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Report

Size Selection in Diamond Mesh Codends for Danish Seining: a Study Based on Computer Simulations and Sea Trials

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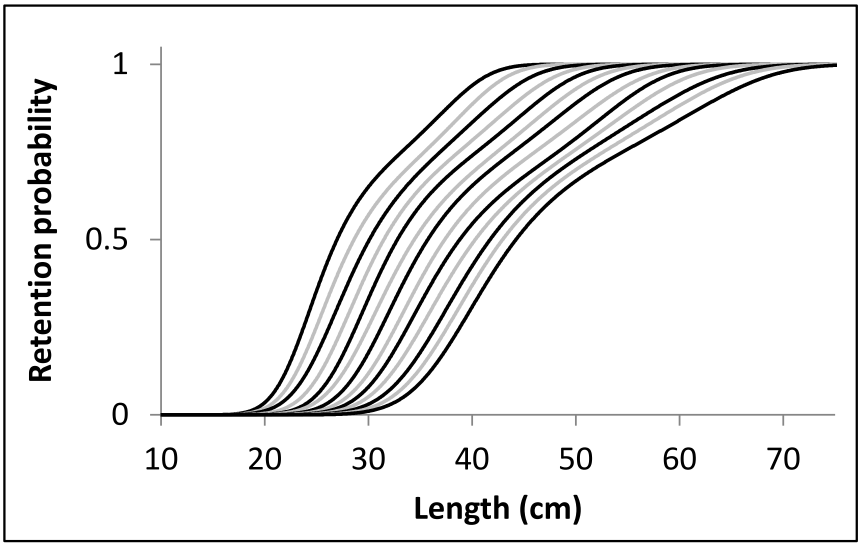

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ABSTRACT
Danish seining and variants of it (Demersal seining) is an important fishing method to harvest demersal fish species like cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). Knowledge about size selectivity in this type of fishing gear is therefore of importance for managing the exploitation of fish resources. However, limited data exist on the size selection of species like cod and haddock in the diamond mesh codends applied in this fishing method fishery. The purpose of the project "Danish Seine: Computer based Development and Operation" (MAROFF-2 project no. 225193 / FHF 900861), funded by Research Council of Norway (RCN) and Norwegian Seafood Research Fund (FHF), is to develop and apply software tools to investigate Danish Seine fishing. One important aspect of this is related to simulate the size selectivity inside the Seine codend. By using knowledge of fish morphology and the computer-based simulation method FISHSELECT, we investigated the size selection of cod and haddock in diamond mesh codends for Danish seining. To calibrate the simulation method new size selectivity data for one specific codend were collected in an international collaboration. Based on the simulation method We were able to explain and understand the experimental selectivity results for both cod and haddock and to predict the effect of design changes in the codend design.

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1 Introduction

1.1 Background and Objectives

The purpose of the project *Danish Seine: Computer based Development and Operation* (MAROFF-2 project no. 225193 / FHF project no. 900861), funded by Research Council of Norway (RCN) and Norwegian Seafood Research Fund (FHF), is to develop and utilize software tools to investigate Demersal Seine fishing. As part of this project, the specific purpose of the present report is to investigate and predict the size selection of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in diamond codends for this type of fishing method.

1.2 The Danish/Demersal Seine Fishing Process

The Danish seine or anchor seine is an active demersal fishing technique which was invented by the Danish fisherman Jens Væver in 1848. In the first half of the 20th century this technique became one of the most important fishing gears used in Denmark (Thomson, 1981). Since this fishing method was brought to other countries, it was adopted and modified to local conditions. Scottish fishermen started to fish without anchoring, making it possible to move the vessel forward during hauling. This technique is known as Scottish seining, 'Fly-dragging' or 'Fly-shooting', and is also the method primarily applied by Norwegian fishermen targeting cod and haddock (Herrmann et al., 2016). However, the principle of Danish or Anchor seining has remained the same and its importance as a commercial fishery in Denmark and in many parts of the world is increasing due to its low fuel consumption, high catch quality and low ecosystem impact when compared to trawling (Thrane, 2004; ICES, 2010; Walsh and Winger, 2011; Suuronen et al., 2012;).
Danish seining consists of three main phases (Fig. 1): setting phase (A & B), collecting phase (C-E) and the closing phase (F). After dropping the anchor, attached to a set of marker buoys, the fishing vessel starts encircling the fishing area by laying out the first lead-filled rope (Fig. 1A), which can be up to 4000m long. The end of this rope is attached to one wing tip of the seine net. A second lead-filled rope is attached to the other wing tip of the seine and laid out afterwards. A common technique in Denmark, especially in the plaice (*Pleuronectes platessa*) fishery, is to start setting the second rope out in a straight line away from the seine net instead of going directly back to the anchor (Fig. 1B). Only the last part of the rope (approximately a quarter) is laid out in the direction of the anchor. The end of the second rope is attached to the vessel and dragged slowly over the sea bottom. This technique increases the size of the area fished. When the vessel returns to the anchor the first rope is retrieved and the collecting/retrieval phase begins (Fig. 1C-E). The movement of the seine ropes along the seafloor herds the fish into the centre of the encircled area. Finally, the closing phase begins when the wings of the net start closing. At this point, the hauling speed of the winches is increased to reduce the fish´s chance to escape. Finally, the seine is retrieved to the vessel and can be emptied (Fig. 1F).

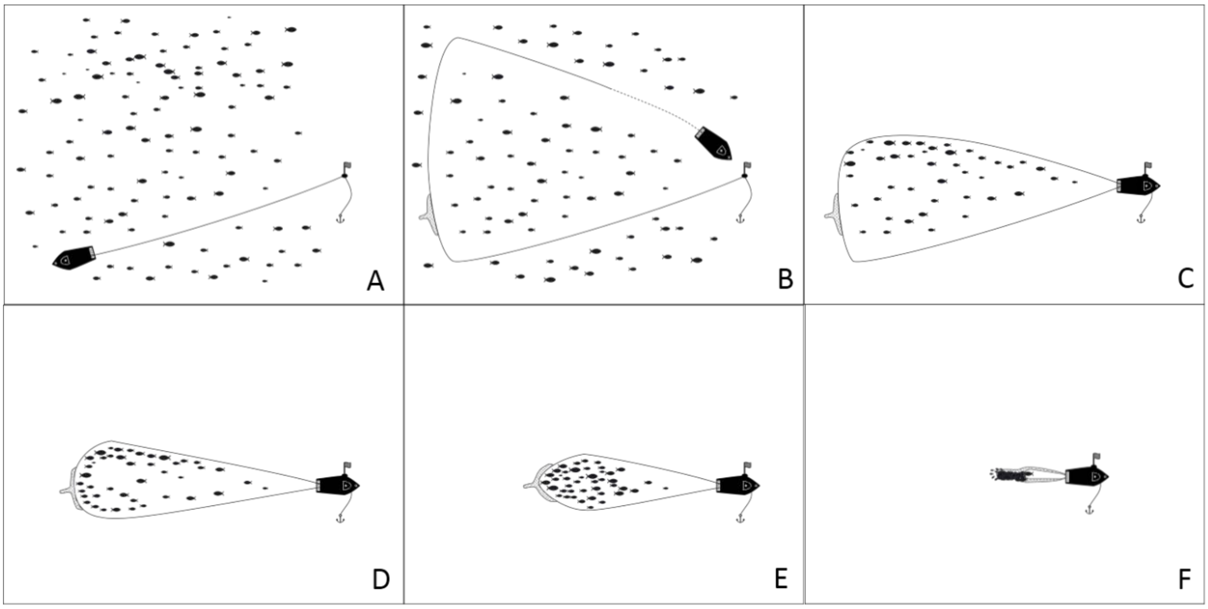

Figure 1: Description of the Danish seining process. A & B: Setting phase. C-E: Collecting phase. F: Closing phase.

The fishing operation in Danish seining is quite different from trawling. During trawling, the trawl is towed with the same speed over the seabed where the gear retains more or less the same global geometry. Danish seines are towed at considerably lower speeds, especially in the early phases of the operation, and the global geometry of the gear gradually goes from being overspread in the setting phase to being completely closed at the end of the collecting/closing phase. However, the netting used for constructing trawls and seines, and to some extent the construction of the gears, are relatively similar. In Denmark and EU waters, the gear regulations pertaining to seining are the same as those for trawling. For gears to be grouped under the same technical legislation it is important that the gears, in terms of selectivity, are comparable, as similar results in terms of management and catch efficiency are then obtained with the same regulations. Considering the differences in the operations of the two gear types, the selectivity process in these two gears can be expected to differ.

