11)	–	44.04 (42.96–45.12)	5.50 (4.93–6.02)	–	–	0.99 (0.98–0.99)	53.1	67	0.890
	30 % SLR	*CRichard*	45.96 (44.92–46.76)	6.07 (4.96–7.62)	0.37 (0.20–0.59)	46.13 (45.05–46.98)	5.69 (4.56–7.28)	–	–	0.97 (0.94–0.99)	36.21	60	0.990
Redfish	0 % SLR	*DLogit*	36.02 (34.72–37.55)	9.46 (6.26–12.16)		42.13 (37.02–42.76)	1.00 (1.00–6.50)	33.48 (18.25–34.95)	5.08 (1.63–7.86)	0.33 (0.23–0.96)	26.12	41	0.966
	15 % SLR	*CRichard*	38.52 (36.52–40.09)	6.93 (5.12–9.24)	0.31 (−0.71 to 0.60)	38.62 (36.70–40.16)	6.69 (4.92–8.98)	–	–	0.98 (0.96–0.99)	47.26	47	0.462
	30 % SLR	*Richard*	38.60 (37.61–39.69)	8.53 (6.25–11.56)	0.10 (−0.01 to 1.65)	–	–	–	–	–	29.45	45	0.965

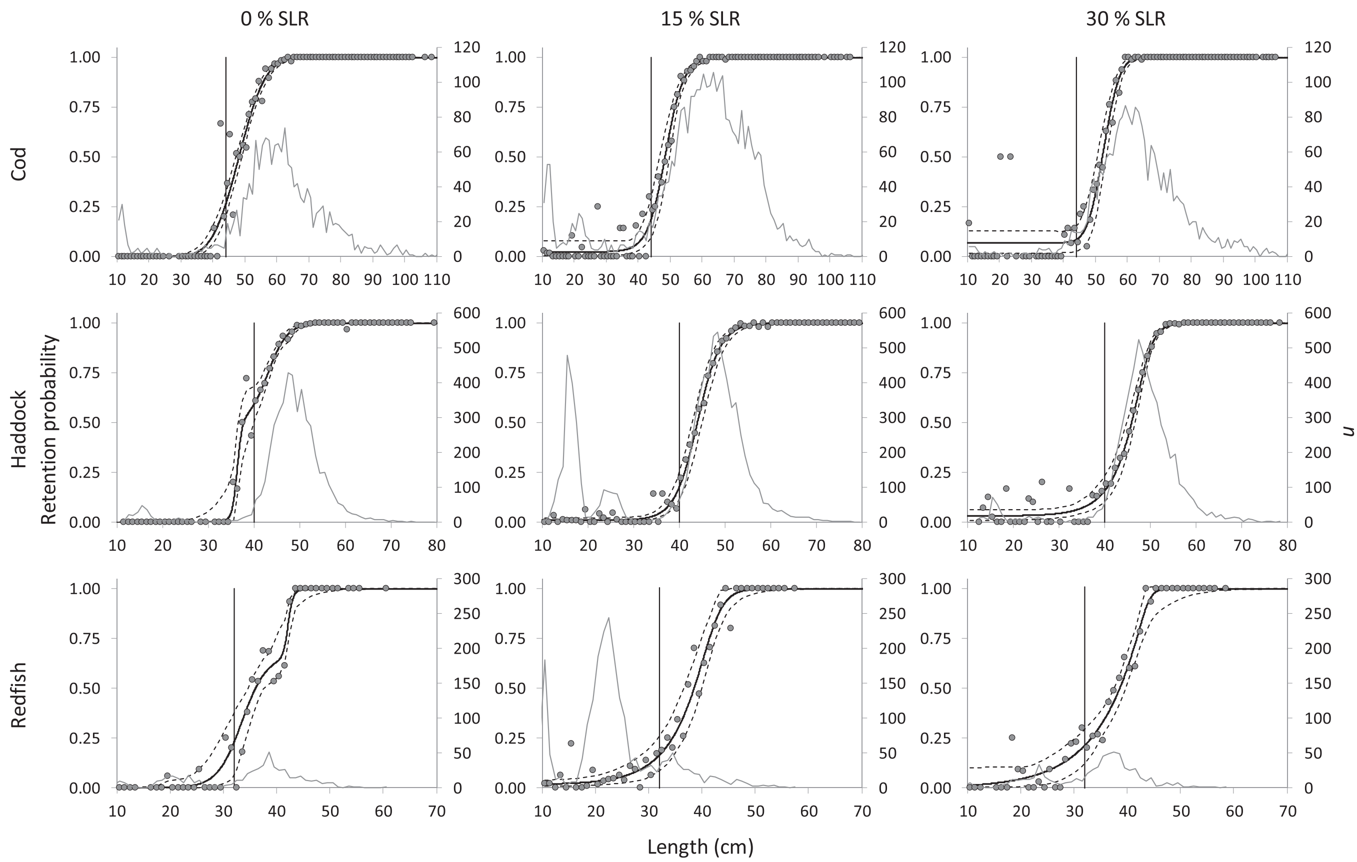

Fig. 3. Length-dependent retention probability for cod, haddock, and redfish with the 0 %, 15 % and 30 % SLR configurations. In each plot, the circles represent the experimental observations, the solid curves represent the models fitted to the data, and the dashed curves represent the 95 % CIs. The grey line represents the population fished by the gear (codend + cover). The vertical black lines show the minimum legal size (*MLS*) for cod (44 cm), haddock (40 cm), and redfish (32 cm).

not as clear, and although the *SR* was largest for the 0 % SLR in every case, the only significant difference observed was for cod between the cases with 0 % and 30 % SLR codends (Table 1).

For five out of the six SLR cases, i.e. 15 % or 30 % and three species, the estimated value for the contact parameter *C* were significantly lower than 1.0, showing that in these cases a proportion of the fish in the

