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Approaching single-species exclusion in mixed demersal trawl fisheries

O. Jonas Palder[a,b], Jordan P. Feekings[a], Shaun Fraser[c], Valentina Melli[a,*]

[a] Technical University of Denmark, National Institute of Aquatic Resources (DTU Aqua), DK-9850, Hirtshals, Denmark
[b] Department of Fish Biology, Fisheries and Aquaculture, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Germany
[c] Shetland UHI – Scalloway Campus, University of the Highlands and Islands, Port Arthur, Scalloway, Shetland, ZE1 0UN, UK

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ABSTRACT

Under a discard ban, mixed fisheries must often reduce catches of low-quota species to allow the continuation of fishing activities. This has led to the development of a range of bycatch reduction devices (BRDs) that aim to exploit morphological and behavioral differences among species to facilitate escape of unwanted catch from the fishing gear. However, the exclusion of unwanted species from the catch is often only possible with concomitant losses of other commercial catches. This is the case for the *Nephrops* (*Nephrops norvegicus*)-directed mixed demersal trawl fishery, where BRDs aiming at the reduction of catches of cod (*Gadus morhua*) often lead to considerable losses of other valuable species. In this study, we developed and tested a BRD aimed at exclusively reducing cod catches without affecting catches of *Nephrops*, flatfish and other roundfish. The design, a bottom escape window, exploits behavioral traits that set cod apart from other species. We collected absolute selectivity data using a paired gears approach and estimated the combined retention of the bottom escape window and a 90 mm diamond mesh codend. The results demonstrated a low total retention of cod (33%) in combination with high retentions of commercial catches of *Nephrops* (89%), haddock (*Melanogrammus aeglefinus*) (76%) and plaice (*Pleuronectes platessa*) (100%), for the populations encountered. This catch profile represents an important and novel achievement for *Nephrops*-directed mixed demersal fisheries. We compared the performance of this new BRD to one of the most used legal gears in this fishery (the SELTRA 270), demonstrated the new catch profile it can offer to the fishers, and discussed its management implications.

1. Introduction

Mixed fisheries often have high levels of bycatch that is caught along with the main target species. A fraction of the bycatch is typically considered wanted, as it can be marketed and contributes to the generated revenue. The unwanted part of the bycatch includes individuals that are undersized, caught in excess of the available quota, or belong to non-commercial species (Catchpole et al., 2005). This fraction is often discarded, a custom that is a waste of both ecological and economic resources (Bellido et al., 2011). To prevent this wasteful practice, fisheries management increasingly relies on discard bans, challenging mixed fisheries to avoid undersized fish and low-quota species (Borges et al., 2016; Condie et al., 2014; European Union, 2013). Under a discard ban, all catches of species subject to catch limits must be landed; thus, quota exhaustion for a single species may result in choking a mixed fishery if additional catches of this species cannot be avoided during further fishing activities (Hatcher, 2014; Mortensen et al., 2018). The so-called "choke species", i.e. species whose quotas are likely to be exhausted before those of other target species, threaten the viability of many mixed-species fisheries (Mortensen et al., 2018). Therefore, research often focuses on the exclusion of choke species from fishing gears, with the objective of exploiting the remaining harvest potential for other species while remaining profitable (Kennelly and Broadhurst, 2021; Krag et al., 2010).

Selectively excluding single species from the catch is challenging when target and non-target species are similar in morphology (Beutel et al., 2008). Interspecific differences in behavior are typically able to facilitate only a partial species separation (Krag et al., 2009; Thomsen, 1993; Winger et al., 2010). The successful exclusion of a single unwanted bycatch species is, therefore, often linked to partial losses of other species that are part of the desired catch (Catchpole and Revill, 2008; Graham, 2010). Sacrificing parts of the commercial catch to achieve the exclusion of only a few unwanted species reduces the efficiency of a fishery and results in lost revenue (Graham, 2010; Krag et al.,

* Corresponding author. Technical University of Denmark, National Institute of Aquatic Resources (DTU Aqua), North Sea Science Park, DK-9850, Hirtshals, Denmark.

E-mail address: vmel@aqua.dtu.dk (V. Melli).

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2010). Furthermore, the acceptance of gear adaptations can be low when fishers fear losing commercial catch (Eayrs and Pol, 2019; Fonseca et al., 2005; Suuronen, 2022). Therefore, the development of selective fishing gears should aim to facilitate the exclusion of unwanted species as specifically as possible, while allowing to maintain high retentions of other commercial species.

Across the North Atlantic Ocean, low catch quotas of cod (*Gadus morhua*) often make it a choke species and various trawl fisheries aim to reduce its catch through gear modifications (Pol and Eayrs, 2021). Among these are *Nephrops* (*Nephrops norvegicus*)-directed mixed demersal fisheries that often have high rates of bycatch of both non-commercial and commercial fish, the latter making up a significant part of the generated revenue (Catchpole et al., 2006; Krag et al., 2008). Such *Nephrops*-directed mixed demersal fisheries often lose revenue when aiming to exclude cod from their catches, as they commonly rely on either a grid that eliminates all commercial bycatch of flatfish and roundfish (Catchpole et al., 2006; Hornborg et al., 2017; Valentinsson and Ulmestrand, 2008), or a top escape panel, which loses large amounts of other commercial roundfish such as haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) along with cod (Catchpole and Revill, 2008; Krag et al., 2016). To date, no gear option for *Nephrops*-directed mixed demersal fisheries allows to specifically exclude cod without losses of commercial bycatch, particularly of other roundfish species.

The reduction of cod catches without large losses of other roundfish species has, however, been achieved in mixed whitefish fisheries in the past using two different gear modifications. First, Krag et al. (2010) developed a trawl with a raised fishing line, allowing fish that swim in close proximity to the seabed, like cod, to pass under the trawl mouth while catching species that swim higher in the water column, such as haddock, whiting and saithe (*Pollachius virens*). Second, Fraser & Angus (2019) used a bottom escape panel located under an inclined net panel in the trawl extension, which exploits two characteristics of cod behavior that distinguish them from many other fish species: their strong swimming capacity (Beamish, 1966) and their tendency to swim in close proximity to the bottom netting of the trawl compared to other roundfish species (Krag et al., 2009). While both designs can facilitate the selective reduction of cod catches in whitefish-directed trawl fisheries, a raised fishing line as described by Krag et al. (2010) is not applicable for *Nephrops*-directed mixed demersal fisheries, where both the target species and commercial bycatch flatfish species are strongly bottom-associated and would escape under the raised fishing line along with cod (Catchpole and Revill, 2008; Ryer, 2008). In contrast, the escape mechanism exploited by the design described by Fraser and Angus (2019) relies on cod swimming forward against the flow at the bottom of the trawl to access the escape panel. Given the limited swimming capacities of *Nephrops* and many flatfish species, a concept based on this escape mechanism could, in principle, offer a novel catch profile to *Nephrops*-directed mixed demersal fisheries that are limited by cod quota availability. The development of such a gear for a *Nephrops*-directed mixed demersal fishery would entail significant engineering challenges to account for factors that might compromise the efficiency of the escape mechanism exploited by Fraser and Angus (2019). First, the small mesh sizes required in the inclined panel for the crustaceans to pass over the escape area may lead to debris accumulation and to the masking of the escape panel. Second, cod escape behavior may be inhibited by factors such as sediment clouds in the lower part of the trawl and by the close proximity of the escape window to the seabed (Main and Sangster, 1981). And third, cod caught in *Nephrops*-directed fisheries are often of smaller size than those encountered in whitefish fisheries (e.g. 30–40 cm as opposed to 60–90 cm), which could have implications for escape behavior and swimming capacity.

This study aimed at:

1) Investigating the applicability of a cod-specific bottom escape window in a *Nephrops*-directed mixed demersal trawl fishery;
2) Assessing the catch performance of this new BRD for most commercial species of interest in the *Nephrops*-directed mixed demersal fishery;
3) Comparing the catch performance to the preferred legal gear used in the *Nephrops*-directed mixed demersal fishery to determine if it creates new opportunities for the fishers in terms of catch profile.

2. Materials and methods

2.1. Test gear design

The codend tested in this study was made of two sheets of standard 90 mm (nominal) diamond mesh (DM) polyethylene (PE) 4 mm double twine (D4) netting. Both, the top and bottom sheets, were subdivided into 3 evenly sized, 20 mesh-wide panels by tying two false selvedges of 2 meshes each along the length of the sheet, resulting in a 6-panel configuration with a circumference of 120 open meshes (Fig. 1). This configuration does not correspond to the codends used in the Danish *Nephrops*-directed mixed demersal trawl fishery in Kattegat and Skagerrak, but was chosen for the experiment as it was expected to maintain a more stable gear geometry. To determine the actual mesh size, two rows of 10 consecutive meshes in longitudinal direction were measured for each of the six panels on the wet codend after the last haul of the trial using an OMEGA gauge (Fonteyne et al., 2007), resulting in an average mesh size of 92.52 mm across the different panels with a standard deviation of 1.77 mm.

