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ARTICLE

Understanding and Predicting Size Selection in Diamond-Mesh Cod Ends for Danish Seining: A Study Based on Sea Trials and Computer Simulations

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Abstract
Danish seining is an important fishing method used to harvest demersal species. Knowledge about the size selectivity of different demersal species with this type of fishing gear is therefore of importance for managing the exploitation of marine resources. However, there are only limited data on size selection in cod ends in this fishery. Sea trials were therefore carried out to collect size selectivity data for Atlantic Cod *Gadus morhua*, Haddock *Melanogrammus aeglefinus*, and Witch Flounder *Glyptocephalus cynoglossus* for a diamond-mesh cod end. For all three species, the data were best described by a double logistic selection curve, implying that two different size selection processes occur in the cod end. The double selection process could be explained by an additional selection process occurring through slack meshes. The results imply that the escapement of 46% and 34% of the larger Atlantic Cod and Haddock (those above 48 cm), respectively, would be through wide-open or slack meshes. Since these mesh states are only likely to be present in the latest stage of the fishing process (e.g., when the cod end is near the surface), a large fraction of the bigger fish probably escaped near the surface, which might influence their likelihood of survival. Furthermore, based on the models established for explaining the experimental size selection, we were able to predict the effect of changing the mesh size on cod end size selection in the Danish seine fishery.

The Danish or anchor seine is an active demersal fishing technique which was invented by the Danish fisherman Jens Væver in 1848, and in the first half of the 20th century it became one of the most important fishing gears used in Denmark (Thomson 1981). When this fishing method was brought to other countries, it was adapted to suit local conditions and behaviors. 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 the method primarily used by Norwegian fishermen targeting Atlantic Cod *Gadus morhua* and Haddock *Melanogrammus aeglefinus* (Herrmann et al. 2016). However, the principle of Danish or anchor seining has remained the same and its importance to the commercial fishery in Denmark and many other parts of the world is increasing due to its low fuel consumption, high catch

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quality, and low ecosystem impacts relative to trawling (Thrane 2004; ICES 2010; Walsh and Winger 2011; Suuronen et al. 2012).

Danish seining consists of three main phases: the setting phase, the collecting phase, and the closing phase (Figure 1). After dropping an anchor attached to a set of marker buoys, the fishing vessel starts encircling the fishing area by laying out the first lead-filled rope (Figure 1A), which can be up to 4,000 m 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 (Figure 1B). Only the last part of the rope (approximately one 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 (Figure 1C–E). The movement of the seine ropes along the seafloor herds the fish into the centre of the encircled area. Finally, the wings of the net start closing and the closing phase begins. At this point, the hauling speed of the winches is increased to reduce the fish's chance to escape. Finally, the seine reaches the vessel and can be emptied (Figure 1F).

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 and closing phases. However, the netting used for constructing trawls and seines, and to some extent the construction of the gears, are relative similar. In Danish and European Union (EU) waters, the gear regulations pertaining to seining are the same as those for trawling. For gears to be grouped under the same technical regulations, it is important that they be comparable in terms of selectivity, as similar results in terms of management and catch efficiency will then be obtained. With the considerable differences in the operations of the two gear types, however, the selectivity of these two gears can be expected to differ.

A recent study of square-mesh cod end selectivity in the Norwegian seine fishery suggested that surface selection through slack or wide-open meshes likely plays an important role for cod end 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 cod end 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 cod end, since some species of fish