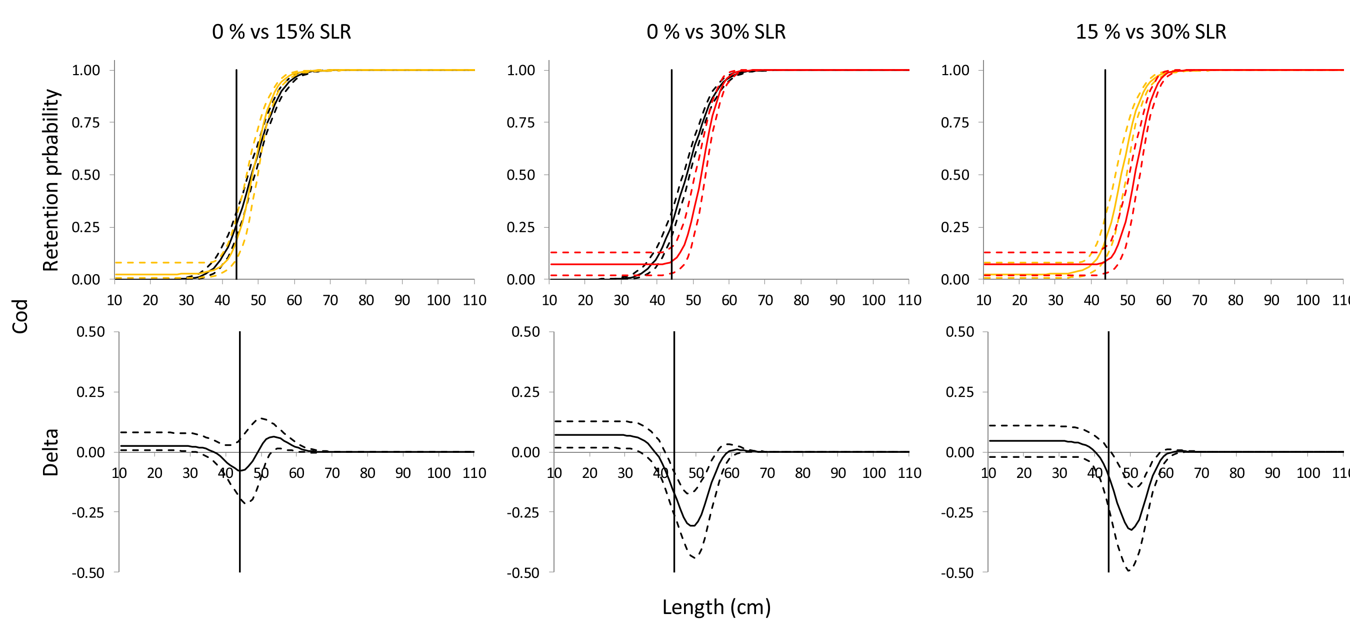

Fig. 4. Comparison of different SLR configurations on the size selection of cod. Top row: individual comparisons of the 0 % (black) and 15 % (orange) SLR configurations (left panel), the 0 % and 30 % (red) SLR configurations (middle panel), and 15 % and 30 % SLR configurations (right panel). Delta plots for each of the comparisons are shown below. Dashed curves correspond to the 95 % CIs in each case and the vertical line corresponds to the *MLS* for cod (44 cm).

codend was not able to find meshes to attempt to escape. However, the reduction was small in all five cases. This result could be a consequence of folding in the codend. Further, for cod and haddock, *C* was slightly reduced when the lastridge ropes were shortened from 15 % to 30 %, which could indicate that the extent of folding in the codend may increase when reducing the length of the lastridge ropes from 15 % to 30 %.

3.2. *Effect of shortening lastridge ropes by 15 % and 30 %*

3.2.1. *Effect of shortening the lastridge ropes for size selectivity of cod*

The comparison of the selection curves obtained with the three SLR configurations tested showed a significant effect of shortening the lastridge ropes for the size selectivity of cod. A similar pattern was observed in the delta plots for the three comparisons carried out (Fig. 4). However, the differences between the configurations became larger when the lastridges were shortened to 30 %. Thus, the retention of cod over 44 cm decreased significantly by shortening the lastridge ropes from 0 % to 30 % or from 15 % to 30 %, but not when they are shortened from 0 % to 15 % (Fig. 4). However, the retention of small cod also increased significantly when the lastridge ropes were shortened, especially when the 0 % and 30 % configurations were compared. The largest difference between the configurations tested for cod was the significant reduction in retention for sizes between ca. 45–55 cm when the lastridge ropes were shortened from 15 % to 30 % (Fig. 4).

3.2.2. *Effect of shortening the lastridge ropes for the size selectivity of haddock*

As for cod, the effect of shortening the lastridge ropes had significant consequences for the size selectivity of haddock (Fig. 5). However, the consequences of shortening the lastridge ropes from 0 % to 30 % were different compared to reducing the lastridge ropes from 0 % to 15 %. The retention of haddock between ca. 37–52 cm decreased significantly and to a similar level by reducing the lastridge ropes by either 15 % or 30 %. Considering that the *MLS* for haddock is 40 cm, the configuration with 15 % SLR offered a greater reduction of haddock below the *MLS*, and a reduced loss of individuals over the *MLS* (Fig. 5).

3.2.3. *Effect of shortening the lastridge ropes for the size selectivity of redfish*

For redfish, the effect of shortening the codend lastridge ropes was not analogous to those obtained for cod or haddock (Fig. 6). The pattern observed in the delta plots was similar for the comparison between the 0 % and 15 % SLR configurations and the 0 % and 30 % SLR configurations. The retention of redfish $<MLS$ was generally slightly higher and retention of redfish $\geq MLS$ was lower for the codend configurations with SLR. However, significant differences between the configurations tested were only found for a few length classes between ca. 35–38 cm when the 0 % and 30 % SLR configurations were compared (Fig. 6).

3.3. *Simulation of size selectivity and contribution of different mesh OAs*

The results from the simulations carried out for cod, haddock and redfish and the 0 %, 15 % and 30 % SLR configurations tested during the trials showed that the selectivity curves fitted to the experimental data can be well explained by combining contributions from meshes with 129 mm and 133 mm mesh size with different OAs in addition to slack and semi-slack meshes. The selectivity curves obtained by simulation (green curves in Fig. 7) in all nine codend configurations investigated were well within the CIs of the selectivity curves modelled based on the experimental data (Fig. 7).

3.3.1. *Simulation of cod size selectivity results*

The results for cod showed that in general, the contribution of meshes with a larger OA and semi-slack meshes for escape became more important when the length of the lastridge ropes was reduced from 0 % or 15–30 % (Fig. 7 and Table 2). This indicated that shortening the lastridge ropes to 30 % for cod not only increased the availability of more open and semi-slack meshes, but also that cod actually used them for escape. The availability of more open meshes with the lastridge rope length reduction was also reflected in Fig. 7, where the selectivity curve for the 15 % SLR codend, and specially the 30 % SLR codend, got closer to the simulation curve obtained with 80° OA meshes.

3.3.2. *Simulation of haddock size selectivity results*

For haddock, meshes with OAs between 35° and 55° contributed towards an explanation of the selectivity curves. This implies that this