An inclined panel and a horizontal panel were used to separate the codend into two sections, similar to Fraser and Angus (2019) (Fig. 1). The inclined and horizontal panels were constructed from a continuous sheet of 40 mm (nominal) DM PE netting to ensure that no *Nephrops* could fall through into the bottom section of the codend and that all individuals of commercial species would first be directed towards the end of the codend. The leading edge of the inclined panel was tied to the bottom and side panels of the codend. The codend section containing the inclined panel measured 1.9 m (stretched length) and the inclined panel was 49 meshes wide at its leading edge and 57 meshes wide at the end, to adjust for the wider distance between the side selvedges of the codend. Once reaching the side selvedges of the codend, the inclined panel transitioned into a horizontal panel that was tied to the side selvedges and continued for another 1.9 m (stretched length). The trailing edge of the horizontal panel was V-shaped with the incision 0.9 m deep towards the front of the codend. The V-shape was chosen to avoid slack netting in this area, which may block access to the bottom section of the codend or influence fish behavior. The back end of the V was 0.7 m ahead of the lifting strap and 2.5 m ahead of the codline. Under the inclined panel, a diamond-shaped opening was cut into the bottom panel of the codend over a length of 1.9 m (20 meshes long and 20 meshes wide), forming the escape window. The back corner of the escape window was located 4.4 m ahead of the codline, 2.6 m ahead of the lifting strap, and 1 m ahead of the tip of the V (Fig. 1). This configuration was expected to prevent losses of *Nephrops* and other commercial catch species due to flow dynamics in the codend, while facilitating escape for those fish that swim forward from the back of the codend into the lower section of it.

To improve gear stability, the two false tied-mesh selvedges of the bottom codend section were weighted with leadline (0.5 kg/m in air). Moreover, in the top codend section, 20 floats (with a buoyancy corresponding to 130 g each) were attached to each of the two false tied-mesh selvedges. The weight and floatation were evenly distributed over the distance from the beginning of the codend to the lifting strap (5.5 m). Two pairs of kites (5 pockets) were attached to the selvedges running along the lateral sides of the codend at the beginning and the end of the horizontal panel. The six-panel codend design in combination with the kites was chosen to reduce slack in the inclined and horizontal panels by applying outward pulling forces.

Before the sea trial, the codend was tested in a flume tank (SINTEF,

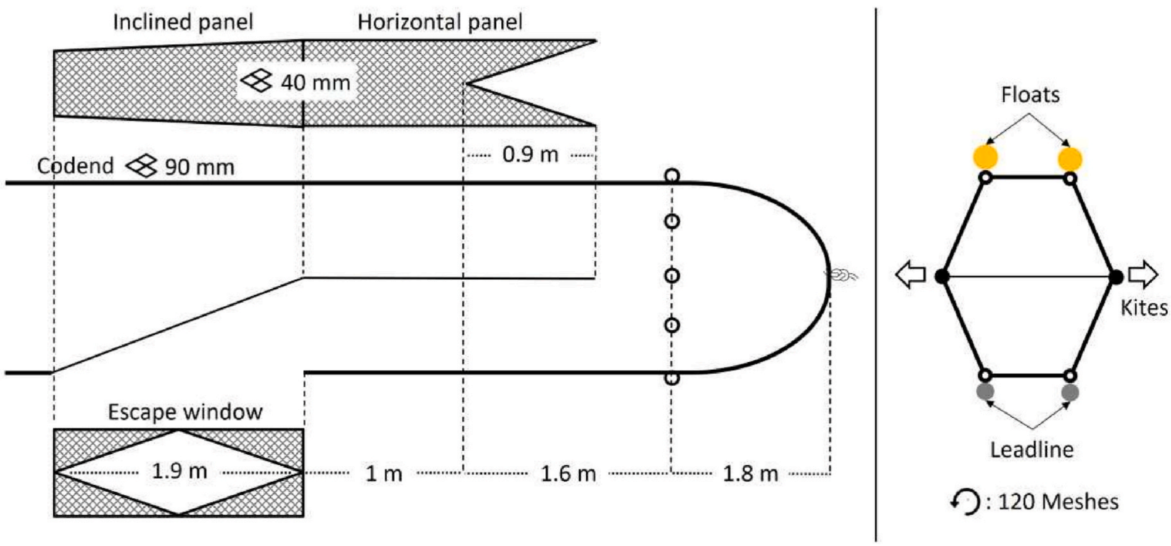

Fig. 1. Test codend design. Left: Side view of the codend along the longitudinal plane. The escape window and the inclined and horizontal panels are further sketched in top-view. Right: Cross section of the codend in the area with the horizontal panel. The selvedges on the top panel of the codend were used as attachment points for floats, and the selvedges of the bottom panel of the codend were weighed with leadline. The selvedges on the sides of the codend were fitted with two kites each. The number of meshes in circumference is shown at the bottom.

Hirtshals 9850, DK), where fishers and fisheries representatives were given the opportunity to provide input regarding the design. Observations during this test resulted in adjustments leading to the final design, including the distribution of floats and leadline as well as the tapering of the inclined panel.

2.2. Data collection

The gear trial was conducted on R/V Havfisken (17 m, 373 kW) that was rigged for three-wire twin trawling using Type 2 Thyborøn doors (1.78 m^2, 197 kg) and a 400 kg triangular central clump. The trawls were Combi-trawls that are designed to catch both fish and *Nephrops* and

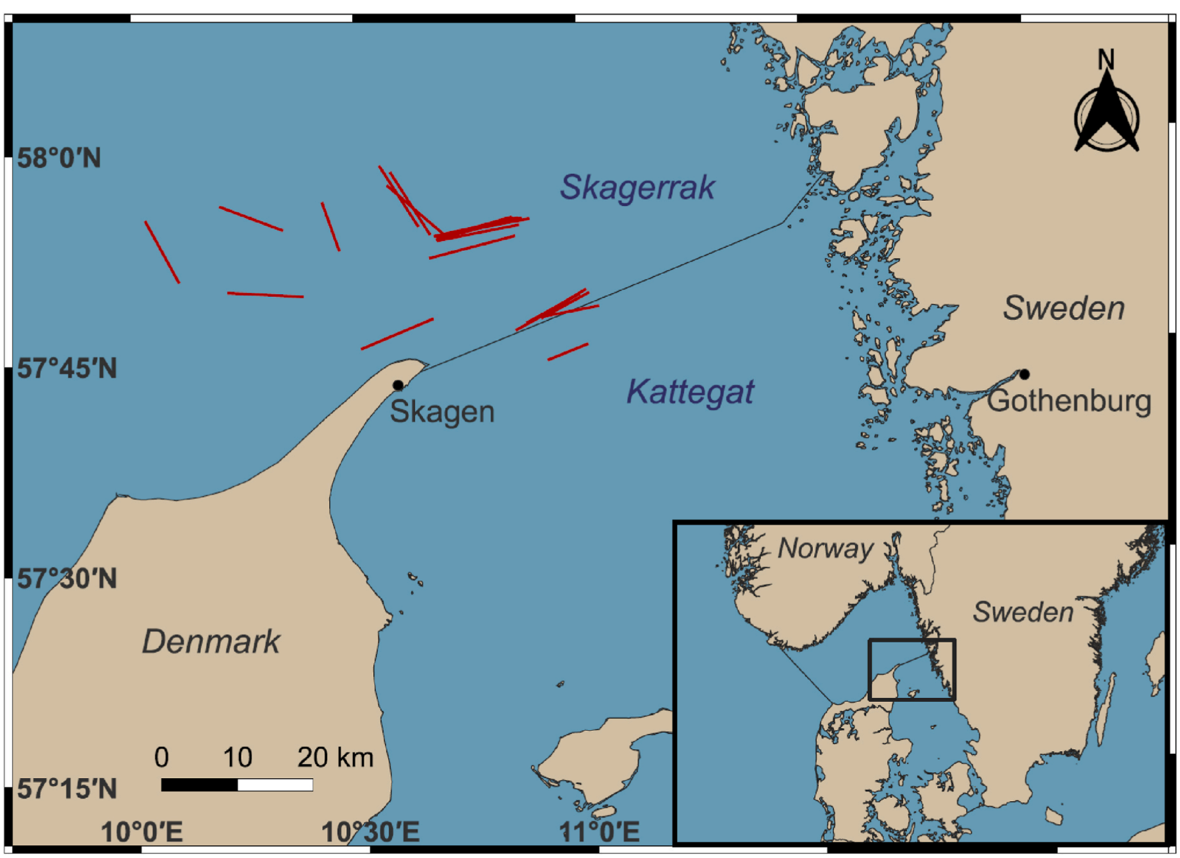

Fig. 2. Locations of the 21 hauls considered in the selectivity analysis in the study. Haul tracks are simplified as straight red lines between the beginning and end coordinates for each haul.