A recent study on square mesh codend selectivity in the Norwegian seine fishery (fly-shooter) suggested that surface selection through slack or wide open meshes likely plays an important role for codend size selection (Herrmann et al., 2016). The authors further suggested that a considerable part of the size selection occurs through slack meshes, indicating that part of the codend selection occurs when the seine is at the surface. Therefore, it is relevant to investigate to what extent surface selection may contribute to the overall size selection in the codend, since some species of fish escaping later in the process might have less likelihood to survive than those escaping at the seabed (Herrmann et al., 2014). Furthermore, such combined selection processes at seabed and surface might result in selectivity descriptions that are different from the more traditional logistic description typically used when describing size selectivity of codends in towed gears (Wileman et al., 1996). However, there is limited information available on species and size selectivity in demersal seines in general, and to our knowledge, no studies have investigated species and size selectivity in diamond mesh codends within Danish seine fisheries.

This study aims to establish codend selectivity curves for cod and haddock which are two of the most important commercial species targeted in the Danish/demersal seine fisheries in Denmark and Norway. Furthermore, the study aims to increase the fundamental understanding about the size selection processes in Danish/demersal seines, specifically in diamond mesh codends. Finally, the selective effect of changing the mesh size on codend size selection in the Danish seine fishery is predicted and those predictions are compared to historical results for codend size selection in similar codends when applied for demersal trawling. The study is based on utilizing simulation methods but uses a set of experimental collected data to calibrate the simulation method.

2 Methods

2.1 Sea Trials and Gear Specifications

To enable prediction of size selection based on the simulation method (section 2.3- 2.4) at set of size selectivity data for one specific codend was needed. Sea trials were therefore carried out in Western Skagerrak off the coast of Denmark in April and May 2015 on board the commercial Danish seiner Ralima HM323 (17.94 m LOA, 300 kW). These sea trials were conducted by DTU Aqua in international research collaboration. All fishing was conducted between sunrise and sunset, which equals normal commercial practices in the Danish seine fishery. The species of interest for this study were cod and haddock. These species are, in addition to plaice, the most important species economically for the Danish seine fishery in Denmark. Cod and Haddock are also the two most important species for the Norwegian demersal seine fishery. Danish fishermen argue that the given technical regulation (120 mm diamond mesh codend) is reasonable for retaining plaice, but results in large losses of cod and haddock of commercial value. Therefore, this study concentrates on these species. The experimental fishing was conducted in two different areas with different depths (Fig. 2).

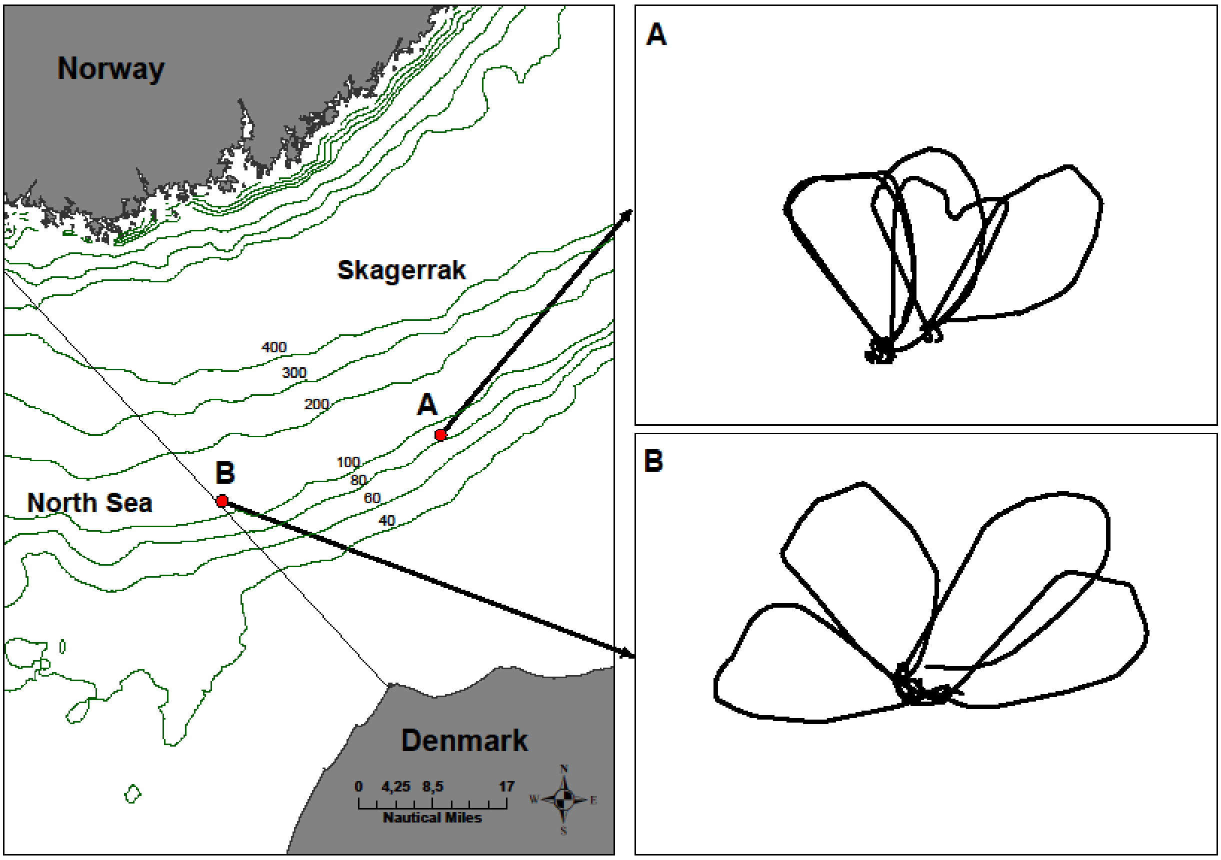

Figure 2: Fishing locations and corresponding close-ups of individual hauls. Area A represents shallower grounds and B represents deeper grounds.

The seine used was a Nymflex combi seine with a nominal mesh size of 120 mm and having 646 meshes in the fishing circle. The footrope of the seine was 42 m long and made of leaded rope. The seine was rigged with a three sweep system, two of 20 meters and one of 30 meters attached to each wing. The vessel used 16 coils of three-strand Hi-Tec Seine Net Rope Type III (Randers Reb International A/S), each 220 m long with a diameter of 32 mm. Each coil of seine rope weighed 170 kg, equivalent to 0.77 kg per meter.

A diamond mesh codend with a nominal mesh size of 120 mm was applied since this represents the minimum legal mesh size for the fishery unless escape panels are to be included. The mesh size was measured to 129.6 mm in dry conditions prior to the experimental fishing using an OMEGA-gauge (Fonteyne et al., 2007). As Danish seiners often catch more than can be taken on-board in one operation, they have to repeat the operation several times. They argue that large mesh escape panels in the aft part of the gear will result in large losses of the catch during catch retrieval where catch is left overboard in the extension as the codend is taken on-board. The codend was 49.5 meshes long and constructed out of double 4 mm PE netting. The codend had 100 open meshes in circumference and had one selvedge of four meshes.

The covered codend method (Wileman et al., 1996) was used to collect fish escaping through the codend meshes. The last 12 meters of the seine were fitted with a small mesh cover made from 50 mm (nominal) PE netting with a twine thickness of 2.2 mm. The cover geometry was obtained using kites and weights based on the design principle described in Madsen et al. (2001). However, since Danish seines are dragged at a slower speed than trawls, especially in the beginning of the fishing process, the use of a cover with kites could potentially lead to masking between codend and cover and thereby bias the codend selectivity in the trials. Therefore, we applied a modified version of the cover with kites to reduce this masking risk. Compared to the version described by Madsen et al. (2001) the one applied here had floats attached to both sides of the upper cover panel and lead ropes attached to the lower panel. Additionally, a 3 m long polyethylene bar was attached across the upper panel of the cover to ensure sufficient horizontal space between the codend and cover when the gear was not moving or was moving very slowly. In each haul, during these covered codend fishing trials, the entire catch was sorted by species. All samples of cod and haddock were measured to the nearest cm below. In the subsequent analysis, 0.5 cm was added to each length class following Krag et al. (2015). Due to large catches subsampling was needed in a few hauls. For hauls where subsampling applied, sampling factors were calculated for both the codend and cover separately.