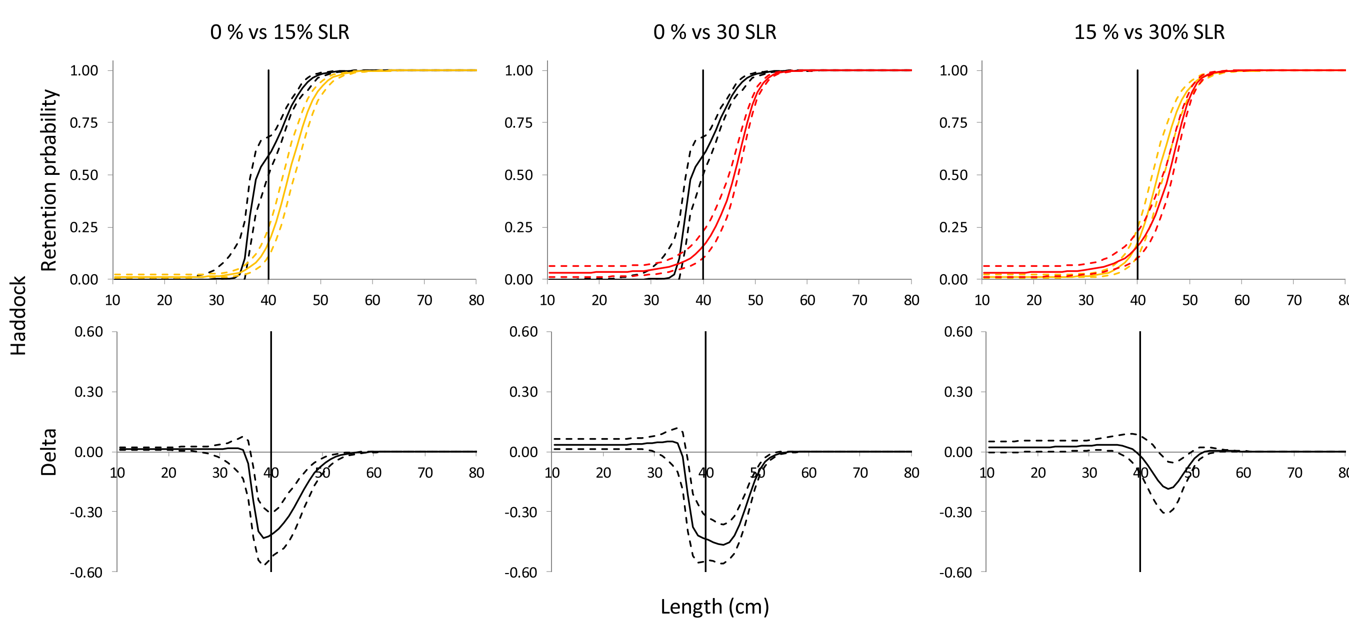

Fig. 5. Comparison of different SLR configurations on the size selection of haddock. Top row: individual comparisons of the 0 % (black) and 15 % (orange) SLR configurations (left panel), the 0 % and 30 % (red) SLR configurations (middle panel), and 15 % and 30 % SLR configurations (right panel). Delta plots for each of the comparisons are shown below. Dashed curves correspond to the 95 % CIs in each case and the vertical line corresponds to the *MLS* for haddock (40 cm).

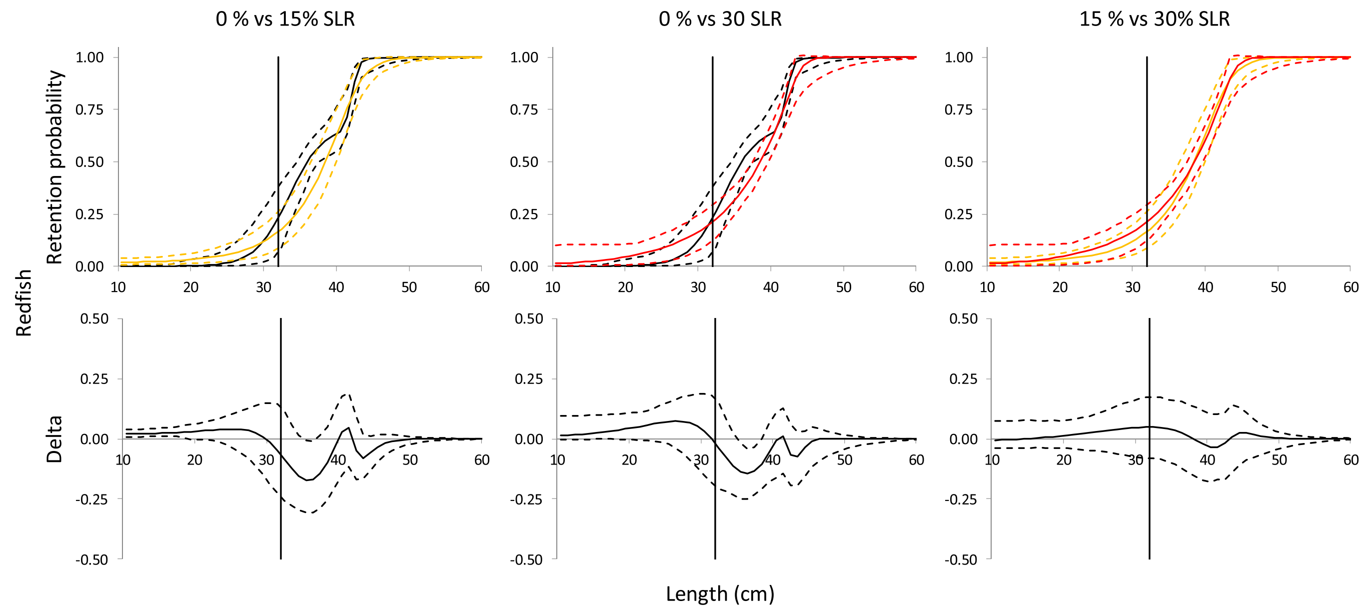

Fig. 6. Comparison of different SLR configurations on the size selection of redfish. Top row: individual comparisons of the 0 % (black) and 15 % (orange) SLR configurations (left panel), the 0 % and 30 % (red) SLR configurations (middle panel), and 15 % and 30 % SLR configurations (right panel). Delta plots for each of the comparisons are shown below. Dashed curves correspond to the 95 % Cis in each case and the vertical line corresponds to the *MLS* for redfish (32 cm).