are commonly used in the case study fishery. The trawls used 40 m footropes, had 10 m long wings, 420 meshes in circumference at the trawl mouth, and a 2-panel trawl body with a stretched length of approximately 26 m (excluding codend) made of 80 mm (nominal mesh) netting (see the net plan in Supplementary Materials). During the trial, one trawl was rigged with the test codend, while the other trawl was rigged with a fine-mesh non-selective control codend. This experimental setup allows to estimate the catch retention in the test codend compared to the encountered population, as retained in the non-selective control codend. The control codend was a 4-panels 90 mm codend with 96 open meshes in circumference, typically used in the fishery, that was blinded with a 40 mm (nominal) inner net that would retain the encountered population ($nPop_l$) across the relevant size ranges for all species. Because of the difference in circumference between the test and control codends (120 vs 96 meshes, respectively), a section of the test trawl body was cut off to ensure equal joining ratio (number of trawl body-meshes attached to each codend-mesh) for both codends. This was done as a precaution since the joining ratio can influence the openness of the codend entrance (Krag et al., 2016).

Data were collected between June 16th and June 24th' 2022 in Kattegat and Skagerrak (FAO Division IIIa) (Fig. 2). Fishing was conducted to match commercial conditions in terms of towing speed and fishing grounds; however, tow durations were shorter (mean ± SD = 1.80 ± 0.31 h) than commonly observed in the fishery (i.e. 3-5 h) to prevent over-filling the small-mesh control codend, where the 40 mm mesh would retain a much larger catch than the 90 mm mesh typically used in the fishery. During towing, the geometry of the gear was monitored using acoustic spread and headline height sensors (SIMRAD PX, www.simrad.com). Headline heights and distances between the trawl doors and the clump were noted by the skipper at the beginning, middle and end of each haul. The values were then averaged for each trawl and haul. Valid hauls were considered those where no systematic differences in gear spread were observed and where a total at least 10 individuals for a given species were caught in both codends (Krag et al., 2014).

Prior to the start of the data collection, five hauls were dedicated to observe the gear geometry and identify potential issues that could affect gear performance. To this end, cameras (Paralenz DC+) and artificial lights (Inon LF 3100-EW, white) were fixed at various positions within the codend and the footage was scanned to verify the shape of the codend cross section and to identify potential issues such as gear collapse, masking of the escape window, catch accumulation at the inclined panel or excessive escape through the window. These hauls were excluded from the analysis to avoid potential behavioral effects on the species of interest caused by the presence of cameras and artificial illumination (Melli et al., 2018a). 21 hauls were then conducted to determine the selectivity of the test codend. All 21 hauls were valid in terms of gear spread, and each haul was valid for analysis for at least four species of interest based on sufficient numbers of individuals. Codends were shifted between trawls after the first 8 valid hauls to account for potential systematic differences of capture efficiency between the trawls.

At the end of each tow, the catches collected in the test and control codends were lifted onboard and processed individually, starting with the test codend to prevent the catch from being selected out at the surface by the codend mesh size. For each codend, the total catch weight was taken prior to sorting. Catches of *Nephrops*, plaice (*Pleuronectes platessa*), lemon sole (*Microstomus kitt*), witch flounder (*Glyptocephalus cynoglossus*), cod, haddock, saithe, whiting and hake (*Merluccius merluccius*) were sorted and weighed. Carapace length was measured to the nearest mm below for *Nephrops* using digital calipers, and total length was measured to the nearest cm below for all fish species. When subsampling was required due to high catches, the weights of a randomly selected sample and the total weight caught of the species were used to calculate the sampling ratio.

2.3. Length-based selectivity

Length-based analysis was conducted for *Nephrops*, plaice, lemon sole, witch flounder, cod, haddock, saithe and whiting. We used a paired gears analysis, where the population encountered during fishing, $nPop_l$, for each species and length class is given by the control codend, allowing to estimate the length-based retention probabilities for the test codend (Wileman et al., 1996). The test codend included two selection devices where an individual could have been selected out by the mesh size in the codend r_{codend} (l) or have swam forward and exited the escape window r_{window} (l). Considering that all individuals contacting the escape window should in principle be able to escape, we modelled the size selection in the test gear by:

$$r_{combined}(l, \boldsymbol{v_{window}}, \boldsymbol{v_{codend}}) = (1.0 - C_{window}(l, \boldsymbol{v_{window}})) \times r_{codend}(l, \boldsymbol{v_{codend}}) \quad (1)$$

Where $C_{window}(l, \boldsymbol{v_{window}})$ is the probability for an individual to contact the window and successfully escape and $r_{codend}(l, \boldsymbol{v_{codend}})$ is the retention process of the codend mesh (*Equation* (1)). Depending on their contribution to the combined selection process, each of these processes can be identified as primary or secondary.

Given that the codend consisted of one mesh size and type, we assumed that the size selection process through the codend mesh could be reasonably well modelled by a logistic curve (Wileman et al., 1996):

$$r_{codend}(l, \boldsymbol{v_{codend}}) = \frac{\exp\left(\frac{ln(9.0)}{SR_{codend}} \times (l - L50_{codend})\right)}{1.0 + \exp\left(\frac{ln(9.0)}{SR_{codend}} \times (l - L50_{codend})\right)} \quad (2)$$

Here, $L50_{codend}$ is the length at which the probability for retention in the codend mesh for an individual is 50%. SR_{codend} is the selection range of the codend mesh and is calculated as the difference in lengths at which individuals have a retention probability of 25 and 75%, respectively (*Equation* (2)).

For the probability of contacting the escape window and escaping $C_{window}(l, \boldsymbol{v_{window}})$, seven different parametric models were considered for each species (Melli et al., 2023). Depending on the specific assumptions regarding the type of contact with the escape window (e.g. length-independent, increasing at length, etc.), $\boldsymbol{v_{window}}$ can include the parameters $L50_{window}$, SR_{window} and A_{window}. The latter is a length-independent contact probability, which can either apply to all length classes (Model 3) or limit the minimum or maximum contact probability (Model 5 and 7, respectively); (Table 1).

Table 1
Assumptions for the seven models used underlying the contact probability expressed by *Equation* (3).

Model	Assumption
1	No individuals contact the escape window.
2	All individuals contact the escape window.
3	A portion of the individuals A_{window}, regardless of length, contacts the escape window.
4	Escape window contact probability increases with length following a logistic curve with parameters $L50_{window}$ and SR_{window}.
5	Similar to Model 4 but with the assumption that for every length class at least a fraction A_{window} of the population contacts the window.
6	Escape window contact probability decreases with length following a logistic curve with parameters $L50_{window}$ and SR_{window}.
7	Similar to Model 6 but with the assumption that for every length class a fraction of the population that cannot be bigger than A_{window} will contact the window.

$$C_{window}(l, \boldsymbol{v_{window}}) = \begin{cases} 0.0 & : Model\,1 \\ 1.0 & : Model\,2 \\ A_{window} & : Model\,3 \\ \dfrac{\exp\left(\dfrac{ln(9.0)}{SR_{window}} \times (l - L50_{window})\right)}{1.0 + \exp\left(\dfrac{ln(9.0)}{SR_{window}} \times (l - L50_{window})\right)} & : Model\,4 \\ 1.0 - \dfrac{A_{window}}{1.0 + \exp\left(\dfrac{ln(9.0)}{SR_{window}} \times (l - L50_{window})\right)} & : Model\,5 \\ \dfrac{1.0}{1.0 + \exp\left(\dfrac{ln(9.0)}{SR_{window}} \times (l - L50_{window})\right)} & : Model\,6 \\ \dfrac{A_{window}}{1.0 + \exp\left(\dfrac{ln(9.0)}{SR_{window}} \times (l - L50_{window})\right)} & : Model\,7 \end{cases} \quad (3)$$

For each of the eight species included in the length-based analysis, we used *Equations* (1) to (3) to describe the selection data collected during the experiment. We maximized the probability to attain the experimental data under the assumptions made by each of the seven escape window contact models to find the values for $\boldsymbol{v_{window}}$ and $\boldsymbol{v_{codend}}$ that best explain the experimental data. This was done through maximum likelihood estimation by minimizing expression (4).