2.2 Analysis of Data from Sea Trials

Analysis of data for cod and haddock was done separately using the same method described hereafter. The applied experimental design enabled analysis of the collected catch data as binominal data, where individuals, either retained by the codend cover or by the codend itself, are used to estimate the size selection in the codend (i.e., length-dependent retention probability). The probability of finding a fish of length l in a codend in haul j is expressed by the function $r_j(l)$. The purpose of the analysis is to estimate the values of this function for all relevant sizes and species individually. The value of $r_j(l)$ is expected to vary between hauls carried out with the same codend (Fryer, 1991). In this study, we were interested in the length-dependent values of $r(l)$ averaged over hauls, since this would provide information about the average consequences for the size selection process when applying the codend in the fishery. Thus, it was assumed that the size selective performance of the codend, for the hauls conducted, was representative of how the codend would perform in a commercial fishery (Millar, 1993; Sistiaga et al., 2010).

Estimation of the average size selection over hauls $r_{av}(l)$ involves pooling data from the different hauls (Herrmann et al., 2012). Since we tested different parametric models for $r_{av}(l)$, we write $r_{av}(l,\boldsymbol{v})$, where $\boldsymbol{v}$ is a vector consisting of the parameters of the model. The purpose of the analysis is to estimate the values of the parameter $\boldsymbol{v}$ that make experimental data (averaged over hauls) most likely to be observed, assuming that the model is able to describe the data sufficiently well. Four different models were chosen as basic candidates to describe $r_{av}(l,\boldsymbol{v})$ for each codend and species individually: Logit, Probit, Gompertz and Richard. The first three models are fully described by the two selection parameters L50 (length of fish with 50% probability of being retained) and SR (difference in length between fish with respectively 75% and 25% probability of being retained) while the Richard model also requires one additional parameter ($1/\delta$) that describes the asymmetry of the curve. The formulas for the four selection models, together with additional information, can be found in Wileman et al. (1996). In addition to the four classic size selection models (Logit, Probit, Gompertz, Richard), which assume that all individual fish entering the codend are subjected to the same size selection process, we also considered one additional model that we refer to as the double logistic model (DLogit). The Dlogit is constructed by assuming that a fraction C_1 of fish entering the codend will be subjected to one logistic size selection process with parameters $L50_1$ and SR_1 while the remaining fraction ($1.0 - C_1$) will be subjected to an additional logistic size selection process but with parameters $L50_2$ and SR_2. Therefore, a total of five models were considered for $r_{av}(l,\boldsymbol{v})$:

$$r_{av}(l,\boldsymbol{v}) = \begin{cases} Logit(l, L50, SR) \\ Probit(l, L50, SR) \\ Gompertz(l, L50, SR) \\ Richard(l, L50, SR, 1/\delta) \\ DLogit(l, C_1, L50_1, SR_1, L50_2, SR_2) = C_1 \times Logit(l, L50_1, SR_1) + (1.0 - C_1) \times Logit(l, L50_2, SR_2) \end{cases} \quad (1)$$

For the DLogit model in (1), C_1 represents the assumed length independent probability that the fish will have their size selection defined by the logistic model with parameters $L50_1$ and SR_1, while the probability for the fish to have their size selection defined by the logistic model with parameters $L50_2$ and SR_2 will be $1.0 - C_1$. Thus, C_1 is a number between 0.0 and 1.0. For the Dlogit model, the overall L50 and SR parameters are estimated based on the numerical approach described in Sistiaga et al. (2010). The same is done for the other retention lengths; L05 to L95 (length with respectively 5% and 95% probability of being retained), in 5% increments.

Evaluating the ability of a model to describe the data sufficiently well is based on calculating the corresponding *p*-value, which expresses the likelihood to obtain at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. Therefore, for the fitted model to be a candidate to model the size selection data, this *p*-value should not be below 0.05 (Wileman et al, 1996). In case of poor fit statistics (p-value < 0.05), the residuals were inspected to determine whether the poor result was due to structural problems when modeling the experimental data using the different selection curves or if it was due to overdispersion in the data (Wileman et al, 1996). Selection of the best model among the five considered in (1) is based on comparing the AIC values for the models. The selected model is the one with the lowest AIC value (Akaike, 1974). Furthermore, based on Wagenmakers and Farrell (2004), we estimate the relative likelihood L_i for each of the other models *i* compared to the model with the lowest AIC value (AIC_{min}) by:

$$L_i = exp\left(-\frac{AIC_i - AIC_{min}}{2}\right) \quad (2)$$

Once the specific size selection model was identified for a particular species and codend, bootstrapping was applied to estimate the confidence limits for the average size selection. We applied the software tool SELNET (Herrmann et al., 2012) for the size selection analysis and utilized the double bootstrap method implemented in this tool to obtain the confidence limits for the size selection curve and the corresponding parameters. This bootstrapping approach is identical to the one described in Millar (1993) and takes both within-haul and between-haul variation into consideration. The hauls for each codend were used to define a group of hauls. To account for between-haul variation, an outer bootstrap resample with replacement from the group of hauls was included in the procedure. Within each resampled haul, the data for each length class was bootstrapped in an inner bootstrap with replacement to account for within-haul variation. Each bootstrap resulted in a “pooled” set of data, which was then analyzed using the identified selection model. Thus, each bootstrap run resulted in an average selection curve. For each species analyzed, 1000 bootstrap repetitions were conducted to estimate the Efron percentile 95% confidence limits (Herrmann et al., 2012).

2.3 Simulating the Selective Potential of the Diamond Mesh Codend Based on Fish Morphology

Several studies have demonstrated that not only mesh size but also the openness of the meshes in diamond mesh codends affects its selectivity (Herrmann, 2005a-b; Herrmann and O'Neill 2005; Herrmann et al., 2007; O'Neill and Herrmann, 2007; Herrmann et al, 2009). During trawling, the codend meshes are stretched by hydrodynamic drag forces that act primarily on the accumulated catch in the aft end of the codend (Herrmann, 2005b and Herrmann et al., 2006) where the mesh openness is unlikely to exceed 75 degrees. The same mesh state can be expected during the closing phase of the Danish seine fishing process where the diamond mesh netting is stretched and under tension due to the pulling by the seine ropes. At this stage, it is unlikely that fish trying to escape through the codend meshes will be able to deform the netting However, when the codend is at the surface it has no tension and the meshes can both be wide open (up to 90 degrees) and slack, which potentially gives fish trying to escape the possibility to distort the mesh shape enough to pass through (Herrmann et al., 2016).

FISHSELECT is a framework of methods, tools, and software developed to determine if a fish is able to penetrate a certain mesh shape and size in active fishing gear (Herrmann et al., 2009). Through computer simulations, FISHSELECT enables the estimation of the size selectivity for a certain species by comparing the morphological characteristics of the fish to the shape and size of the mesh. FISHSELECT enables the possibility to simulate both situations where the mesh shape cannot be deformed by fish trying to escape through it (stiff mesh state), and situations where the meshes are slack and can potentially be fully deformed (soft mesh state). Therefore, the FISHSELECT methodology is applied here to estimate the size selective potential for the diamond mesh codend applied during the experimental fishing. To be able to apply FISHSELECT for simulating size selectivity through codend meshes for a species it requires: i) a morphological model describing the cross sections relevant for the size selection of the species and ii) a model describing how and to what extent the fish cross sections can be squeezed when trying to pass through a mesh. The FISHSELECT methodology has previously been applied to investigate size selectivity for numerous different species in different fisheries (Frandsen et al., 2010; Herrmann et al., 2012; Herrmann et al., 2013b; Herrmann et al., 2016; Krag et al., 2011; Krag et al., 2014; Sistiaga et al., 2011; Tokac et al., 2016). The FISHSELECT models necessary to study cod and haddock size selectivity in diamond mesh codends were already available through the studies by Herrmann et al. (2009) and Krag et al. (2011), and were adapted to the present study.

Based on the FISHSELECT models for cod and haddock (Herrmann et al., 2009; Krag et al., 2011), we simulated the size selection in stiff diamond meshes with a mesh size identical to the codend applied in the experimental fishing. Mesh opening angles between 15 and 90 degrees, in 5 degrees increments, were tested to establish the potential size selection in the codend and its dependency on the opening angle in the meshes. In addition, we simulated the potential size selection in slack meshes (soft mesh state) of the same mesh size. For each simulated size selection data set obtained in this way, we fitted a logit selection model to obtain a size selection curve.