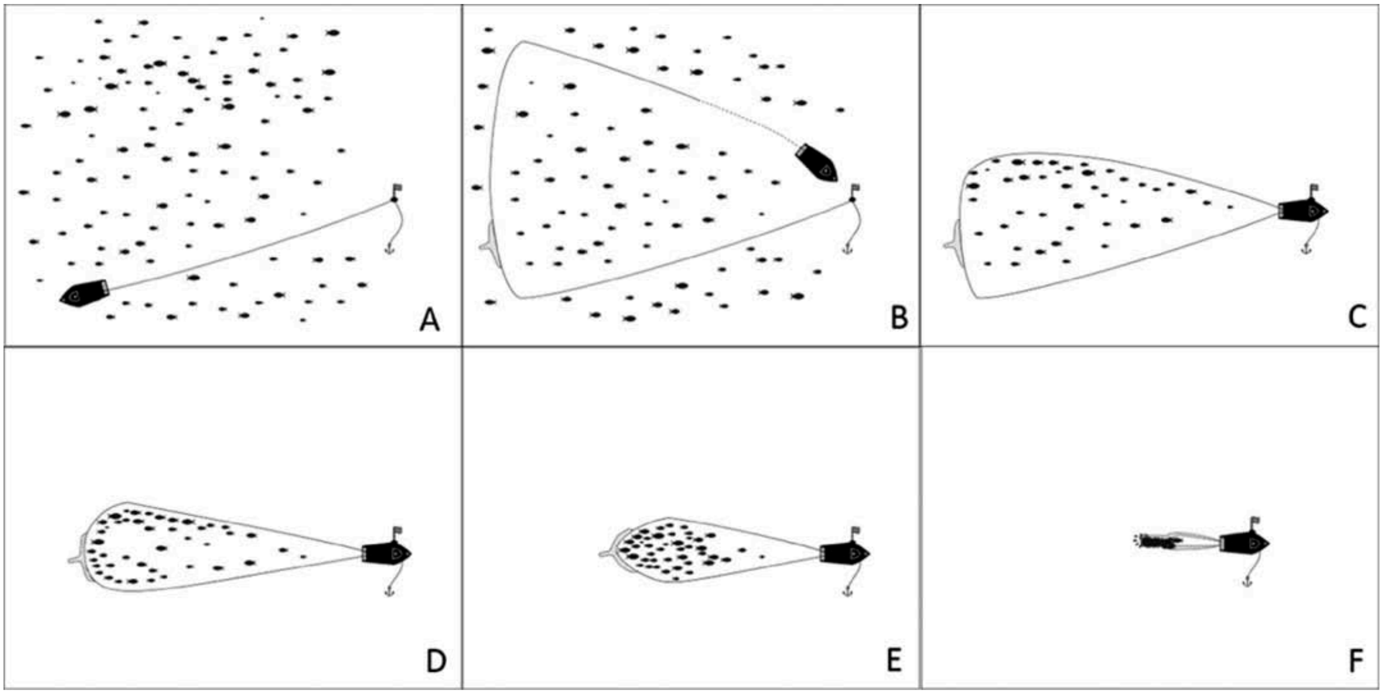

FIGURE 1. Depiction of the three phases of the Danish seining process: **(A)–(B)** the setting phase, **(C)–(E)** the collecting phase, and **(F)** the closing phase.

escaping later in the process might have less likelihood of surviving than those escaping at the seabed (Herrmann et al. 2014). Furthermore, such combined selection processes might result in selectivity models that are different from the more traditional logistic models typically used when describing size selectivity in standard trawl cod ends (Wileman et al. 1996). However, limited information is 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 cod ends within Danish seine fisheries.

This study aimed to establish cod end selectivity curves for some of the most important commercial species targeted in the Danish seine fisheries in Denmark. Furthermore, we sought to increase fundamental understanding of the size selection processes in Danish seines, specifically in diamond-mesh cod ends. Finally, the selective effect of changing the mesh size on cod end size selection in the Danish seine fishery was predicted, and those predictions were compared with historical results for cod end size selection in similar cod ends when applied to demersal trawling.

METHODS

Sea trials and gear specifications.—Sea trials were 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 length overall; 300 kW). All fishing was conducted between sunrise and sunset, which is the normal commercial practice in the Danish seine fishery. The target species were Atlantic Cod, Haddock, and Witch Flounder *Glyptocephalus cynoglossus*. Along with Plaice, these are the most important species economically for the Danish seine fishery in Denmark. The fishermen argue that the current technical regulation (requiring a 120-mm diamond-mesh cod end) is reasonable for retaining Plaice but results in large losses of Atlantic Cod, Haddock, and Witch Flounder of commercial value. Therefore, this study concentrated on these species. Atlantic Cod and Haddock are typically found in shallower depths (80–90 m; Figure 2A) than Witch Flounder (>100 m; Figure 2B). Hence, the experimental fishing was conducted in two different areas representing different depths (Figure 2).