$$-\sum_{j=1}^{m}\sum_{l}\left\{\frac{nTest_{lj}}{qTest_j} \times ln\left(\frac{SP \times r_{combined}(l, \boldsymbol{v_{window}}, \boldsymbol{v_{codend}})}{SP \times r_{combined}(l, \boldsymbol{v_{window}}, \boldsymbol{v_{codend}}) + 1 - SP}\right) + \frac{nControl_{lj}}{qControl_j} \times ln\left(1.0 - \frac{SP \times r_{combined}(l, \boldsymbol{v_{window}}, \boldsymbol{v_{codend}})}{SP \times r_{combined}(l, \boldsymbol{v_{window}}, \boldsymbol{v_{codend}}) + 1 - SP}\right)\right\} \quad (4)$$

Here, the outer summation includes all m valid hauls per species and the inner summation includes all length classes l in the data for that given species. $nTest_{lj}$ is the number of individuals in length class l measured in haul j from the test codend, and $qTest_j$ is the sampling fraction for the test codend. Likewise, $nControl_{lj}$ is the number of individuals in length class l measured in haul j in the control codend and $qControl_j$ is the sampling fraction for the control codend. SP is the split parameter quantifying the sharing rate of the total catch between the test and control gears (Wileman et al., 1996). Although the SP was not the primary interest of this study, catch sharing rates were included to assess the goodness of fit (Millar and Walsh, 1992). In an initial run, the tested models for cod partially attributed the much lower catches in the test codend to a difference in fishing power between trawls, rather than a reduction through selection. Predicted split parameters for other species that had high retention in the test codend and were encountered in large numbers ranged close to 0.5, giving no indication of an uneven split between trawls (e.g. $SP_{plaice} = 0.5079$, $SP_{whiting} = 0.5010$). SP was, therefore, fixed to 0.5 for all length-based analyses.

Among the models 1 to 7, the best model was identified based on the lowest AIC value (Akaike, 1998). Candidate models, identified as those that deviated less than 6 AIC points from the best model (Wagenmakers and Farrell, 2004), were considered competing scenarios. The aptness of the model fit for the best model for each species was assessed by the p-value and by confirming that deviance and degrees of freedom were in the same order of magnitude (Wileman et al., 1996). A significant p-value would indicate that the variance in the residuals was unlikely to be a coincidence, suggesting potential issues in the model fit to the data. In case of a significant p-value ($p < 0.05$), the predicted curve was, therefore, plotted against the data and the residuals were examined for patterns. When no clear patterns could be identified, it was assumed that the poor fit statistics were a result of overdispersion in the data, rather than the model's inability to describe the experimental data (Wileman et al., 1996). Between and within-haul variation was accounted for by using the double bootstrapping method with 1000 iterations to generate 95% Efron confidence intervals (CIs) (Efron, 1982; Millar, 1993). In the bootstrapping, the single case of subsampling was accounted for by resampling before the data were raised by the subsampling fraction (Melli et al., 2023). For each species, the best model was used to plot the catch sharing rate. The combined selection curve and its CIs for each species were obtained based on the model parameters, excluding SP, estimated by minimizing *Expression* (4) within each bootstrap repetition.

2.4. Assessment of fishing gear performance

Stakeholders are often interested in quantification of the performance of fishing gear in terms of catch weight retention, as quotas and sales are usually based on weight. Fishing gears indicators of performance are a useful tool to quantify the percentage of weight retained above and below the minimum conservation reference size (MCRS) (Melli et al., 2020). It should be noted that these indicators are dependent on the structure of the encountered population and provide only a static picture of the gear performance. Nonetheless, if used carefully, they can strongly support the communication of selectivity experiment results to stakeholders (e.g. fishers and managers; Melli et al., 2020).

First, we estimated uncertainties (95% Efron CIs) for $nPop_l$ based on the previously described double-bootstrap method to include both between and within-hauls variability in the structure of the population. Second, we converted length to weight using the length-weight relationship $w(l) = a \times l^b$. Coefficients a and b were taken from the closest matching entry in terms of area and season on *FishBase* (Froese and Pauly, 2022) for all fish species, and from the Data Collection Framework (DCF) and International Bottom Trawl Survey (IBTS) programs in Skagerrak and Kattegat for *Nephrops* (Melli et al., 2020). Third, for each species, we multiplied the length-weight relationship $w(l)$ with the population encountered during the trial $nPop_l$ and the modelled retention of the test codend $r_{combined}(l)$ to calculate the catch in weight at length, following Melli et al. (2020). And fourth, to quantify the retained portions of the catch in weight above and below MCRS and in total, catch weight at length was summed over all respective size classes, and divided by the weight of the encountered population of the respective size classes (above and below MCRS, and across length range, respectively).

Fishing gears indicators of performance were expressed in percent weight retained below MCRS ($wP_{undersized}$), above MCRS ($wP_{commercial}$), and for the total catch (wP_{total}) in relation to the total population encountered by multiplying the proportion of retained weight by 100 (*Equation* (5)).

$$wP_{undersized} = 100 \times \frac{\sum_{l<MCRS}\{a \times l^b \times r_{combined}(l) \times nPop_l\}}{\sum_{l<MCRS}\{a \times l^b \times nPop_l\}}$$

$$wP_{commercial} = 100 \times \frac{\sum_{l>MCRS}\{a \times l^b \times r_{combined}(l) \times nPop_l\}}{\sum_{l>MCRS}\{a \times l^b \times nPop_l\}} \quad (5)$$

$$wP_{total} = 100 \times \frac{\sum_{l}\{a \times l^b \times r_{combined}(l) \times nPop_l\}}{\sum_{l}\{a \times l^b \times nPop_l\}}$$

For each species and indicator, the uncertainties were estimated using the bootstrap set for $r_{combined}(l)$ and $nPop_l$. Using *Equation* (5) to calculate the retention percentages for each bootstrap repetition, a bootstrap set for the indicators was generated. From this bootstrap set, Efron 95% confidence intervals were estimated (Efron, 1982).

2.5. Comparison of performance with respect to legal gear (SELTRA 270)

To investigate if the test gear offered a different performance with respect to the predominant legal gear currently in use, we used existing selectivity data and estimated the fishing gears indicators of performance of the SELTRA 270 (Skagerrak version; Krag et al., 2016). The legal fishing gear SELTRA 270 was chosen because it is the preferred option in the *Nephrops* fishery in Skagerrak to simultaneously target both crustaceans and fish. The SELTRA 270 is a 4-panel codend with a 270 mm diamond mesh top panel located 4–7 m ahead of the codline, joined to the 90 mm codend mesh at a ratio of 1:3 (Skagerrak version; Krag et al., 2016). The combined selectivity $r_{combined\_SELTRA}(l)$ for the SELTRA 270 estimated by Krag et al. (2016) was available for cod, haddock, *Nephrops*, and plaice. To enable the comparison between the test codend and the SELTRA 270, we applied $r_{combined\_SELTRA}(l)$ to the population encountered in the present study, as fishing gear indicators of performance are population-dependent The performance of the two gears was considered significantly different when the 95% CIs estimated individually for each gear did not overlap (Melli et al., 2020).

All length-based analyses and fishing gears indicators of performance were modelled using SELNET software (Herrmann et al., 2012).

3. Results

3.1. Data collection

Fishing was conducted at depths between 36 and 139 m, as not all target species of interest could be found at the same depths. Towing times varied from 60 to 136 min depending on weather conditions and species abundance on the fishing grounds (Table 2). No haul was considered invalid due to issues with gear geometry, as the maximum difference in door-spread between trawls was 3.2 m, which is assumed to have minimal consequences in terms of wing-spread (Melli et al., 2018b). However, not all hauls were considered valid for all species due to the low number of individuals caught in some of them. Total catch weights ranged between 59 and 568 kg in the test codend and between 139 and 1425 kg in the control codend.

The camera footage collected prior to data collection allowed the inspection of the gear geometry during both towing and haul-back. During towing, the test codend had a hexagonal cross section with the kites pulling outward. Given the water flow pressing on the inclined panel during towing, the inclined and horizontal panels took on a concave shape and were marked by a gradual incline throughout the full length, rather than clear division between inclined and horizontal sections. The gear geometry was stable, and no slack or fluttering was observed in the inclined and horizontal panels. No clogging of the inclined panel, which would result in masking of the escape window, was observed. When haul-back was interrupted, the lack of outward pulling forces allowed the sides of the codend to move inwards, resulting in a more rectangular cross section and a greater height for both sections above and below the horizontal panel than during towing. In this phase, species vertical segregation is visible in the footage, with haddock seemingly taking position in the upper half of the codend and cod in the bottom half (Fig. 3). Species distribution during towing could not be evaluated as the suspended sediment obstructed the view.