2.4 Understanding the Experimentally Obtained Size Selection Based on Fish Morphology

It was of specific interest to investigate whether the experimental size selection data for both cod and haddock obtained from the sea trials could be understood based on the FISHSELECT simulations described in section 2.3. Specifically, information on the extent of escapement through slack meshes (soft mesh state) and through non-distorted meshes (stiff mesh state) was required. Accordingly, we explored if the experimental size selection curve based on the data collected during the sea trial could be replicated by simulating scenarios assuming different combinations of mesh states. We considered the following scenarios: (i) stiff diamond meshes with opening angles between 15 and 75 degrees, as could be expected during the collection phase; (ii) stiff diamond meshes with opening angles between 15 and 90 degrees, as could be expected if some of the fish first escaped at the surface when some of the meshes are possibly wide open; (iii) stiff diamond meshes with opening angles between 15 and 75 degrees combined with slack meshes, as could be the situation if some of the fish first escaped as the surface where some of the meshes might be slack; (iv) stiff diamond meshes with opening angles between 15 and 90 degrees combined with slack meshes, as could be the situation if some of the fish first escaped as the surface where some of the meshes might be wide open or slack. For each of the scenarios, the combination of varying mesh openness and state that was best able to reproduce the experimental size selection curves obtained during the experimental fishing was obtained.

To carry out the above outlined procedure, we used the selection curves, with confidence intervals and retention lengths, obtained from the analysis of the sea trial data (section 2.2). We then used the simulated retention data for different mesh openness's and the different mesh states from FISHSELECT (Section 2.3). For each of the scenarios (i)–(iv), we estimated the contributions needed from the different retention data to obtain combined selection curves that fitted the experimentally obtained values L05… L95 best possible. This procedure is identical to the one applied in Herrmann et al. (2013b), which contains detailed information on the technical aspects of the method. The simulation scenarios, which were able to reproduce the entire size selection curve accurately based on the experimental fishing, enabled estimating how much each mesh state contributed to the codend size selection process. Therefore, providing the possibility to describe how and when the size selection process occurs.

2.5 Predicting Size Selectivity in Different Diamond Mesh Codends

To explore the potential consequences of making design changes to the currently legal codend, we simulated the size selection of a number of other mesh sizes using FISHSELECT, following the procedure described in section 2.3. Based on the level of contribution found for each mesh state for the experimental codend we could predict the codend size selection for Danish seining with codends of other mesh sizes. Thereby, we assumed that the contribution would be similar for codends with other mesh sizes. This procedure is identical to the one, applied by Krag et al. (2014) to predict size selection of krill in a range of codends with varying mesh sizes. In this study, we used the procedure described in Krag et al. (2014) to predict the codend size selection of cod and haddock in Danish seining diamond mesh codends with mesh sizes between 90 and 150 mm in 5 mm increments.

2.6 Comparing the Predicted Codend Size Selectivity for Danish seines with size selectivity of trawls in similar codends

In Denmark and EU waters, the gear regulations pertaining to seining are the same as those for trawling. It is therefore of relevance to compare the predicted size selectivity in diamond mesh codends when applied for Danish seining with the size selectivity in similar codends when applied in demersal trawling. The predictions made herein for cod and haddock in Danish seines (section 2.5) were compared with previous results for similar codends applied in demersal trawl fisheries. The comparisons were based on the estimated size selection parameter L50. For cod, we based this comparison on the size selectivity estimates summarised in Madsen (2007) for double twined diamond mesh codends. For haddock, we used the model for size selection in demersal trawl codends provided in Fryer et al. (2015) to predict the size selection in 4 mm double twine diamond mesh codends with 100 open meshes in circumference. This specification complies with the codend we applied in the Danish seine experiment. Using the model provided by Fryer et al. (2015) we made predictions for codends with mesh sizes ranging from 90 mm to 150 mm in 5 mm increments.

In addition to the selectivity parameter (L50) used to compare selectivity in trawls and seines, SR values could have also been compared. However, the values for demersal trawls provided in Madsen (2007) and those obtained by the model in Fryer et al. (2015) are mean values based on a group of hauls following the estimation method of Fryer (1991). This estimation differs from the type of SR values we have estimated, which are averaged over hauls. Such values tend to be bigger than the mean estimates based on the method of Fryer (1991), since they will incorporate the effect of between haul variation in selectivity into the estimated SR values (Frandsen et al., 2011). Therefore, it is not possible to know to what extent a potential difference in SR values would be due to differences in selectivity between the two fishing methods or due to difference in estimation methods. Since L50 values will not be affected to the same extent by the different estimation methods, we have chosen to make the comparison solely based on L50 values.

3 Results

3.1 Size Selection Obtained from Sea Trials

A total of 9 valid hauls were carried out during the sea trials. Table 1 summarizes the catch data for cod and haddock in each of these hauls. In total, 7307 cod and 6901 haddock were length measured and used to form the basis for the size selectivity analysis and calibration of the simulation method.

Table 1: Catch data for cod and haddock from individual hauls.

Haul	Species	Length span (cm-cm)	Number measured in codend	Number measured in cover	Sampling rate in codend	Sampling rate in cover
1	cod	15 – 71	81	270	1.0000	1.0000
2	cod	16 – 90	155	938	1.0000	0.3007
3	cod	16 – 112	104	886	1.0000	1.0000
4	cod	12 – 90	174	527	1.0000	1.0000
5	cod	15 – 86	322	643	1.0000	0.3093
6	cod	15 – 110	424	625	1.0000	0.1791
7	cod	17 – 90	159	777	1.0000	0.8000
8	cod	18 – 74	80	129	1.0000	1.0000
9	cod	14 – 85	147	866	1.0000	0.1920
1	haddock	18 – 52	30	673	1.0000	0.3443
2	haddock	16 – 66	378	683	1.0000	0.1164
3	haddock	17 – 62	72	550	1.0000	1.0000
4	haddock	20 – 57	20	504	1.0000	1.0000
5	haddock	19 – 72	768	663	0.7021	0.1723
6	haddock	17 – 75	361	711	1.0000	0.1384
7	haddock	17 – 62	20	506	1.0000	1.0000
8	haddock	19 – 50	18	121	1.0000	1.0000
9	haddock	18 – 65	201	622	1.0000	0.2928

For both cod and haddock, the average size selectivity was best described by the DLogit model. This was especially clear when inspecting the relative likelihoods for the other models (Table 2). This result could indicate that size selection in a diamond mesh codend when applied for Danish seining involves more than one size selection process.

The size selection curves for all three species are described and quantified in Fig. 3 and Table 3, respectively. For haddock, the p-value < 0.05 could indicate problems describing the experimental data, but since an inspection of the deviance residuals did not show any patterns, we considered it a case of overdispersion in the data and are confident in applying the DLogit model to describe the size selection of haddock. The lack of patterns in the deviation between model and experimental data is also clear from Fig. 3.

Table 2: AIC-values obtained for the five different models fitted to the experimental selectivity data. Models with the lowest AIC values are in bold. Relative likelihood denotes how probable the model is relative to the model with the lowest AIC.

Species	Model	AIC-value	Relative likelihood
	Logit	6322.30	8.16E-13 %
	Probit	6266.67	0.98 %
Cod	Gompertz	6281.87	4.91E-04 %
	Richard	6264.26	3.27 %
	DLogit	**6257.42**	**100.00 %**
	Logit	7638.62	3.46E-66 %
	Probit	7510.10	2.80E-38 %
Haddock	Gompertz	7335.40	2.41 %
	Richard	7350.32	1.39E-03 %
	DLogit	**7327.95**	**100.00 %**
	Logit	9132.42	4.44E-25 %
	Probit	9198.86	1.66E-39 %