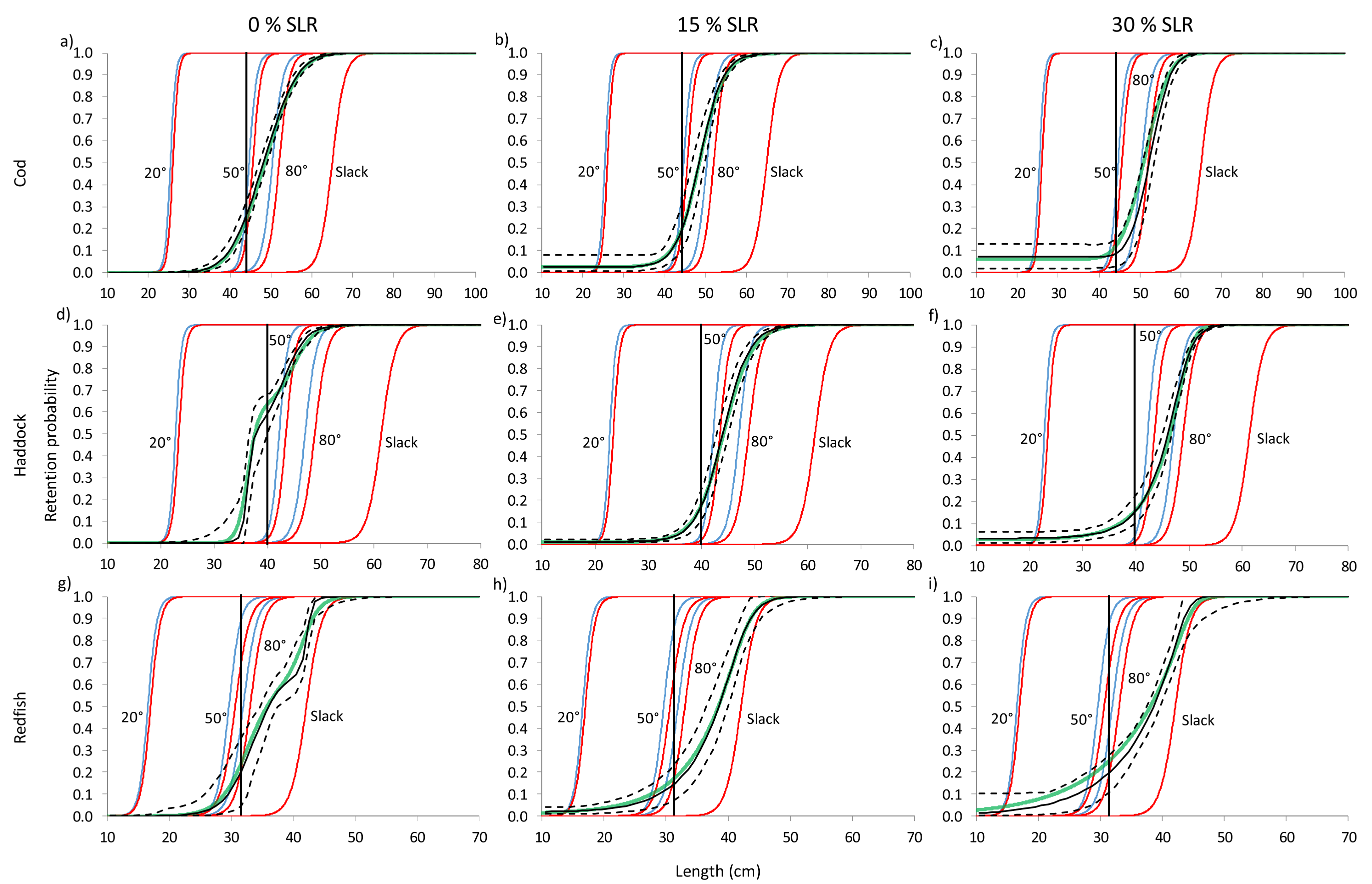

Fig. 7. The plots show the experimental (black) and simulated (green) size-selection curves for cod (top), haddock (middle) and redfish (below) with the three codend configurations tested during the trials: 0 % SLR (left), 15 % SLR (middle) and 30 % SLR (right). Dashed curves represent the 95 % CIs. As reference, simulated size selection curves for 129 mm diamond meshes with 20°, 50° and 80° OAs are provided in blue whereas equivalent curves for 133 mm diamond meshes are provided in red. Additionally, a curve for the selectivity of a 133 mm slack mesh is also provided in each case. Vertical lines in each plot show the *MLS* for cod (44 cm), haddock (40 cm), and redfish (32 cm).

Table 2
Estimated potential contribution of different mesh sizes and opening angles (OA) to explain the experimental size selection curves for cod, haddock and redfish, and the three codend configurations tested. The potential contribution to escape of mesh sizes of 129 mm and 133 mm with different OAs (range: 10 − 90°), semi-slack and slack meshes is provided in %. Contributions < 1 % are omitted from the table.

		Cod			Haddock			Redfish		
Mesh size	OA	0 %	15 %	30 %	0 %	15 %	30 %	0 %	15 %	30 %
	No contact	–	2.89	7.13	–	1.10	3.10	–	1.24	5.45
129 mm	10°	–	–	–	–	–	–	–	–	–
129 mm	15°	–	–	–	–	–	–	–	–	–
129 mm	20°	–	–	–	–	–	–	–	1.30	–
129 mm	25°	–	–	–	–	–	–	–	1.84	1.39
129 mm	30°	–	–	–	–	–	–	2.99	–	–
129 mm	35°	4.05	–	–	7.33	1.80	2.47	–	–	–
129 mm	40°	3.90	1.37	–	24.57	4.48	2.30	–	–	–
129 mm	45°	5.07	4.42	–	–	7.17	–	–	–	–
129 mm	50°	4.44	5.39	–	7.67	9.87	6.94	–	–	–
129 mm	55°	–	2.80	–	6.91	9.88	12.16	–	–	–
129 mm	60°	–	–	–	–	7.90	2.09	–	1.11	–
129 mm	65°	–	3.16	–	–	–	–	–	–	–
129 mm	70°	–	3.54	1.50	–	–	–	–	1.19	–
129 mm	75°	6.06	5.10	3.42	–	–	–	–	–	–
129 mm	80°	6.33	5.39	5.86	1.52	1.49	–	–	–	–
129 mm	85°	2.66	4.88	2.84	–	–	–	–	–	–
129 mm	90°	–	4.76	0.43	–	2.98	1.61	–	–	–
129 mm	Semi-slack 25 %	5.55	2.23	8.17	–	–	–	11.68	9.39	11.83
129 mm	Semi-slack 50 %	–	–	–	–	1.03	–	–	2.38	4.76
129 mm	Semi-slack 75 %	–	–	–	–	–	–	9.41	14.46	9.84
129 mm	Slack	–	–	–	–	–	–	12.50	15.22	14.72
133 mm	10°	–	–	–	–	–	–	–	–	–
133 mm	15°	–	–	–	–	–	–	–	–	–
133 mm	20°	–	–	–	–	–	–	–	–	–
133 mm	25°	–	–	–	–	–	–	–	–	–
133 mm	30°	–	–	–	–	–	–	–	–	–
133 mm	35°	1.65	1.07	–	22.36	–	2.06	–	–	–
133 mm	40°	5.87	3.07	–	12.25	3.24	1.13	–	–	–
133 mm	45°	6.00	4.91	2.00	–	5.42	1.73	–	–	–
133 mm	50°	6.74	5.39	1.83	1.44	9.55	8.46	–	–	–
133 mm	55°	–	1.27	–	3.70	5.31	1.97	–	–	–
133 mm	60°	–	2.48	1.11	–	–	–	4.94	3.75	2.40
133 mm	65°	4.06	5.15	3.37	–	–	–	8.81	5.29	3.46
133 mm	70°	6.92	5.39	9.00	–	6.77	15.08	6.96	–	–
133 mm	75°	7.16	5.39	8.96	1.42	8.66	16.39	5.27	–	–
133 mm	80°	5.46	5.36	13.50	7.82	7.75	16.39	4.64	–	–
133 mm	85°	3.39	3.73	8.69	–	–	3.31	2.90	–	–
133 mm	90°	5.46	5.38	8.68	–	–	–	2.03	–	–
133 mm	Semi-slack 25 %	5.19	1.28	11.21	–	–	–	–	7.91	6.19
133 mm	Semi-slack 50 %	–	–	–	–	–	–	–	4.96	3.38
133 mm	Semi-slack 75 %	–	–	–	–	–	–	11.98	11.82	15.61
133 mm	Slack	2.972	1.516	–	–	–	–	12.515	15.574	15.609

species can potentially use meshes with a lower OA than cod to escape from the codend. In addition, the relevance of OAs between 70−80° increased when the lastridge ropes were shortened from 0 % to 15 % and further to 30 %. There was no contribution of slack or semi-slack meshes to the simulated curves for any of the three codend configurations (Table 2).

3.3.3. Simulation of redfish size selectivity results

The results for redfish showed that slack and semi-slack meshes play an important role for the size selection of this species, independent of the degree of SLR used. This means that redfish potentially have a greater ability to use this type of mesh when available than cod and haddock. Further, the results obtained indicate that the potential availability and use of slack meshes was largest when the configurations with SLR were used (Table 2). This result is illustrated by plots g−i in Fig. 7 which show that for all three SLR configurations tested the size selection curves for redfish lay between the 80° OA curves and the curve representing the selectivity with 133 mm slack meshes.