Table 2
Characteristics of the 21 hauls considered in the selectivity analysis: test codend position (s for starboard and p for portside trawl within the twin-trawl rig), haul time and duration, depth at the start of haul, wind and towing speed, total catch weight by codend, average distances between the clump and trawl doors and average headline height for each trawl.

Haul No.	Test trawl	Start time (hh:mm; UTC+2)	Duration (hh:mm)	Depth (m)	Wind (m/s)	Speed (kn)	Total catch test (kg)	Total catch control (kg)	Door distance (m) portside trawl	Door distance (m) starboard trawl	Headline height (m) portside trawl	Headline height (m) starboard trawl
1	s	07:37	01:30	105	8	2.4	95	139	55.2	56.9	1.4	1.3
2	s	10:35	01:59	135	7	2.9	114	321	56.3	53.7	1.0	1.2
3	s	14:11	02:00	NA	10	2.8	183	305	56.5	57.6	0.9	1.1
4	s	06:36	02:00	137	10	2.9	135	302	54.6	56.8	1.1	1.1
5	s	10:47	02:16	138	12	3.0	88	320	55.4[a]	53.0[a]	0.9[a]	1.1[a]
6	s	07:34	02:00	80	6	2.6	125	305	53.9	52.9	0.9	1.1
7	s	10:41	02:00	66	4	2.6	69	185	53.2	54.9	1.1	1.3
8	s	13:44	01:45	80	6	2.2	77	220	55.1	55.5	1.1	1.0
9	p	06:57	02:00	135	2	2.6	84	445	55.9	58.4	1.1	1.1
10	p	09:56	02:00	138	1	2.6	92	218	56.2	54.8	1.1	1.2
11	p	12:52	02:00	139	1	2.8	138	273	56.1	56.9	1.1	1.1
12	p	06:44	02:00	75	10	2.7	568	1425	53.5	54.1	1.2	1.5
13	p	13:21	02:00	139	12	3.1	176	207	63.7	60.8	0.9	1.1
14	p	06:58	02:00	138	9	3.0	122	235	58.0	56.7	1.0	1.0
15	p	12:26	02:00	123	11	3.1	226	623	62.0	59.7	0.9	1.0
16	p	06:04	01:02	36	10	2.9	59	268	51.4[b]	49.0[b]	1.2[b]	1.2[b]
17	p	08:21	01:30	45	10	2.7	105	356	55.6	56.0	1.2	1.1
18	p	10:58	01:20	50	8	2.8	125	382	53.8	52.1	1.0	1.2
19	p	13:20	01:29	50	8	2.8	351	402	51.1	49.5	1.0	1.2
20	p	06:05	01:30	50	5	2.8	160	545	49.0	50.3	1.2	1.2
21	p	08:59	01:30	50	5	2.9	112	388	49.0	52.2	1.2	1.2

[a] Based on two measurements at start and end of haul, respectively.
[b] Based on a single measurement at the start of the haul.

Fig. 3. Video frame of the codend at the beginning of the haul-back phase. The camera was located on the middle of the V-shaped edge of the horizontal panel looking backwards, towards the codline. Haddock were observed in the upper half of the codend whereas cod were seen in the lower half of the codend.

3.2. Length-based selectivity

For each species, information on the number of valid hauls (i.e. including more than 10 individuals), the number of individuals included in the analysis, the best model and its fit statistics are listed along with the model parameters in Table 3. With the exception of cod, all models described the experimental data well, as demonstrated by *p*-values >0.05, with deviances and degrees of freedom ranging within the same orders of magnitude (Wileman et al., 1996). For cod, no clear pattern of deviation was observed in the model residuals. The poor fit ($p = 0.0145$, df = 67, deviance = 94.72) was therefore attributed to overdispersion in the experimental data and the model was trusted to represent the data relatively well. For all species considered, the primary selection process was identified to be the one occurring in the codend.

The modelled catch sharing rates described the data sufficiently well for all species (Figs. 4 and 5). The data for *Nephrops* could be represented equally well by all models except the one assuming full contact. This implies that the secondary selective process through the escape window had a minor contribution to the combined size-selection, thus preventing conclusive results in terms of type of contact with the window. The best model assumed increasing contact with length with the window; however, due to convergence issues during bootstrapping, we chose the second-best model (Δ AIC = 0.06), which assumes decreasing contact with length. The best models for the three flatfish species all assumed decreasing window contact likelihood with length, with a maximum contact probability (A_{window}) of 91% for plaice, 99% for lemon sole and 51% for witch flounder on average. This relatively high contact probability for the lower length classes suggests that the secondary selection process identified by the model is not related to the escape window, but is rather an additional selection process occurring in the codend (e.g. haul-back selection process occurring while the catch is retrieved at surface; Madsen et al., 2008). The results are conclusive for plaice and lemon sole, but for witch flounder four other models scored as candidates, resulting in competing scenarios in terms of type of contact.

Cod selectivity was best described by increasing escape window contact likelihood with length, resulting in a bell-shaped selection curve (Fig. 5). The $L50_{window}$ of 31.03 cm (21.26–41.03) and the SR_{window} of 47.36 cm (31.25–54.13) describe the gradual increase of escape with length. One other model was considered to fit the data equally well and described a similar scenario, but assuming that every length class had at least an A_{window} probability of contacting the window. The best model for haddock followed the same assumptions of increased escape likelihood with length as that for cod. Two candidate models within 6 AIC points were identified, but only one scenario competed in terms of type of contact (length-independent; model 3). While the best model for saithe assumed a decreasing contact likelihood with length, four models described the data equally well, some assuming competing types of contact. Thus, the results regarding type of contact with the window are inconclusive for this species. Finally, the best model for whiting assumed a decreasing window escape likelihood with length, but with the assumption that for every length class at least a fraction of 1% of the population would not contact the window. Similarly to the results for flatfish, this suggests that the secondary selection process identified by the model does not describe escape through the bottom window, but rather an additional process in the codend.

Table 3
Data for the different species included in the analysis. In the case of subsampling, the raised number of individuals is given with the measured number in parentheses. Best model, candidate models (within 6 AIC points), model fit and selectivity parameters for the best model. A_{window}, $L50_{window}$ and SR_{window} are the parameters used to describe the contact probability with the escape window (NA = parameter not used by the best model). $L50_{codend}$ and SR_{codend} describe the selectivity of the codend mesh (92.5 mm DM, 6 panels, 120 mesh circumference).

	Nephrops	Plaice	Lemon Sole	Witch flounder	Cod	Haddock	Saithe	Whiting
Valid hauls	19	13	12	14	21	21	16	13
No. Ind. test	1072	2956	143	291	2129	1406	334	606
No. Ind. control	1262	5912	3194 (2235)	315	6280	2571	1433	6043
Best model	4 (6)[a]	7	7	7	4	4	6	7
Candid. models	1, 3, 5, 6, 7	none	none	1, 3, 4, 5	5	3, 5	3, 5, 7	none
***p*-value**	0.5711	0.6479	0.6324	0.1692	0.0145	0.0641	0.0577	0.3738
df	44	33	20	22	67	54	52	35
Deviance	41.69	29.38	17.32	28.2	94.72	70.61	68.96	37.07
A_{window}	NA	0.91 (0.67–0.97)	0.99 (0.58–1.00)	0.51 (0.28–0.72)	NA	NA	NA	0.99 (0.25–0.99)
$L50_{window}$	28.00 (1.18–32.47)	20.67 (20.10–21.20)	24.37 (21.56–29.02)	28.59 (25.92–29.49)	31.03 (21.26–41.03)	65.41 (52.73–89.39)	42.97 (32.74–76.07)	25.51 (22.49–37.22)
SR_{window}	1.00 (0.00–43.38)	1.34 (1.10–2.01)	1.56 (1.05–2.94)	1.00 (1.00–1.70)	47.36 (31.25–54.13)	40.11 (8.81–57.81)	44.59 (31.03–80.03)	2.30 (1.33–3.39)
$L50_{codend}$	25.21 (0.00–29.82)	17.11 (14.32–20.38)	17.31 (14.88–24.68)	18.98 (0.90–22.28)	21.59 (18.91–24.40)	23.90 (16.78–28.18)	22.56 (15.02–55.59)	22.90 (12.85–27.53)
SR_{codend}	22.22 (15.25–64.25)	2.43 (1.75–4.55)	1.99 (0.63–6.73)	2.46 (2.11–5.56)	4.82 (3.04–6.96)	3.16 (1.43–4.89)	1.59 (0.00–37.14)	11.97 (4.37–49.28)

[a] Because of convergence issues with the best model, the model in parentheses was chosen for the analyses. Fit statistics and selectivity parameters refer to the model used for the analyses.