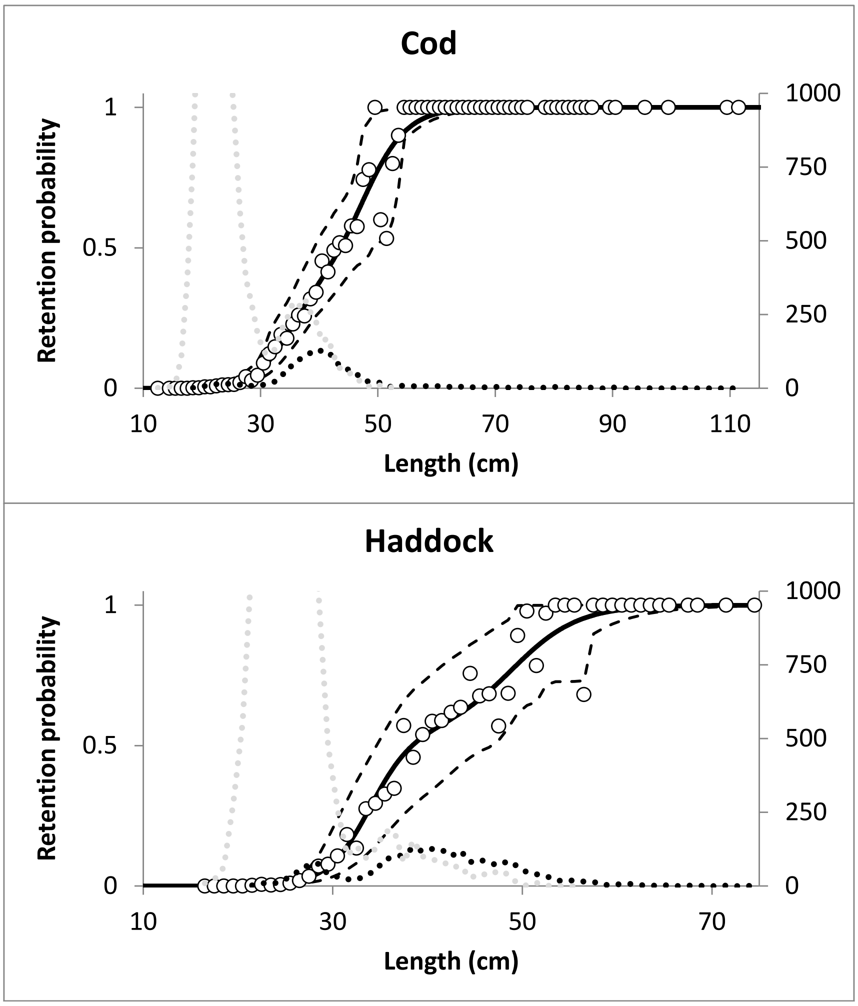

Figure 3: Experimental results. Circle marks represent experimental retention rates. Black curve represent the modelled size selection. Stippled curves represent 95% confidence limits for the estimated size selection curve. Black dotted curve represents the population retained in the codend while the grey dotted curve presents the population collected in the codend cover.

Table 3: Results for the Double Logit model fitted to the experimental data for cod and haddock, respectively. Values in () represent 95% confidence intervals. DOF denotes degree of freedom.

	Cod	Haddock
C_1	0.65 (0.24 – 0.92)	0.46 (0.18-0.83)
$L50_1$ (cm)	47.49 (42.73 – 53.96)	48.93 (40.76 – 57.04)
SR_1 (cm)	8.20 (0.10 – 10.94)	7.64 (0.10 – 10.03)
$L50_2$ (cm)	34.63 (29.99 – 39.80)	33.92 (29.49 – 38.65)
SR_2 (cm)	6.57 (0.10 – 9.56)	4.91 (2.08 – 7.07)
L_{05} (cm)	28.96 (26.51 – 31.27)	28.72 (27.05 – 31.07)
L_{10} (cm)	31.52 (29.42 – 33.87)	30.52 (28.33 – 33.16)
L_{15} (cm)	33.29 (30.64 – 36.10)	31.69 (29.19 – 34.62)
L_{20} (cm)	34.79 (31.68 – 37.86)	32.63 (29.86 – 35.84)
L_{25} (cm)	36.22 (32.96 – 39.68)	33.46 (30.53 – 37.26)
L_{30} (cm)	37.68 (34.26 – 41.26)	34.27 (31.19 – 38.98)
L_{35} (cm)	39.20 (35.70 – 42.74)	35.08 (31.94 – 40.90)
L_{40} (cm)	40.73 (36.97 – 44.64)	35.98 (32.59 – 42.67)
L_{45} (cm)	42.20 (38.14 – 47.23)	37.02 (33.55 – 44.35)
L_{50} (cm)	43.56 (39.41 – 48.69)	38.38 (34.34 – 46.91)
L_{55} (cm)	44.79 (40.64 – 51.87)	40.32 (35.04 – 48.38)
L_{60} (cm)	45.95 (42.14 – 52.84)	42.76 (36.01 – 49.42)
L_{65} (cm)	47.06 (43.49 – 53.42)	44.93 (37.09 – 52.27)
L_{70} (cm)	48.17 (44.86 – 53.50)	46.71 (38.39 – 52.92)
L_{75} (cm)	49.33 (45.68 – 53.56)	48.28 (40.42 – 56.95)
L_{80} (cm)	50.58 (46.39 – 53.60)	49.89 (42.79 – 57.00)
L_{85} (cm)	52.03 (46.62 – 53.77)	51.41 (44.69 – 57.04)
L_{90} (cm)	53.89 (47.12 – 55.29)	53.35 (46.61 – 57.49)
L_{95} (cm)	56.80 (47.96 – 58.59)	56.21 (48.54 – 60.79)
p-value	0.9991	0.0103
deviance	40.87	74.79
DOF	73	49

Fig. 3 and Table 3 demonstrate very low retention probability at the minimum conservation reference sizes (MCRS; previously known as minimum landing size (MLS)) of 30 and 27 cm for cod and haddock in this fishery respectively (EU Regulation No. 850/98).

3.2 Simulating the Selective Potential of the Diamond Mesh Codend Based on Fish Morphology

The potential size selection in the experimental codend for cod and haddock based on different mesh situations (opening angle and mesh state) are presented in Fig. 4. The fish lengths for which full retention is obtained (≈0.95) in the experimental curve seems to comply with the fish lengths that are predicted to occur for slack mesh selection for both cod and haddock (Fig. 4). Furthermore, results indicate that stiff mesh selection alone cannot explain the upper part of the experimental size selection curves since the full retention probabilities should also be reached for smaller cod and haddock.

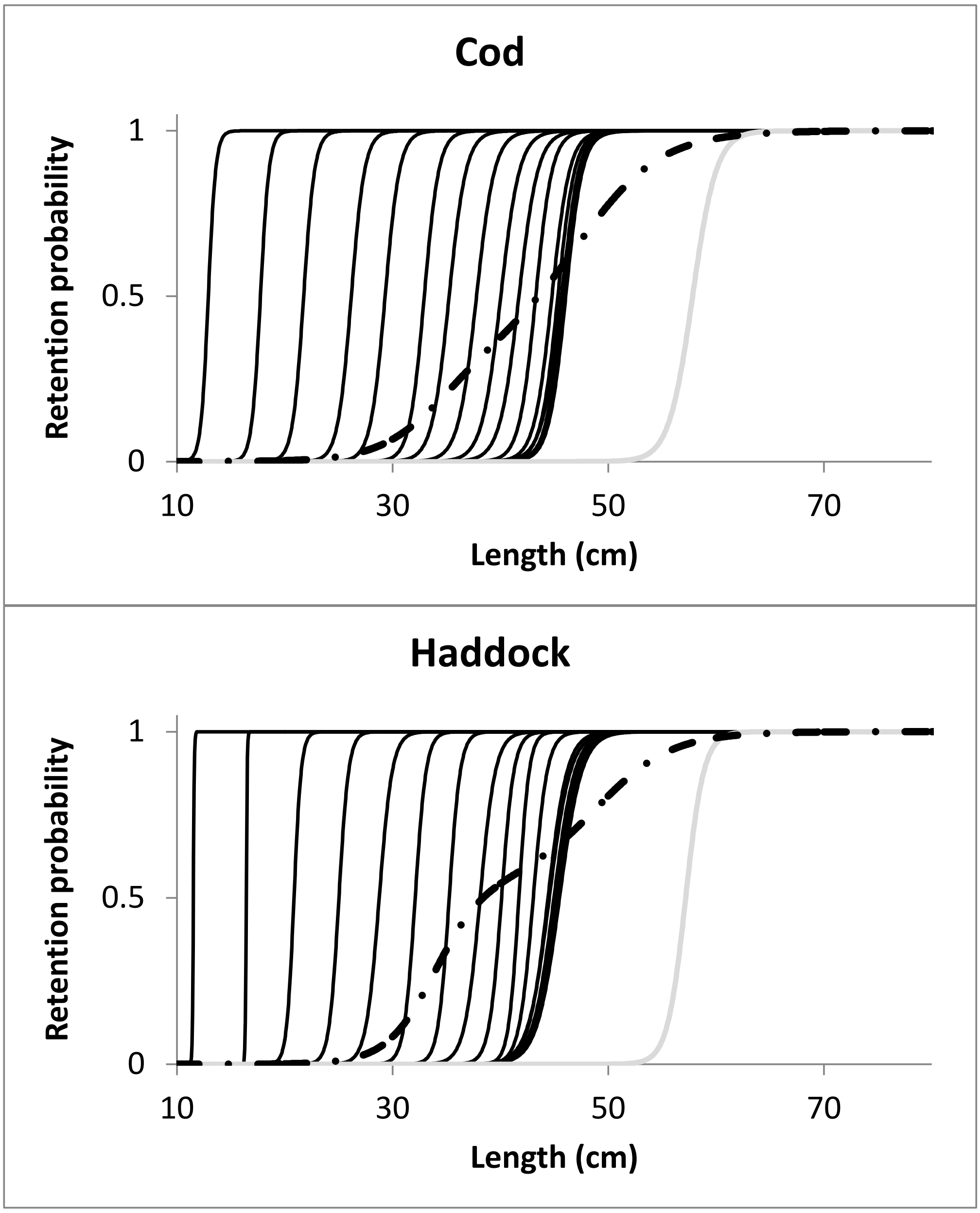

Figure 4: Experimental size selection curve (black stippled) and FISHSELECT predicted curves for different mesh states: stiff mesh state with OA from 15 to 90 degrees (black curves from left to right) and soft mesh state (grey curve).