3.4. Exploitation pattern indicators for the codends with 0 %, 15 % and 30 % SLR

Most cod captured during the trials ranged from 40 cm to 90 cm in length and the fraction of fish under the *MLS* that entered the gear was small compared to the fraction of cod over the *MLS*. As for cod, the number of haddock over the *MLS* in the fishing area greatly exceeded the number of haddock under the *MLS*. Although for haddock there was a noticeable representation of fish between 10 cm and 20 cm. Further, most haddock in the fishing area ranged from 40 cm and 60 cm in length. Contrary to cod and haddock, the population of redfish encountered during the fishing trials was dominated by fish under the *MLS* with high abundances between 15 cm and 25 cm (Fig. 8).

3.4.1. Exploitation pattern indicators for cod

The exploitation pattern indicators for cod showed that considering the *MLS* of 44 cm as in the fishery today, the only noteworthy difference obtained between the codends tested was that the 30 % SLR codend had a significantly lower probability for retention of fish over the *MLS* compared to the other two codend configurations tested. Else, the discard ratio for all three configurations was < 1 %, which is substantially lower than the 15 % limit established in the fishery today. An

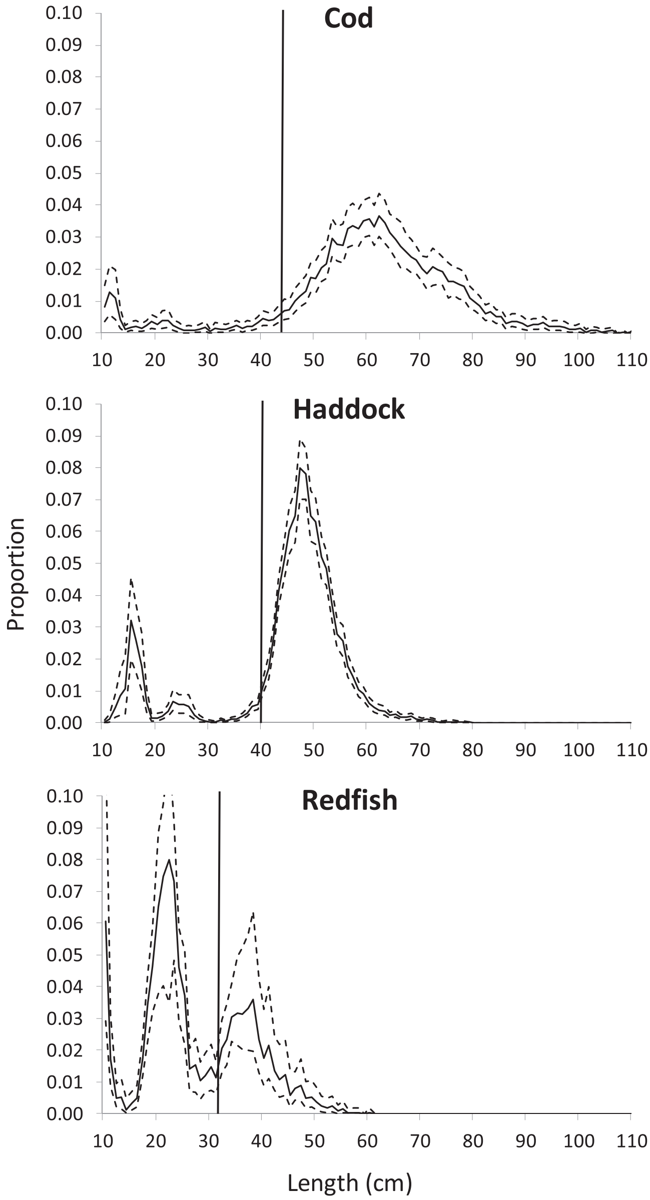

Fig. 8. Normalized populations of cod, haddock, and redfish that entered the experimental trawl during the trials. The black dashed lines show the 95 % confidence intervals for the variation in the populations encountered, and the vertical line in each plot represents the *MLS* for the species i.e. cod (44 cm), haddock (40 cm), and redfish (32 cm).

Table 3
Exploitation pattern indicators for cod, haddock and redfish with the 0 %, 15 % and 30 % SLR codend configurations tested during the trials. In addition to values based on the current legal *MLS* of 44 cm for cod, 40 cm for haddock and 32 cm for redfish, indicator values based on minimum sizes of 50 and 45 cm for respectively cod and haddock are also provided. Values in brackets represent 95 % CIs.

		0 % SLR	15 % SLR	30 % SLR
Cod	nP^- 44 cm	3.88 (2.29–6.38)	4.64 (1.94–9.53)	6.56 (2.17–12.48)
	nP^+ 44 cm	91.04 (89.23–92.74)	92.35 (90.29–94.22)	85.86 (82.34–89.17)
	nDiscard	0.49 (0.28–0.70)	0.58 (0.24–1.18)	0.88 (0.30–1.64)
	nP^- 50 cm	20.42 (15.90–25.77)	19.37 (14.00–26.99)	11.12 (4.96–18.08)
	nP^+ 50 cm	94.62 (93.34–95.85)	96.35 (95.03 97.24)	91.27 (88.59–93.87)
	nDiscard	4.24 (3.47–5.24)	3.96 (2.93–5.38)	2.44 (1.09–3.95)
Haddock	nP^- 40 cm	5.04 (3.22–8.00)	2.25 (1.19–4.03)	4.10 (1.89–6.96)
	nP^+ 40 cm	92.88 (91.63–94.11)	80.06 (74.18–84.63)	71.84 (67.50–76.56)
	nDiscard	1.05 (0.80–1.47)	0.55 (0.28–1.00)	1.11 (0.53–2.21)
	nP^- 45 cm	38.47 (29.82–48.36)	21.41 (15.18–28.95)	16.43 (11.80–22.72)
	nP^+ 45 cm	96.56 (95.20–97.67)	88.03 (83.30–91.43)	80.75 (76.88–84.68)
	nDiscard	15.25 (14.19–16.46)	9.89 (7.87–11.79)	8.41 (6.60–10.46)
Redfish	nP^- 32 cm	2.08 (0.44–5.44)	4.47 (2.24–8.52)	6.33 (1.72–12.36)
	nP^+ 32 cm	61.44 (55.29–67.35)	54.95 (46.63–65.49)	54.81 (49.07–60.84)
	nDiscard	5.89 (1.53–16.41)	13.10 (5.21–25.98)	17.62 (5.98–36.24)

increase of the minimum size of cod from 44 to 50 cm, resulted in a higher discard ratio for all three codend configurations, although this increase was not significant for the 30 % SLR codend. Nevertheless, the discard ratio was well below the 15 % limit in every case. It is also noteworthy that the probability of capturing fish above 50 cm decreased significantly from the 15 % to the 30 % SLR configuration, while the probability of capturing fish below 50 cm decreased but the difference was not significant (Table 3).