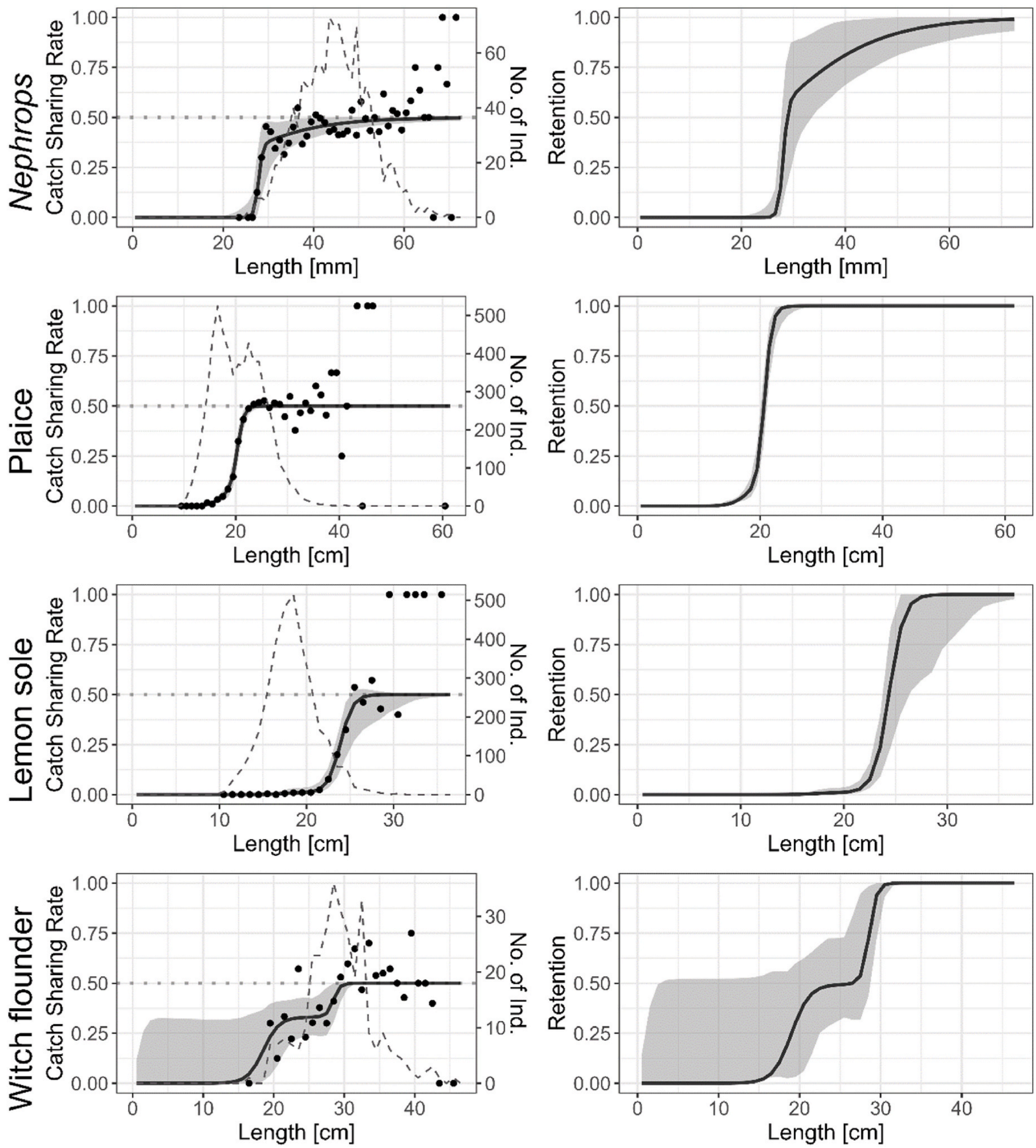

Fig. 4. Left: Catch sharing curves between test and control codends for *Nephrops* and the three species of flatfish (black with grey-shaded 95% CIs). Black points represent the experimental data. The dashed curve represents the population as retained by the 40 mm control codend and refers to the secondary y-axis. Right: Combined selection curves of the test codend.

3.3. Assessment of fishing gear performance

The performance indicators for each species and size category (undersized, commercial, and total) are listed in Table 4 along with the length-weight parameters *a* and *b* and the minimum size used to classify the size category. Based on the structure of the population encountered, the retention of commercially sized *Nephrops* was 89.3% (77.2–99.2) and that of flatfish was 100% (99.7–100.0) for plaice, 97.7% (59.6–100.0) for lemon sole and 95.8% (88.8–100.0) for witch flounder. Haddock retention was 75.8% (58.7–96.8) of commercially sized catch, while saithe and whiting had retentions of 55.2% (25.6–92.0) and 62.2% (41.8–81.5), respectively. The total retention in weight of the choke species, cod, was low: 33.1% (26.0–41.5).

3.4. Comparison of performance with respect to legal gear (SELTRA 270)

The performance indicators of the test gear and those of a SELTRA 270 are compared in Fig. 6. The SELTRA 270 indicators are based on the selectivity predicted by Krag et al. (2016) and the population encountered in this study. The retention of *Nephrops* was similar between the designs both below and above MCRS. Plaice retention of undersized individuals was similar between designs, but the test gear retained significantly more plaice of commercial size (100.0% (99.7–100.0)) than the SELTRA 270 (77.9% (70.1–85.4)). The gears had similar total retention of cod weight; however, the test codend retained significantly less commercially sized cod (26.5% (18.7–36.1) compared to the SELTRA 270's 66.7% (60.4–74.7)) and significantly more undersized cod than the SELTRA 270, 39.0% (29.3–51.3) compared to 18.3%

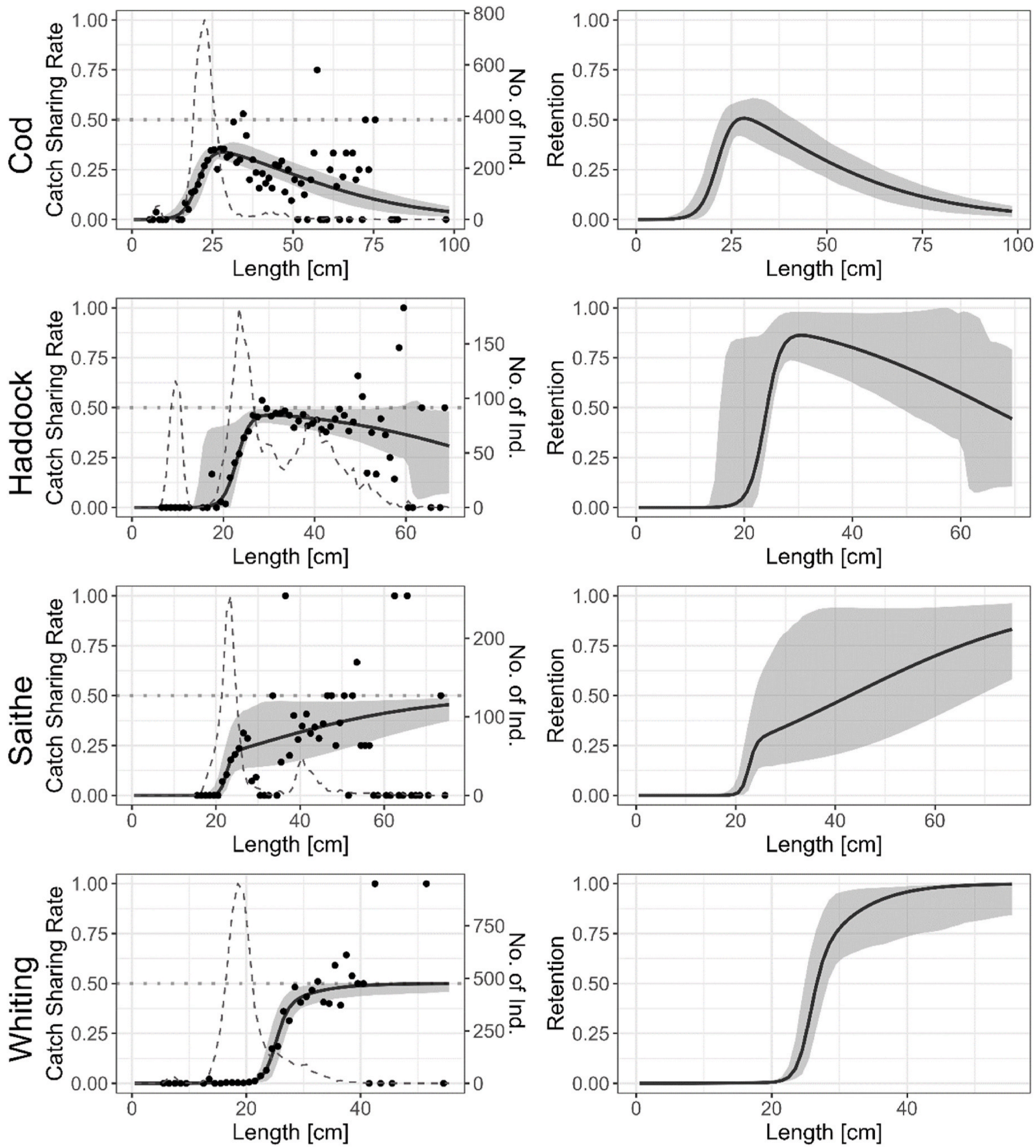

Fig. 5. Left: Catch sharing curves between test and control codend for the four species of roundfish (black with grey-shaded 95% CIs). Black points represent the experimental data. The dashed curve represents the population as retained by the 40 mm control codend and refers to the secondary y-axis. Right: Combined selection curves of the test codend.