3.3 Understanding the Size Selection Process in the Experimental Diamond Mesh Codend

Following the results obtained in section 3.2 regarding the ability to reproduce the experimentally obtained size selection curves for cod and haddock based on FISHSELECT simulations, we applied the procedure described in section 2.3 to investigate this in more detail. This was investigated for each of the four scenarios (Fig. 5).

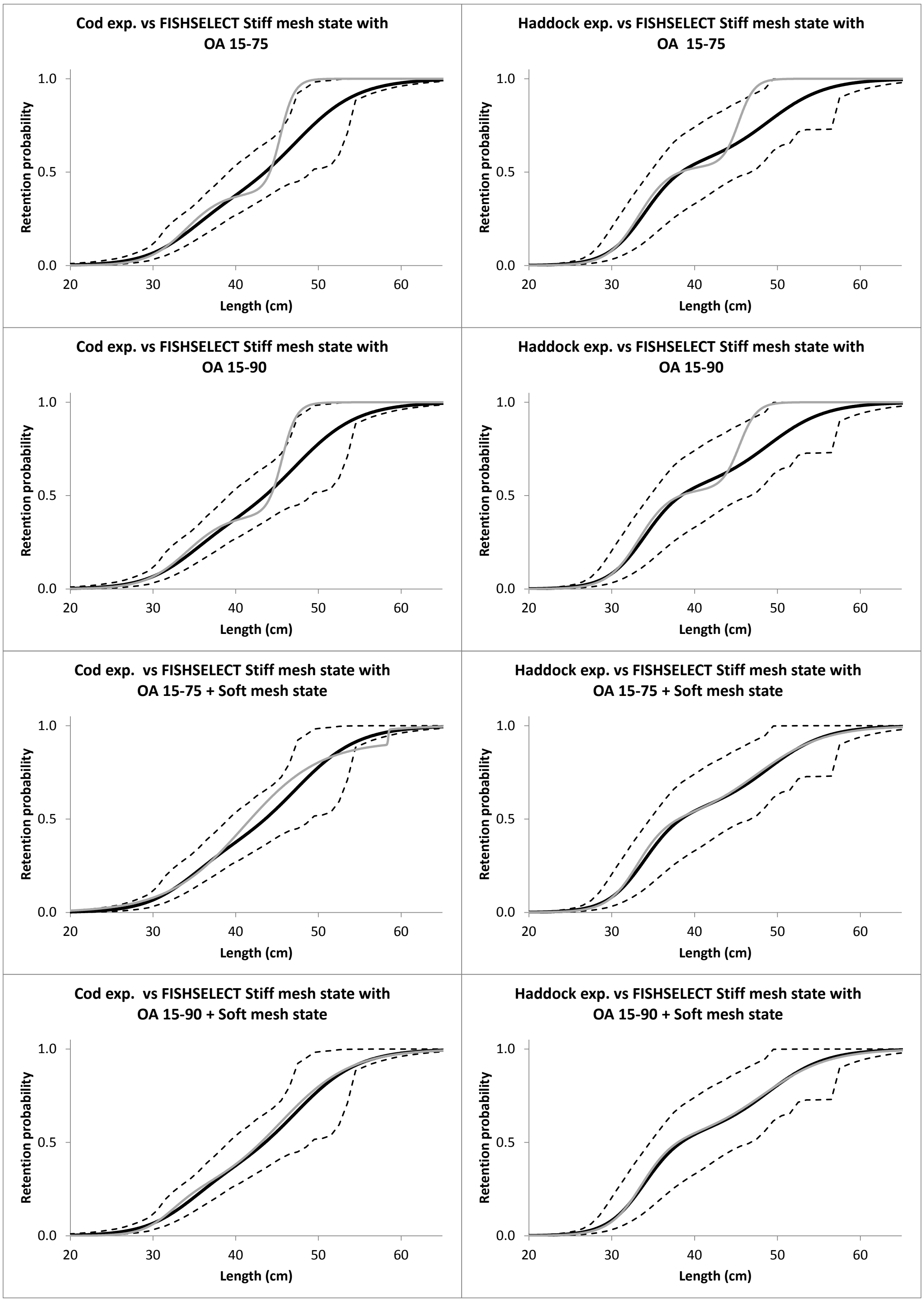

Figure 5: Experimental size selection (back curve) with confidence limits (stippled curves) versus best fit (grey curve) for FISHSELECT simulations considering the four different scenarios: i) stiff mesh state with mesh opening angles in the range 15 to 75 degrees (first row); ii) stiff mesh state with mesh opening angles in the range 15 to 90 degrees (second row); iii) stiff mesh state with mesh opening angles in the range 15 to 75 degrees and soft mesh state (third row)); iv) stiff mesh state with mesh opening angles in the range 15 to 90 degrees and soft mesh state (fourth row).

It was evident that the two first scenarios were not able to reproduce the experimentally obtained size selection curves for neither cod nor haddock since part of the simulated curves are outside the confidence limits for the experimental curve (Fig. 5). For scenario three, part of the simulated size selection curve for cod was still outside the confidence bands for the experimental curve, while the simulated curve for haddock reflected the experimental curve quite well. However, the simulated curve for scenario four accurately reproduced the experimentally obtained size selection for both cod and haddock. Based on these results, it is highly likely that slack (soft) mesh size selection plays an important role for size selection in diamond mesh codends in Danish seining. Specifically, it is likely that the mesh state conditions modelled by scenario four are likely to be the most representative for the Danish seine fishing process and the further investigation is therefore based on this scenario. For both species, it is estimated that around 15% of the fish are subjected to slack mesh selection, which most likely occurs when the codend is at the surface (Table 4). If we assume that the widest open meshes (opening angle > 75 degrees) only occur at the surface, then the results in Table 4 imply that 46% and 34% of cod and haddock respectively will have their size selection at the sea surface, at least for the biggest fish (> 48 cm) that manage to escape (see Fig. 5)) .

Table 4: Estimated contributions for the different mesh states. FISHSELECT simulations are based on the mesh state scenario considering stiff mesh states with OA range 15 to 90 degrees and in addition the soft mesh state.

Mesh state mode	Contribution (%)	
	Cod	Haddock
Stiff with OA=15°	0.00	0.00
Stiff with OA=20°	0.00	0.00
Stiff with OA=25°	2.62	0.26
Stiff with OA=30°	5.35	11.12
Stiff with OA=35°	13.28	14.88
Stiff with OA=40°	8.34	14.64
Stiff with OA=45°	6.09	12.18
Stiff with OA=50°	4.79	0.80
Stiff with OA=55°	1.93	0.20
Stiff with OA=60°	1.66	0.02
Stiff with OA=65°	1.48	0.14
Stiff with OA=70°	2.83	3.02
Stiff with OA=75°	5.93	8.45
Stiff with OA=80°	11.89	9.36
Stiff with OA=85°	9.75	5.60
Stiff with OA=90°	9.03	4.29
Soft	15.04	15.05

3.4 Predicting Size Selectivity in Different Diamond Mesh Codends

The predictions for cod and haddock size selection in codends with alternative mesh sizes can be applied to estimate the consequences if a codend of a different mesh size were to be applied in the fishery (Fig. 6, Table 5). Such an objective could be motivated based on the poor retention efficiency for the targeted witch flounder sizes (see section 3.1). If we attempt to match the MCRS for cod and haddock (30 and 27 cm respectively) with the L25 values for the codend size selection, as suggested by Reeves et al. (1992), we predict that it would be appropriate to reduce the codend mesh size to 105 mm (Table 5).