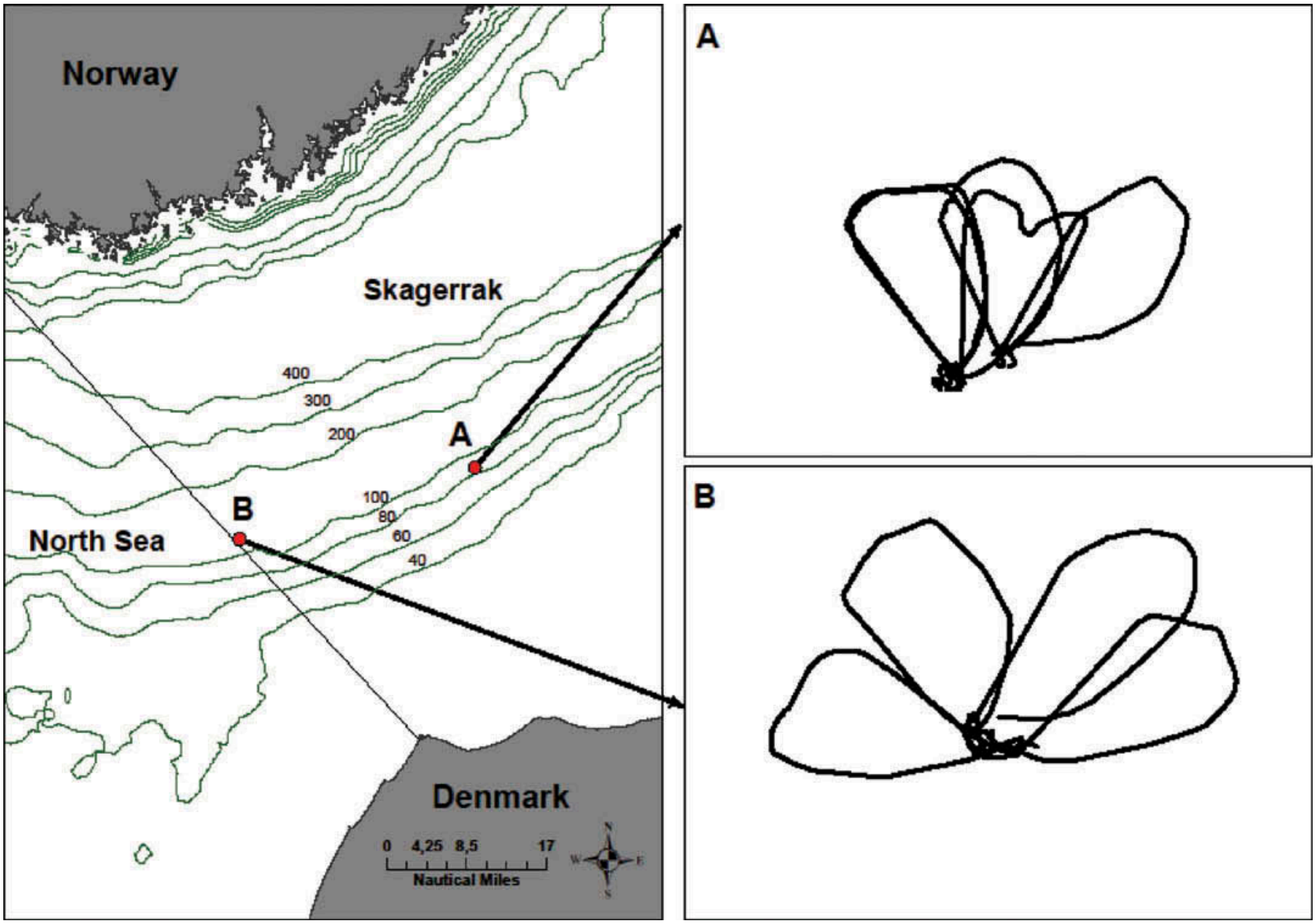

FIGURE 2. Fishing locations and close-ups of individual hauls. Area A represents the shallower Atlantic Cod–Haddock grounds and area B the deeper Witch Flounder grounds. The two right-hand panels show the vessel tracks for individual hauls.

The seine used was a Nymflex combi-seine with a nominal mesh size of 120 mm 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 m and one of 30 m, 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/m.