3.4.2. *Exploitation pattern indicators for haddock*

Shortening the length of the lastridge ropes resulted in a significant reduction in the probability of capturing haddock above the *MLS* of 40 cm without significantly reducing the probability of capturing fish below the *MLS*. The discard ratio, which was lowest for the 15 % SLR configuration, did not differ significantly between the configurations and was < 1.30 % in all cases (Table 3). An increase of the minimum size for haddock from 40 cm to 45 cm resulted in a substantial increase of the discard ratio for all three configurations, especially for the 0 % SLR configuration. The discard ratio for this configuration increased from 1.05 % to 15.25 % and was significantly higher than the value for the 15 % SLR configuration (Table 3). The probability of capturing haddock < 45 cm decreased significantly when the lastridge ropes were shortened by both 15 % and 30 %. This was also the case for haddock > 45 cm, which was reduced from 96.56 % with the 0 % SLR configuration to 88.03 % and 80.95 % with the 15 % and 30 % SLR configurations, respectively (Table 3).

3.4.3. *Exploitation pattern indicators for redfish*

The results for redfish were less clear than for cod and haddock. There was an increase in the probability of redfish below *MLS* and a decrease in the probability to catch fish above *MLS* when the lastridge ropes were shortened from 0 % to either 15 % or 30 %. This resulted in an increase of the discard ratio from 4.59 % with the 0 % SLR configuration to 13.10 % for the 15 % SLR configuration and further to 17.62 % for the 30 % SLR configuration. However, none of these differences between the different configurations for any of the indicators calculated here were significant (Table 3).

4. Discussion

The results of the present study demonstrate that the size selectivity properties of diamond mesh codends change when the lastridge ropes are shortened, which is well in agreement with the results reported by previous studies (Isaksen and Valdemarsen, 1990; Lök et al., 1997; Ingólfsson and Brinkhof, 2020; Sistiaga et al., 2021). However, they also show that the effect of shortening the lastridge ropes to different levels does not affect the size selectivity for the investigated species to the same extent.

For cod, shortening the lastridge ropes by 15 % did not result in a significant difference in size selectivity, and it was first when the length of the lastridge ropes were shortened by 30 % that the release of cod around the *MLS* was increased significantly compared to 0 % SLR. This result partially agrees with Sistiaga et al. (2021), who reported non-significant differences in the selectivity of a codend with 128 mm mesh size and with 0 % and 15 % SLR configurations. However, in the same study significant differences were found for a codend with 137 mm diamond meshes in the same two configurations. Contrary to cod, the results for haddock show that shortening the lastridge ropes from 0 % to 15 % increases the release of fish above ca. 35 cm significantly and that reducing the length of the lastridge ropes further to 30 % has little additional effect. Unlike for cod and haddock, shortening the lastridge ropes by 15 % or 30 % had a more limited effect on the size selectivity of redfish. Only the release of a few length classes between 35 cm and 40 cm increased significantly as a result of shortening the lastridge ropes. While the results presented for haddock were in line with those presented in Sistiaga et al. (2021), the results for redfish differ substantially as they reported significant differences in the size selection properties of redfish with 0 % and 15 % SLR codend configurations. When comparing the results between the present study and Sistiaga et al. (2021), it needs to be considered that while the codend in the latter was constructed with two panels, the codend in the present study was constructed with four panels. This could potentially influence the effect of shortening the lastridge ropes in the codend netting panels as the effect of SLRs may be better transferred to the netting panels in the codend when four lastridge ropes are applied instead of two.

An important result of the size selectivity analysis, which can be observed for the three species studied here, is that shortening codend lastridge ropes can increase the retention of fish under *MLS*, especially the smallest sizes. This result is reflected by the models that provided the best fit to the data in the different cases. In all configurations with SLR except for the redfish with 30 % SLR configuration, the models that fitted the data best were models with the contact parameter *C,* i.e. where not all the fish entering the codend contact the meshes in the codend. We attribute this lack of contact to potential folding in the codend, which can occur due to shortening the lastridge ropes. It is likely that the more the lastridge ropes are shortened, the larger the potential folding in the codend netting and, consequently, the lower the available surface for size selection in the codend. This finally results in lower contact and higher retention of all sizes of fish.

The simulations show that the selectivity curves estimated for cod, haddock and redfish and the three codend configurations tested can be explained successfully with potential contributions of meshes with different OAs and slack and semi-slack meshes in the codend. There are, however, substantial differences between cod, haddock and redfish. While haddock potentially use meshes with smaller OAs to escape the codend, cod possibly need larger OAs to escape and most redfish probably escape through slack or semi-slack meshes. These results are well in line with those obtained by Sistiaga et al. (2021), where redfish were also found to potentially use slack meshes to escape in codends with shortened lastridge ropes. Although redfish have been reported to strongly squeeze through the codend meshes (Isaksen and Valdemarsen, 1986), the authors could not find an explanation for how redfish can squeeze themselves through relatively stiff codend meshes. However, the findings in the present study corroborate the results in Sistiaga et al. (2021).

Unlike size selection curves, exploitation pattern indicators depend on the given size structure of a population. To obtain realistic indicators, we used the fish population size structure in the fishing area at the time the sea trials were carried out. The results obtained for the different indicators calculated in this study show that the 15 % SLR configuration provides results that may be beneficial for the management of the Barents Sea gadoid bottom trawl fishery and other fisheries involving the three species included in the present study. However, the use of the 30 % SLR configuration adds drawbacks such as lower retention of fish above the *MLS* (nP^{+}) combined in several cases with higher retention of fish below the *MLS* (nP^{-}), which makes this configuration less recommendable. Thus, the present study suggests that although there can be benefits of reducing lastridge ropes up to as much as 30 % in, for example, the selectivity of cod, the increase in the retention of undersized fish, presumably resulting from folding in the codend netting, suggests that reducing the length of the lastridge ropes more than 15 % is not necessary or recommendable.

In fisheries management, size selection devices that offer knife-edged shape selection curves are sought because they would allow maximizing the yield of fish above *MLS* and minimizing the catch of fish below *MLS*. A comparison of the *SR* obtained for the codend tested here and the *SR* values obtained for grid and codend systems used in the Barents Sea (Sistiaga et al., 2010; Brinkhof et al., 2020), suggests that SLR codends can provide a selection curve as sharp as those obtained by the combined grid and codend systems, but not sharper. Further, the *SR* values obtained for cod, 6.37 cm and 5.92 cm for the 15 % and 30 % SLR codends respectively, are far from the potential that diamond meshes have. Specifically, according to Herrmann et al. (2009) and simulations conducted using FISHSELECT with cod from Skagerrak for diamond meshes with 113 mm mesh size, the use of diamond meshes would result in *SR*s < 2 cm conditioned optimal contact of the fish with the meshes. Therefore, despite the potential of SLR codends to deliver as sharp selection curves as combined grid and codend systems, there is still a substantial margin for improvement regarding the performance of diamond mesh codends. A recent study has demonstrated that codends with fixed mesh shapes have more well-defined size selection properties (Bak-Jensen et al., 2022) and the potential to deliver selectivity curves closer to a knife-edge curve. In general, it can be complex to apply rigid or semi-rigid structures to codends in trawl fisheries, especially fisheries where the catches can reach several tons per haul. However, if the insertion of such structures is feasible, the potential size selection benefits of fixed mesh shapes may be worth exploring in the Barents Sea gadoid fishery and other similar demersal trawl fisheries.