(13.6–24.7), respectively. Haddock retention in the test codend was significantly higher than in the SELTRA 270 for undersized individuals (46.4% (27.0–83.8) compared to 11.4% (7.0–16.4)) and, albeit not significant, there is a clear tendency for a greater retention of haddock above MCRS in the test codend, 75.8% (58.7–96.8), compared to 42.8% (28.9–72.0) in the SELTRA 270.

4. Discussion

In this study, we successfully developed and tested a BRD with low total retention of cod and high retention of most commercially important species in a *Nephrops*-directed mixed demersal trawl fishery. To the best of our knowledge, such species-specific exclusion of cod has never been achieved in *Nephrops*-directed mixed demersal trawl fisheries, where previous attempts to reduce catches of commercially sized cod inevitably led to other commercial losses (Catchpole and Revill, 2008; Krag et al., 2016). At present, *Nephrops* fisheries that use top escape panels lose large fractions of the commercial roundfish along with cod. Likewise, sorting grids employed in *Nephrops* fisheries eliminate almost all commercial fish catch (Valentinsson and Ulmestrand, 2008), causing high levels of lost revenue if their use is only directed at the avoidance of cod. Therefore, avoiding catches of a single choke species, cod, has resulted in losses of many wanted bycatch species to date, reducing the efficiency of this fishery (Krag et al., 2010).

Cod retention was low across lengths and the data showed that larger individuals have higher probability of escaping through the window. This supports the assumption that strong swimming fish are more likely to swim forward in the codend and access the BRD, as cod endurance

Table 4
Performance indicators in % weight retained for undersized, commercial, and total catch per studied species using the tested gear. a and b parameters for the length-weight conversion as taken from various referenced sources. Minimum conservation reference size (MCRS) is given as carapace length for *Nephrops* and total length for all fish species. The listed performance indicators are specific to the structure of the encountered population.

Species	*a*	*b*	Reference	MCRS (mm)	undersized (% weight)	commercial (% weight)	total (% weight)
Nephrops	0.000765	2.98025	DCF and IBTS[a]	32	52.8 (30.4–75.9)	89.3 (77.2–99.2)	88.9 (76.9–98.8)
Plaice	0.010700	2.97000	Froese and Sampang (2013)	270	66.3 (47.1–78.4)	100 (99.7–100.0)	74.7 (56.0–84.9)
Lemon sole	0.010600	2.99000	Wilhelms (2013)	260[b]	6.6 (2.6–15.0)	97.7 (59.6–100.0)	9.3 (3.4–23.3)
Witch flounder	0.003200	3.19000	Wilhelms (2013)	280[b]	49.6 (30.5–73.1)	95.8 (88.8–100.0)	86.0 (76.0–94.6)
Cod	0.006690	3.10000	Froese and Sampang (2013)	300	39.0 (29.3–51.3)	26.5 (18.7–36.1)	33.1 (26.0–41.5)
Haddock	0.009200	3.00800	Wilhelms (2013)	270	46.4 (27.0–83.8)	75.8 (58.7–96.8)	72.1 (56.3–94.6)
Saithe	0.016400	2.85900	Wilhelms (2013)	300	18.8 (6.3–42.1)	55.2 (25.6–92.0)	42.2 (17.5–73.3)
Whiting	0.011100	2.86000	Wilhelms (2013)	230	0.7 (0.2-1.5)	62.2 (41.8–81.5)	26.9 (11.1–48.0)

[a] Data Collection Framework (DCF) and International Bottom Trawl Survey (IBTS) programs in Skagerrak and Kattegat.
[b] For species, for which there is no MCRS, a minimum marketable size (MMS) was used instead.

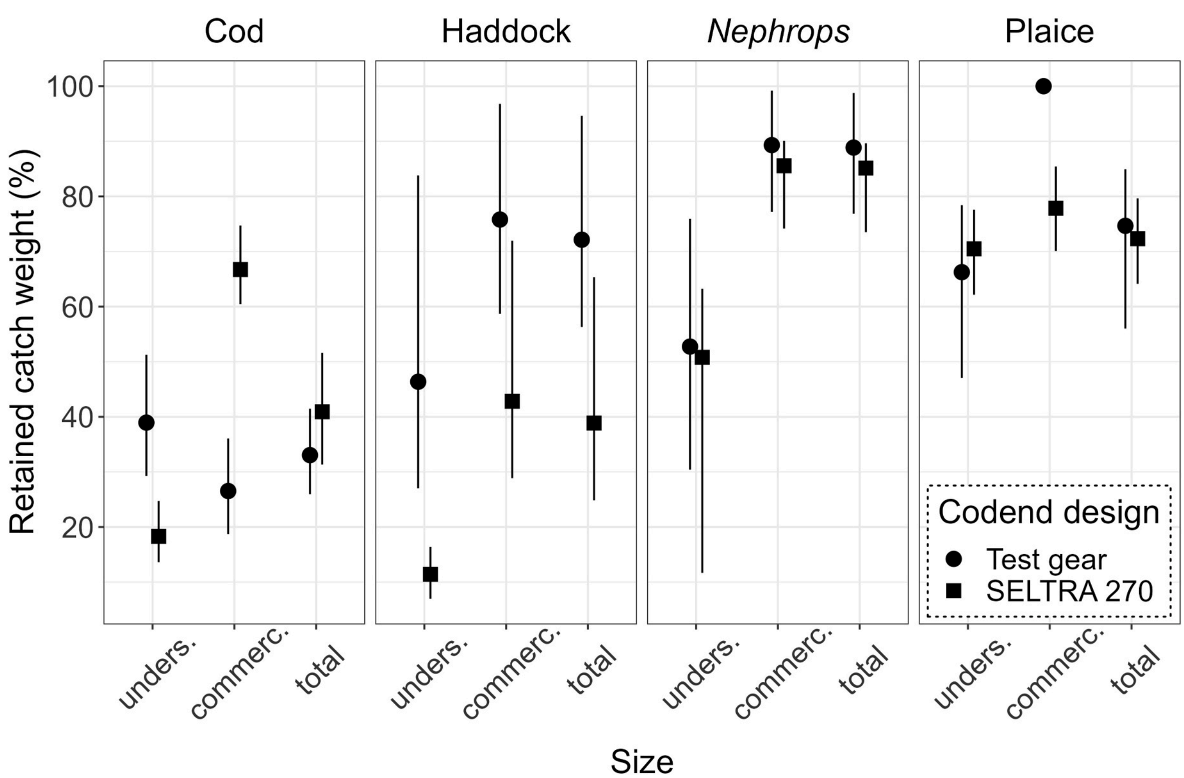

Fig. 6. Retained catch weight (%) for the SELTRA 270 DM 4–7 (Skagerrak version) and the test codend. "unders." and "commerc." refer to undersized and commercially sized individuals in relation to the respective minimum commercial reference size in Kattegat and Skagerrak (30 cm for cod, 27 cm for haddock and plaice, and 32 mm carapace length for *Nephrops*). Error bars indicate 95% confidence intervals. The displayed retention fractions are specific to the population encountered in the experiment.

and swimming speed have been described to increase with size (He, 1993; Main and Sangster, 1981). Bycatch reduction devices that exploit differences in swimming capacity have been successfully used in the past and are showing great potential for mixed fish and crustacean fisheries (Lomeli and Wakefield, 2012; Watson et al., 1993). Moreover, the results of this study support the assumption that, compared to many other roundfish species, cod are more closely associated with the bottom half of a trawl codend and have a preference for escaping downwards (Eayrs et al., 2017; Ferro et al., 2007; Krag et al., 2009, 2015). The results for cod match those obtained by Fraser and Angus (2019) with a bottom escape panel in a demersal whitefish fishery; here reductions of cod were obtained across the length range with the exception of individuals up to 36 cm, where higher catch rates occurred in the modified gear, albeit not significantly. Further studies are required to clarify the causes of this effect: a change in flow dynamics inside the trawl due to the presence of the inclined panel could be impairing mechanical selection through the codend meshes (e.g. Santos et al., 2018), small fish may be exploiting low flow zones generated by the BRD and holding position ahead of the catch accumulation zone, where selection occurs (e.g. Engaas et al., 1998), or a combination of behavioral and mechanical factors may be in play. The limited footage collected in our study did not allow for quantitative analyses of behavior but given that most BRDs aiming at the avoidance of cod rely on behavior (e.g. Melli et al., 2023), and considering the recent developments in underwater observation technologies, future research should focus on increasing the range of observation, suppressing sediment clouds, and limiting the behavioral bias of the observation platform to allow for simultaneous observation of behavior and catch performance assessments (Abangan et al., 2023; Sokolova et al., 2022).