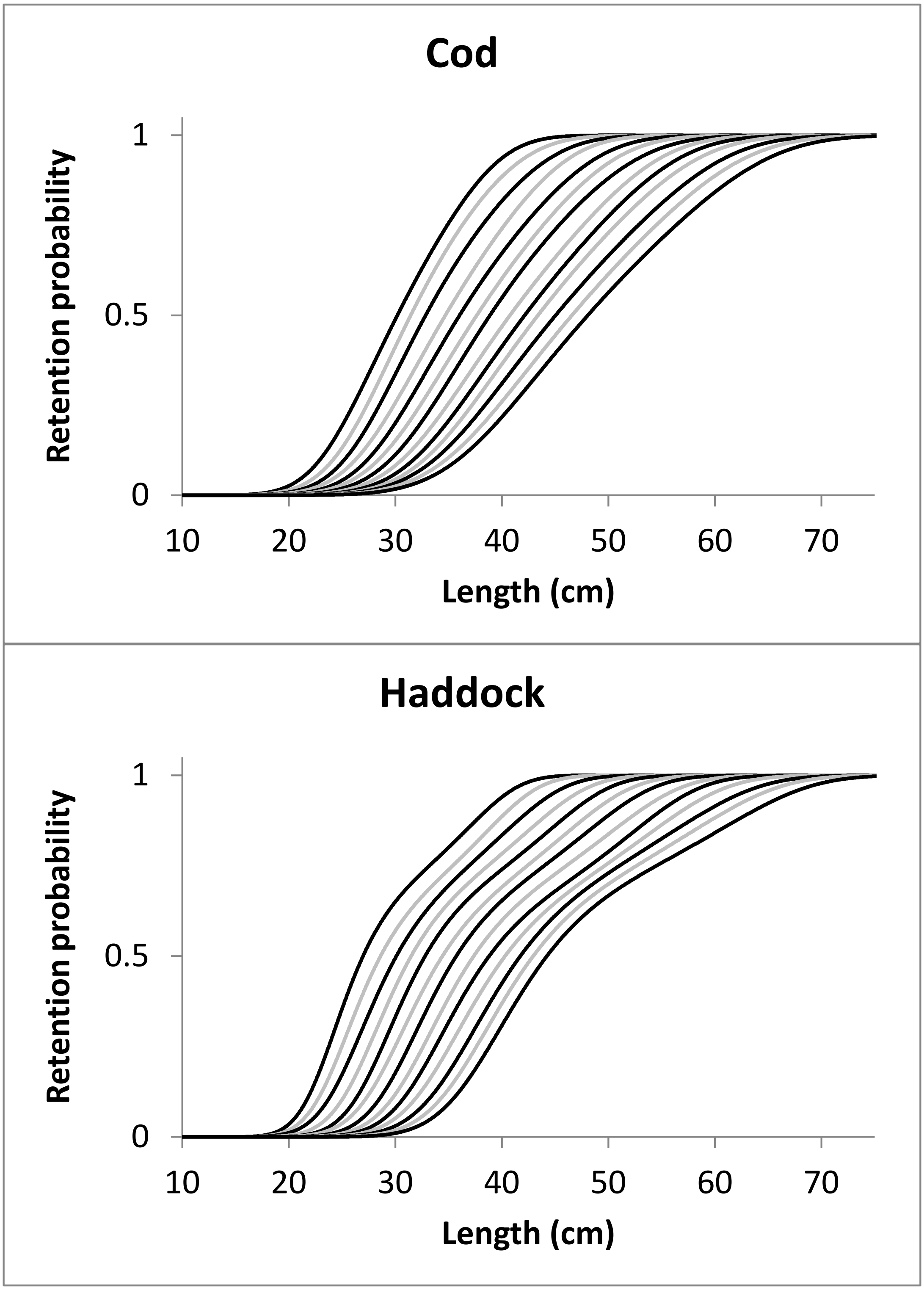

Figure 6: Prediction of size selection in codends with mesh sizes between 90 and 150 mm. Black curves (from left to right) represent mesh sizes 90, 100, 110, 120, 130 , 140 and 150 mm. Grey curves (from left to right) represent mesh sizes 95, 105, 115, 125, 135 and 145 mm.

Table 5: FISHSELECT predictions of codend size selection using the mesh state contributions estimated for the experimental fishing trials (Table 4). L05, L25, L50, L75 and L95 denote the length of a fish predicted to have respectively 5%, 25%, 50%, 75% and 95% probability of being retained by the codend.

Codend	cod					haddock				
Mesh size (mm)	L05 (cm)	L25 (cm)	L50 (cm)	L75 (cm)	L95 (cm)	L05 (cm)	L25 (cm)	L50 (cm)	L75 (cm)	L95 (cm)
90	21.3	26.0	30.2	34.9	40.6	20.5	23.8	27.0	33.2	40.5
95	22.5	27.3	31.5	36.3	42.9	21.4	25.0	28.6	35.4	42.6
100	23.5	28.5	32.9	38.2	45.3	22.3	26.2	30.1	36.9	44.9
105	24.4	29.9	34.7	40.2	47.1	23.5	27.5	31.5	38.7	47.1
110	25.5	31.1	36.0	42.1	49.7	24.8	28.8	32.8	40.5	49.1
115	26.4	32.3	37.7	43.9	51.6	25.6	30.0	34.4	42.4	51.2
120	27.4	33.5	38.9	45.4	53.8	26.8	31.3	35.7	44.0	53.1
125	28.4	34.9	40.8	47.6	55.7	27.9	32.6	37.4	46.1	55.6
130	29.5	36.1	42.2	49.2	57.6	28.9	33.8	38.8	48.3	57.5
135	30.4	37.2	43.4	50.7	59.4	29.9	35.1	40.3	49.7	59.8
140	31.2	38.4	45.1	52.8	61.9	31.2	36.5	41.7	51.1	62.5
145	32.2	39.7	46.6	54.5	63.8	32.2	37.6	42.9	52.7	64.4
150	33.2	41.0	48.1	56.4	66.1	33.3	38.8	44.2	54.5	67.1

3.5 Comparing the Danish Seine Codend Size Selectivity with Codend Size Selectivity of Trawls

The predicted codend size selectivity for Danish seine codends of different mesh size (section 3.4) were compared with the size selectivity in similar codends applied in demersal trawl fisheries following the procedure described in section 2.6. Fig. 7 summarises the results based on this comparison.