CRediT authorship contribution statement

Manu Sistiaga: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. Bent Herrmann: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. Jesse Brinkhof: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. Roger B. Larsen: Conceptualization; Data curation; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Roles/Writing - original draft. Juan Santos: Conceptualization; Data curation; Investigation; Methodology; Validation; Visualization; Roles/Writing - original draft. Daniel Stepputtis: Conceptualization; Data curation; Investigation; Methodology; Validation; Visualization; Roles/Writing - original draft. Ilmar Brinkhof: Conceptualization; Data curation; Investigation; Validation; Visualization; Roles/Writing - original draft. Nadine Jacques: Conceptualization; Data curation; Investigation; Validation; Visualization; Roles/Writing - original draft. Kristine Cerbule: Conceptualization; Data curation; Investigation; Validation; Visualization; Roles/Writing - original draft. Andrea Petetta: Conceptualization; Data curation; Investigation; Validation; Visualization; Roles/Writing - original draft. Elsa Cuende: Conceptualization; Data curation; Roles/Writing - original draft. Liz Kvalvik: Visualization; Roles/Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial

Data availability

Data will be made available on request.

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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.2023.106671.

References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Autom. Control 19, 716–723. https://doi.org/10.1109/TAC.1974.1100705.

Alzorriz, N., Arregi, L., Herrmann, B., Sistiaga, M., Casey, J., Poos, J.J., 2016. Questioning the effectiveness of technical measures implemented by the Basque bottom otter trawl fleet: implications under the EU landing obligation. Fish. Res. 175, 116–126. https://doi.org/10.1016/j.fishres.2015.11.023.

Bak-Jensen, Z., Herrmann, B., Santos, J., Jacques, N., Melli, V., Feekings, J.P., 2022. Fixed mesh shape reduces variability in codend size selection. Can. J. Fish. Aquat. Sci. 79, 1820–1829. https://doi.org/10.1139/cjfas-2022-0049.

Bergstad, O.A., Jørgensen, T., Dragesund, O., 1987. Life history and ecology of the gadoid resources of the Barents Sea. Fish. Res. 5, 119–161. https://doi.org/10.1016/0165-7836(87)90037-3.

Beverton, R.J.H., 1963. Escape of fish through different parts of a codend. The selectivity of fishing gear. ICNAF Spec. Publ, pp. 9–11.

Brčić, J., Herrmann, B., Sala, A., 2018. Can a square-mesh panel inserted in front of the cod end improve size and species selectivity in Mediterranean trawl fisheries? Can. J. Fish. Aquat. Sci. 75, 704–713. https://doi.org/10.1139/cjfas-2017-0123.

Brinkhof, J., Larsen, R.B., Herrmann, B., Sistiaga, M., 2020. Size selectivity and catch efficiency of bottom trawl with a double sorting grid and diamond mesh codend in the North-east Atlantic gadoid fishery. Fish. Res. 231, 105647 https://doi.org/10.1016/j.fishres.2020.105647.

Brinkhof, J., Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R.B., 2022. Managing size selectivity: the relevance of compulsory and alternative selection devices in the Northeast Atlantic bottom trawl fishery. ICES J. Mar. Sci. 79, 2399–2412. https://doi.org/10.1093/icesjms/fsac174.

Cheng, Z., Einarsson, H.A., Bayse, S., Herrmann, B., Winger, P., 2019. Comparing size selectivity of traditional and knotless diamond-mesh codends in the Iceland redfish (*Sebastes spp*.) fishery. Fish. Res. 216, 138–144. https://doi.org/10.1016/j.fishres.2019.04.009.

Cheng, Z., Winger, P.D., Bayse, S.M., Kebede, G.E., DeLouche, H., Einarsson, H.A., Pol, M.V., Kelly, D., Walsh, S.J., 2020. Out with the old and in with the new: T90 codends improve size selectivity in the Canadian redfish (*Sebastes mentella*) trawl fishery. Can. J. Fish. Aquat. Sci. 77, 1711–1720. https://doi.org/10.1139/cjfas-2020-0063.

Clark, J.R., 1963. Size selection of fish by otter trawls. Results of recent experiments in the Northwest Atlantic. In: The selectivity of fishing gear, 5. ICNAF Spec. Publ, pp. 24–96.

Cuende, E., Arregi, L., Herrmann, B., Sistiaga, M., Basterretxea, M., 2020a. Release efficiency and selectivity of four different square mesh panel configurations in the Basque mixed bottom trawl fishery. Sci. Mar. 84, 39–47. https://doi.org/10.3989/scimar.04975.17A.

Cuende, E., Arregi, L., Herrmann, B., Sistiaga, M., Aboitiz, X., 2020b. Prediction of square mesh panel and codend size selectivity of blue whiting based on fish morphology. ICES J. Mar. Sci. 77, 2857–2869. https://doi.org/10.1093/icesjms/fsaa156.

Cuende, E., Sistiaga, M., Herrmann, B., Arregi, L., 2022. Optimizing size selectivity and catch patterns for hake (*Merluccius merluccius*) and blue whiting (*Micromesistius poutassou*) by combining square mesh panel and codend designs. PLoS ONE 17, e0262602. https://doi.org/10.1371/journal.pone.0262602.

Efron, B., 1982. The jackknife, the bootstrap and other resampling plans. SIAM Monograph No 38. CBSM-NSF.

Einarsson, H.A., Cheng, Z., Bayse, S.M., Herrmann, B., Winger, P.D., 2021. Comparing the size selectivity of a novel T90 mesh codend to two conventional codends in the northern shrimp (*Pandalus borealis*) trawl fishery. Aquacult. Fish. 6, 382–392. https://doi.org/10.1016/j.aaf.2020.09.005.

Herrmann, B., 2005a. Effect of catch size and shape on the selectivity of diamond mesh cod-ends: I model development. Fish. Res. 71, 1–13. https://doi.org/10.1016/j.fishres.2004.08.024.

Herrmann, B., 2005b. Effect of catch size and shape on the selectivity of diamond mesh cod-ends: II theoretical study of haddock selection. Fish. Res. 71, 15–26. https://doi.org/10.1016/j.fishres.2004.08.021.

Herrmann, B., O'Neill, F.G., 2005. Theoretical study of the between-haul variation of haddock selectivity in a diamond mesh cod-end. Fish. Res. 74, 243–252. https://doi.org/10.1016/j.fishres.2005.01.022.

Herrmann, B., Priour, D., Krag, L.A., 2007. Simulation-based study of the combined effect on cod-end size selection for round fish of turning mesh 90 degrees and of reducing the number of meshes in the circumference. Fish. Res. 84, 222–232. https://doi.org/10.1016/j.fishres.2006.10.020.

Herrmann, B., Krag, L.A., Frandsen, R.P., Madsen, N., Lundgren, B., Stæhr, K.J., 2009. Prediction of selectivity from morphological conditions: methodology and a case study on cod (*Gadus morhua*). Fish. Res. 97, 59–71. https://doi.org/10.1016/j.fishres.2009.01.002.

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (*Sebastes spp.*) in North Atlantic trawl codends. J. North. Atl. Fish. Sci. 44, 1–13. https://doi.org/10.2960/J.v44.m680.

Herrmann, B., Sistiaga, M., Larsen, R.B., Nielsen, K.N., Grimaldo, E., 2013. Understanding sorting grid and codend size selectivity of Greenland halibut (*Reinhardtius hippoglossoides*). Fish. Res. 146, 59–73. https://doi.org/10.1016/j.fishres.2013.04.004.