Among the target species, *Nephrops* and flatfish proved to have negligible contact with the escape window. *Nephrops'* type of contact with the window was inconclusive, as most models scored as candidates, including the one assuming zero contact. We can therefore conclude that the presence of the bottom escape window did not substantially affect catches of *Nephrops*, a critical result to even initiate a dialogue with fishers regarding the uptake of such gear design (Milliken and DeAlteris, 2004). Similarly, all three flatfish species had very high retention rates, in line with the results obtained by Fraser and Angus (2019), who found no indication of reduction of plaice catches in their catch comparison analysis. Despite their strong association with the bottom of trawls, we did not find conclusive evidence that flatfish were able to swim forward and escape through the window. This is likely due to their low swimming endurance (Ryer, 2008). Catches of flatfish are an important contributor to the fishery's revenue and some of the legal gears used in the *Nephrops*-directed fishery have shown evidence of losses of commercially sized plaice (Krag et al., 2016; Melli et al., 2023). The retention of target roundfish varied among species. Haddock, the most valuable roundfish in this fishery, showed an increasing escape through the window at length, similar to the results obtained for cod. However, the retention was relatively high for most commercial length classes, as the $L50_{window}$ describing the length-based contact probability with the window for haddock was double that of cod (65.41 cm vs 31.03 cm, respectively, on average). This implies that losses of commercial haddock would be limited to the very large individuals, a sub-optimal result but with minimal consequences to the fishers given the structure of the population, at least in the North Sea region (Needle, 2016). The results for saithe were inconclusive with multiple contact scenarios scoring as candidates. There is an indication of higher escape of large individuals through the window, which would indicate a similar behavior to cod. Potential losses of commercially sized saithe were also noted by Fraser and Angus (2019), albeit not significant. In the *Nephrops*-directed fishery, such losses may be acceptable to fishers as saithe have a comparatively low commercial value and are thought to damage *Nephrops* when thrashing in the codend (Savina et al., 2022). Finally, the best contact model for whiting identified a decreased probability of window contact at length, supporting the notion that, like haddock, whiting are associated with the top of the trawl extension (Ferro et al., 2007; Krag et al., 2009). This contact type does not, however, explain the losses of commercially sized whiting described by the performance indicators. We attribute most of these losses to the codend selection as the species has a low MCRS of 23 cm in comparison to the $L50$ of the codend mesh (22.90 cm (12.85–27.53)). While large whiting are generally considered wanted bycatch in the fishery, this species can be encountered in very high numbers, causing delays in sorting of the catch and limiting fishing time to prevent excessive catch weights (Catchpole and Revill, 2008). The higher variability in retention rate detected for haddock and saithe, although possibly related to the limited amount of data available, suggest that some confounding factors may be affecting escape through the window. For example, the catch size and its accumulation in relation to the back edge of the horizontal panel may have influenced the holding position of fish and created crowding effects that led them to enter the section under the horizontal panel (e.g. Herrmann et al., 2015). Moreover, environmental parameters such as depth, temperature, time of day, weather conditions etc. may have affected species behavior and distribution inside the codend (Olla et al., 2000; Payne et al., 2016). The focus of this study, however, was to determine if the tested design and the underlying escape mechanism have relevance for the case-study fishery and can provide fishers with the opportunity of diversifying their catch goals within the management framework (Melli et al., 2020). Nonetheless, future assessments of gear performance should consider the consistency of the selection over a range of environmental and fishing conditions.

The fishing gears indicators of performance used in this study show that the retained commercial weight of most target species of interest to the fishery would be relatively high under the current structure of the populations fished. However, these offer just a temporary picture of performance and are most useful when adopted to compare the performance of the test gear with the legal gears in use (Santos et al., 2022; Wienbeck et al., 2014). The comparison of catch performance between the test codend and the SELTRA 270 revealed that there are currently pros and cons. In terms of pros, the test codend reduces the retention of large cod and increase that of commercially sized plaice. Moreover, the retention of commercially sized haddock is substantially increased on average, although the results are not significant to the broad confidence intervals for both gears. In terms of cons, the test codend retains more undersized weight of both cod and haddock, which in the case of cod leads to similar total retentions, as undersized individuals were more abundant in the population encountered during the trial. If on one side it could be argued that the increased retention of undersized individuals poses conservation concerns, as for a given weight small individuals are more numerous than large ones, recent gear development studies have stressed the importance of protecting the older and larger stock spawners (e.g. Santos et al., 2022; Stepputtis et al., 2016). This is based on the concept of reproductive hyperallometry, which recognizes that fecundity often increases over-proportionally to mass, and stresses the benefits of management approaches that protect larger individuals (Garcia et al., 2012; Marshall et al., 2021). Nonetheless, further reductions in catches of undersized cod would benefit both the stock and quota-limited fishers and should, therefore, be pursued in future gear development studies.

When putting the results into the fishers' perspective, the catch profile offered by the test gear has a great economic benefit. The similar total retention of cod obtained with both test and legal gears show that this species could still choke the fishery, causing a premature interruption of fishing effort depending on quota availability, but it would at least ensure that more quota of the other target species is exploited before that of cod is exhausted (Santos et al., 2022). Moreover, in an individual transferable quota system, this design offers the opportunity to diversify catch goals across vessels, and increase adaptability in response to changes in catch composition (Feekings et al., 2019; Hoshino et al., 2020).

Future steps in the development of this promising design involve the improvement of selectivity for undersized individuals by investigating length-dependencies in escape behavior and the influence of design factors such as the distance from codline of the bottom escape window, the height of top and bottom sections, the codend construction (i.e. number of panels, meshes in circumference etc.), as well as the influence of environmental and fishing parameters (e.g. towing speed). The BRD tested here caused no issues during use and no signs of clogging by debris or catch were observed, one of the major concerns often tied to the use of guiding and sieve panels (Fraser and Angus, 2019; Larsen et al., 2018). Nonetheless, the design could be rather complex to maintain or even control if introduced in legislation. Therefore, while the specific components and dimensions of the codend were chosen to demonstrate the applicability of the escape mechanism to a crustacean fishery, future developments should aim at a simplified design, for example by reducing the number of panels and the circumference of the codend. Indeed, design simplicity plays a major role in the uptake of the new technology in a fishery (Milliken and DeAlteris, 2004) and a smaller codend circumference would likely facilitate a better selectivity for undersized individuals of many species including cod through more widely open meshes (Herrmann et al., 2007). Finally, it could be important to understand the role that escape during towing and haul-back plays in the reduction of cod catches. High escape rates through BRDs during haul-back have been observed in other fisheries (Engaas et al., 1999; Yochum et al., 2021) and would imply a dependence of BRD efficiency on haul duration, rendering them less effective during longer hauls. Moreover, fish that escape during haul-back may have lower chances of survival than those escaping during towing because they may have been exhausted for longer and have experienced increased stress (Madsen et al., 2008; Wood et al., 1983).

5. Conclusions

The design developed and tested in the present study consisted of an escape window located under an inclined and horizontal panel that could be accessed by fish swimming forward from the codend near the bottom of the trawl. The results demonstrate the unique ability of this design to specifically exclude cod, and in particular the commercially sized individuals, from a fish and crustacean demersal trawl, while maintaining most valuable catches. The design shows great potential to provide fishers with a valuable tool to diversify their catch goals. Future developments should focus on simplifying the gear design to facilitate uptake, investigating its performance across fishing conditions, and further improving size selective properties especially for undersized fish.

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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Appendix A. Supplementary data

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