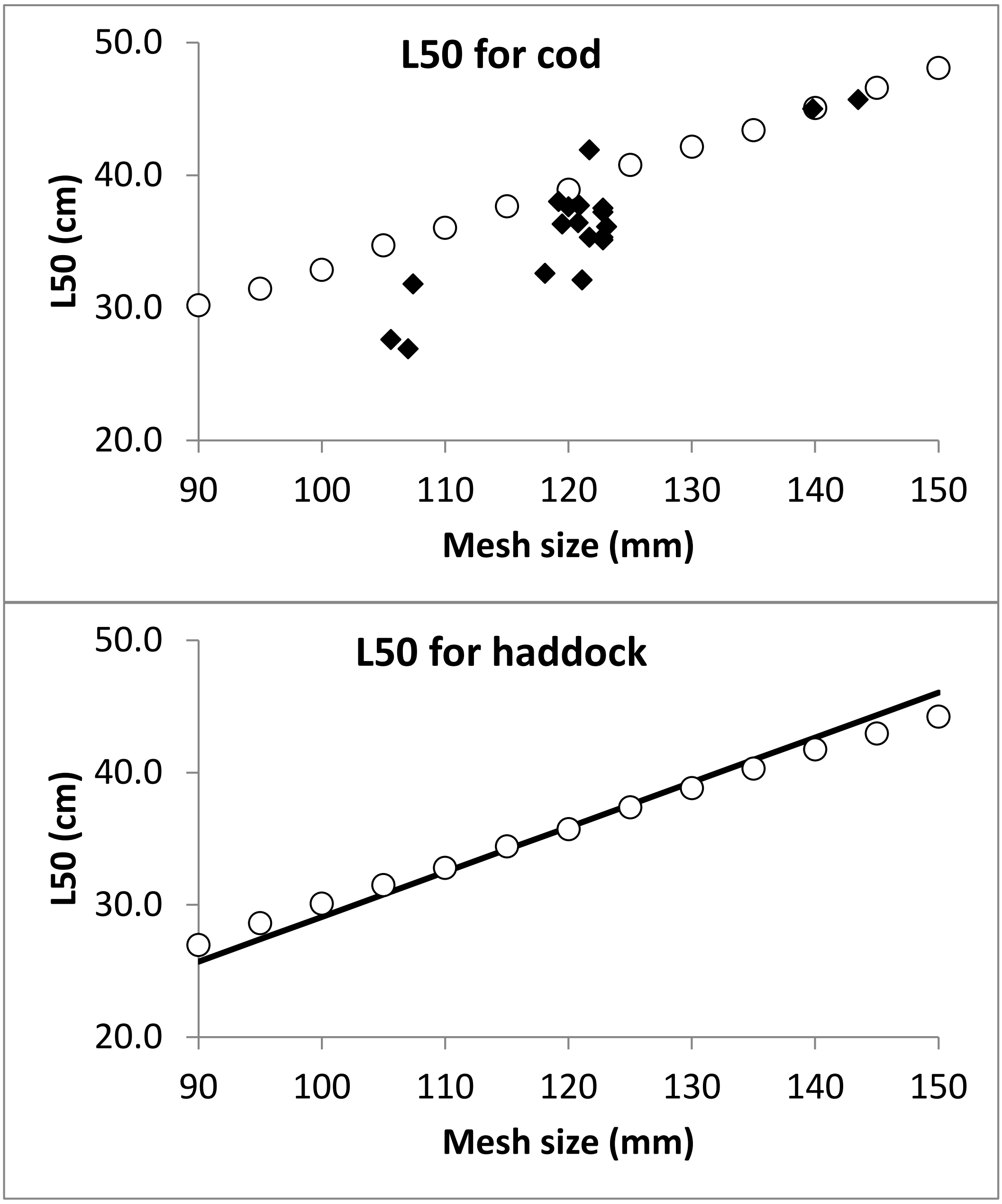

Figure 7: Comparing the FISHSELECT based predictions for Danish seine codend size selectivity (white circle marks) with historical results for trawl size selectivity in similar codends. Comparisons are made in terms of L50 for codends with mesh size 90 to 150 mm. For cod (top), comparisons are made against 4 mm double twine codend selectivity results (black diamond marks) that are summarised in Madsen (2007). For haddock, the comparisons are made against results (black line) obtained by using the model in Fryer et al. (2015) for codends with 4 mm double twine and 100 open meshes in circumference.

From Fig. 7 it is observed that the predicted L50 values for the codend size selectivity of cod seem to be higher for Danish seining when compared to demersal trawling, as most data points for demersal trawling are below those for Danish seining. Contrary, for haddock the L50 values obtained for the two different fishing processes seem to match nearly perfectly across the entire range of codend mesh sizes investigated.

4 Discussion

In this study we used the covered codend method to investigate the size selectivity in a 120 mm diamond mesh codend in the Danish seine fishery for cod and haddock. The codend selectivity for both species was best described by the double logistic model, indicating that more than one process affects codend size selectivity. This dual-selectivity pattern for a diamond mesh codend is different from what is typically observed when describing the size selectivity in similar codends in demersal trawl fisheries targeting the same species (e.g. Galbraith et al., 1994; O'Neill and Kynoch, 1996; Dahm et al., 2002; Frandsen et al., 2011; Herrmann et al., 2013c). However, as far as we know, none of these studies formally investigated if the double logistic model may have been superior at describing their diamond mesh codend size selectivity data compared to the single logistic model they applied. Therefore, we cannot definitively rule out that a similar double logistic size selection pattern in some cases could occur in demersal trawling using diamond mesh codends. Based on this, it is only possible to speculate on what could be the reason for the double logistic size selection observed for the Danish seine fishing and not make further speculations about how the size selection would be in a similar codend when applied in a demersal trawl fishery.

The experimental fishing was conducted using a cover with kites without supporting hoops. Such covers can potentially lead to masking between the codend and cover, consequently inhibiting size selection. To reduce this risk we used a modified cover concept specifically developed to mitigate such an effect in relation to Danish seine fishing. During the experimental fishing no indication of cover masking was observed. Furthermore, the obtained codend size selection, demanding wide open meshes to be explained, neither indicates that the codend size selection would have been biased by a masking cover. Additionally, the comparison made with trawl selectivity results for similar codends does not indicate that our experimental seine results should have been biased due to masking. Based on this, we assume that our results have not been affected by cover masking.

The size selectivity estimates obtained herein are based on experimental hauls carried out on a commercial fishing vessel following normal commercial fishing practices. The only exception is the additional handling of the cover during the final part of the fishing operation. Therefore, we assume that the estimated size selection based on the hauls conducted is representative for how the size selectivity of the codend would be when in commercial use. However, some precaution needs to be taken since our fishing trial is based on only 9 hauls and therefore we assume that these 9 hauls reflect the average size selection of the codend when employed by the commercial fleet. Furthermore, due to the number of hauls, the amount of fish caught is limited, which leads to uncertainty in the estimated size selection curves. This also needs to be considered when making conclusions based on the results obtained. These uncertainties are however reflected in the confidence bands around the size selection curves and parameters that are provided along with the results. Therefore, as long as these confidence bands are considered when making conclusions, the limited number of fish caught and measured in this study should not be a problem. This has been considered when drawing the conclusions made in this study.

Using FISHSELECT, we demonstrated that the experimentally obtained double logistic size selection curves can only be explained if we assume that a part of the fish is able to escape through slack and wide open codend meshes. This finding is in line with Herrmann et al. (2016) which investigated the size selection of cod in a square mesh codend applied in a Norwegian demersal seine fishery (fly-shooter). Herrmann et al. (2016) further speculated that the slack mesh size selection might occur at the last stages of the fishing process when the codend is at the surface. Based on this, we could speculate that a similar situation occurs when Danish seining with a diamond mesh codend.

In towed fishing gears, late escapement through codend meshes is a known phenomenon, as various demersal trawl selectivity studies have reported it in the past (Grimaldo et al., 2009 and Herrmann et al., 2013a). In particular, Herrmann et al. (2013a) reported that about 30 % of the cod in the codend made their first escape attempt after the haul-back operation had begun. Because the fish in a Danish seine are expected to have spent less time in contact with the gear than in a demersal trawl, both fishermen and scientists claim that fish harvested with demersal seines are less exhausted (e.g. Dreyer et al., 2008). Since seine caught fish maintain a good physiological state as they reach the surface, late escapement might be even more prominent in Danish seines than it is for demersal trawls. Tensionless/slack mesh escapement at the last stages of the fishing process, including at the surface, could therefore play an important role for the size selection process in the diamond mesh codend when applied for Danish seining. Therefore, one could speculate what would be the survival rate of those fish escaping that late in the fishing process since Physoclistous fishes like cod and haddock might suffer considerably during the haul-back process because their swim bladder cannot adapt instantaneously to changes in hydrostatic pressure. Consequently, the survival rate is expected to be reduced if the fish escape during the later stages of fishing (Herrmann et al., 2013a).

By using knowledge of fish morphology and the computer-based simulation method FISHSELECT, we investigated the potential for size selection of cod and haddock in diamond mesh codends for Danish seining. We were able to explain and understand the experimental selectivity results and hence, also to make predictions. Using the combination of this morphological description and experimental selectivity data, we were able to estimate and predict the selectivity for cod and haddock for diamond mesh codends with different mesh sizes. This is the first time this has been attempted for diamond mesh codend selectivity for the Danish seine fishery, and it could be a useful tool for predicting the size selectivity of other relevant netting configurations and optimizing the size selectivity e.g. during a landing obligation system as introduced under the new common fisheries policy in EU waters.

Considering the MCRSs of 30 and 27 cm for cod and haddock in this fishery respectively, the results obtained show that the codend applied in the sea trials (mesh size 129 mm) results in a very small retention probability for undersized fish for both species (Fig. 3).

The fishing operation in Danish seining is quite different from trawling. During trawling, the trawl is towed with the same speed over the seabed where the gear retains more or less the same global geometry. Danish seines are towed at considerably lower speeds, especially in the early phases of the operation, and the global geometry of the gear gradually goes from being overspread in the setting phase to completely closed at the end of the collecting/closing phase. However, the netting used for constructing trawls and seines, and to some extent the construction of the gears, are relative similar. In Denmark and EU waters, the gear regulations pertaining to seining are the same as those for trawling. Therefore, we compared our predicted codend size selectivity to the size selectivity in similar codends when applied for demersal trawling. For cod this comparison indicates that the size selection is lower for demersal trawling since most L50 values were lower for demersal trawling. For haddock, the obtained L50 values were nearly identical for the two fishing processes. The results of these comparisons therefore could imply that the difference in codend selectivity between Danish seining and demersal trawling is species dependent.

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