Herrmann, B., Krag, L.A., Feekings, J., Noack, T., 2016. Understanding and predicting size selection in diamond mesh codends for Danish seining: a study based on sea trials and computer simulations. Mar. Coast. Fish. 8, 277–291. https://doi.org/10.1080/19425120.2016.1161682.

Ingólfsson, O.A., Brinkhof, J., 2020. Relative size selectivity of a four-panel codend with short lastridge ropes compared to a flexigrid with a regular codend in the Barents Sea gadoid trawl fishery. Fish. Res. 232, 105724 https://doi.org/10.1016/j.fishres.2020.105724.

Isaksen, B., Valdemarsen, J.W., 1986. Selectivity experiments with square mesh codends in bottom trawl. ICES C. M. 1986/B:28.

Isaksen, B., Valdemarsen, J.W., 1990. Codend with short lastridge ropes to improve size selectivity in fish trawls. ICES CM 1990/. B46:8.

Jacques, N., Pettersen, H., Cerbule, K., Herrmann, B., Ingólfsson, Ó.A., Sistiaga, M., Larsen, R.B., Brinkhof, J., Grimaldo, E., Brčić, J., Lilleng, D., 2022. Bycatch reduction in the deep-water shrimp (*Pandalus borealis*) trawl fishery by increasing codend mesh openness. Can. J. Fish. Aquat. Sci. 79, 331–341. https://doi.org/10.1139/cjfas-2021-0045.

Kalogirou, S., Pihl, L., Maravelias, C.D., Herrmann, B., Smith, C.J., Papadopoulou, N., Notti, E., Sala, A., 2019. Shrimp trap selectivity in a Mediterranean small-scale-fishery. Fish. Res. 211, 131–140. https://doi.org/10.1016/j.fishres.2018.11.006.

Kennelly, S.J., Broadhurst, M.K., 2021. A review of bycatch reduction in demersal fish trawls. Rev. Fish. Biol. 31, 289–318. https://doi.org/10.1007/s11160-021-09644-0.

Larsen, R.B., Herrmann, B., Sistiaga, M., Grimaldo, E., Tatone, I., Onandia, I., 2016. Size selection of redfish (*Sebastes spp*.) in a double grid system: quantifying escapement through individual grids and comparison to former grid trials. Fish. Res. 183, 385–395. https://doi.org/10.1016/j.fishres.2016.07.013.

Larsen, R.B., Herrmann, B., Sistiaga, M., Brčić, J., Brinkhof, J., Tatone, I., 2018. Could green artificial light reduce bycatch during Barents Sea deep-water shrimp trawling? Fish. Res. 204, 441–447. https://doi.org/10.1016/j.fishres.2018.03.023.

Lök, A., Tokaç, A., Tosunoğlu, Z., Metin, C., Ferro, R.S.T., 1997. The effects of different codend design on bottom trawl selectivity in Turkish fisheries of the Aegean Sea. Fish. Res. 32, 149–156. https://doi.org/10.1016/S0165-7836(97)00048-9.

Lomeli, M.J.M., 2019. Bycatch Reduction in Eastern North Pacific Trawl Fisheries. A dissertation for the degree of Doctor Philosophiae. The Arctic University of Norway, Faculty of Biosciences, Fisheries and Economy, Norwegian College of Fishery Science, Tromsø, Norway. ISBN 978–82-8266–175.

Melli, V., Herrmann, B., Karlsen, J.D., Feekings, J.P., Krag, L.A., 2020. Predicting optimal combinations of bycatch reduction devices in trawl gears: a meta-analytical approach. Fish Fish. 21, 252–268. https://doi.org/10.1111/faf.12428.

Millar, R.B., 1993. Incorporation of between-haul variation using bootstrapping and nonparametric estimation of selection curves. Fish. Bull. 91, 564–572.

fsp229 O'Neill, F.G., Herrmann, B., 2007. PRESEMO — a predictive model of codend selectivity — a tool for fisheries managers. ICES J. Mar. Sci. 64, 1558–1568. https://doi.org/10.1093/icesjms/fsm101.

Olsen, E., Aanes, S., Mehl, S., Holst, J.C., Aglen, A., Gjøsæter, H., 2010. Cod, haddock, saithe, and capelin in the Barents Sea and adjacent waters: a review of the biological value of the area. ICES J. Mar. Sci. 67, 87–101. https://doi.org/10.1093/icesjms/.

Petetta, A., Herrmann, B., Virgili, M., De Marco, R., Canduci, G., Li Veli, D., Bargione, G., Vasapollo, C., Luchetti, A., 2020. Estimating selectivity of experimental diamond (T0) and turned mesh (T90) codends in multi-species Mediterranean bottom trawl. Med. Mar. Sci. 21, 545–557. https://doi.org/10.12681/mms.22789.

Petetta, A., Herrmann, B., Virgili, M., Bargione, G., Vasapollo, C., Lucchetti, A., 2021. Dredge selectivity in a Mediterranean striped venus clam (*Chamelea gallina*) fishery. Fish. Res. 238, 105895 https://doi.org/10.1016/j.fishres.2021.105895.

Robertson, J.H.B., Stewart, P.A.M., 1988. A comparison of size selection of haddock and whiting by square and diamond mesh codends. J. Cons. CIEM 44, 148–161. https://doi.org/10.1093/icesjms/44.2.148.

Santos, J., Herrmann, B., Mieske, B., Stepputtis, D., Krumme, U., Nilsson, H., 2016. Reducing flatfish by-catches in roundfish fisheries. Fish. Res. 184, 64–73. https://doi.org/10.1016/j.fishres.2015.08.025.

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R.B., 2010. Assessment of dual selection in grid-based selectivity systems. Fish. Res. 105, 187–199. https://doi.org/10.1016/j.fishres.2010.05.006.

Sistiaga, M., Herrmann, B., Nielsen, K.N., Larsen, R.B., 2011. Understanding limits to cod and haddock separation using size selectivity in a multispecies trawl fishery: an application of FISHSELECT. Can. J. Fish. Aquat. Sci. 68, 927–940. https://doi.org/10.1139/f2011-017.

Sistiaga, M., Brinkhof, J., Herrmann, B., Grimaldo, E., Langård, L., Lilleng, D., 2016. Size selective performance of two flexible sorting grid designs in the Northeast Arctic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) fishery. Fish. Res. 183, 340–351. https://doi.org/10.1016/j.fishres.2016.06.022.

Sistiaga, M., Brinkhof, J., Herrmann, B., Larsen, R.B., Grimaldo, E., Cerbule, K., Brinkhof, I., Jørgensen, T., 2021. Potential for codends with shortened lastridge ropes to replace mandated selection devices in demersal trawl fisheries. Can. J. Fish. Aquat. Sci. 79, 834–849. https://doi.org/10.1139/cjfas-2021-0178.

Manual of methods of measuring the selectivity of towed fishing gears. In: Wileman, D., Ferro, R.S.T., Fonteyne, R., Millar, R.B. (Eds.), 1789. ICES Cooperative Research report No. 215. https://doi.org/10.17895/ices.pub.4628.