A diamond-mesh cod end with a nominal mesh size of 120 mm was used since this represents the minimum legal mesh size for the fishery unless escape panels are included. The mesh size was measured to 129.6 mm under 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 onboard in one operation, they have to repeat the operation several times. Fishermen argue that large mesh escape panels in the aft part of the gear will result in large losses of the catch during catch retrieval, during which the catch is left overboard in the extension as the cod end is taken onboard. The cod end was 49.5 meshes long and constructed of double 4-mm polyethylene (PE) netting. The cod end had 100 open meshes in circumference, which included one selvedge of 4 meshes.

The covered cod end method (Wileman et al. 1996) was used to collect fish escaping through the cod end meshes. The last 12 m of the seine was 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 lead to masking between cod end and cover and thereby bias cod end selectivity in the trials. Therefore, we applied a modified version of the cover with kites to reduce this masking risk. This version was specifically developed for and tested during experimental selectivity trails by the fourth author (unpublished data). Compared with the version described by Madsen et al. (2001), the one employed 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 cod end and cover when the gear was not moving or was moving very slowly. Underwater recordings collected during fishing trials in the development phase of this cover concept did not indicate any masking problems during any stage of the fishing process (personal observation by the fourth author).

During these covered cod end fishing trials, the entire catch in each haul was sorted by species. All samples of Atlantic Cod, Haddock, and Witch Flounder were measured to the nearest centimeter below. In the subsequent analysis, 0.5 cm was added for fish following Krag et al. (2015). Due to large catches in a few hauls it was possible to measure only a fraction of the fish. For hauls in which subsampling was carried out, sampling factors were calculated for the cod end and cover separately.

Analysis of data from sea trials.—Analysis of each species was done separately using the method described hereafter. The experimental design enabled analysis of the catch data as binominal data, whereby individuals (either retained by the cod end cover or by the cod end itself) were used to estimate size selection in the cod end (i.e., length-dependent retention probability). The probability of finding a fish of length l in a cod end in haul j was expressed by the function $r_j(l)$. The purpose of the analysis was to estimate the values of this function for all relevant sizes and species individually. Between hauls with the same cod end, the value of $r_j(l)$ is expected to vary (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 outcomes for the size selection process when using the cod end in the fishery. Thus, it was assumed that the size selective performance of the cod end in our experiment was representative of how the cod end 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 $r_{av}(l,\mathbf{v})$, where $\mathbf{v}$ is a vector consisting of the parameters of the model. The purpose of the analysis was to estimate the values of $\mathbf{v}$ that make the 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 for each cod end and species individually: Logit, Probit, Gompertz, and Richard. The first three models are fully described by the two selection parameters L50 (the length of fish with a 50% probability of being retained) and SR (the difference in length between fish with 75% and 25% probabilities of being retained), while the Richard model 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 these four classical size selection models, which assume that all fish entering the cod end are subject to the same size selection process, we considered a model that we refer to as the double logistic model (DLogit). This model was constructed by assuming that a fraction C_1 of the fish entering the cod end will be subjected to one logistic size selection process with parameters $\mathrm{L50}_1$ and SR_1 while the remaining fraction $(1.0 - C_1)$ will be subjected to a logistic size selection process with parameters $\mathrm{L50}_2$ and SR_2. Therefore, a total of five models were considered for $r_{av}(l,\mathbf{v})$:

$$r_{av}(l,\mathrm{v}) = \begin{cases} \mathrm{Logit}(l, \mathrm{L50}, \mathrm{SR}) \\ \mathrm{Probit}(l, \mathrm{L50}, \mathrm{SR}) \\ \mathrm{Gompertz}(l, \mathrm{L50}, \mathrm{SR}) \\ \mathrm{Richard}(l, \mathrm{L50}, \mathrm{SR}, 1/\delta) \\ \mathrm{DLogit}(l, C_1, \mathrm{L50}_1, \mathrm{SR}_1, \mathrm{L50}_2, \mathrm{SR}_2) \\ \quad = C_1 \times \mathrm{Logit}(l, \mathrm{L50}_1, \mathrm{SR}_1) + (1.0 - C_1) \\ \quad \times \mathrm{Logit}(l, \mathrm{L50}_2, \mathrm{SR}_2) \end{cases} \tag{1}$$

For the DLogit model in (1), C_1 represents the assumed length-independent probability that the size selection of the fish will be defined by the logistic model with parameters $\mathrm{L50}_1$ and SR_1, while the probability for the size selection of the fish to be defined by the logistic model with parameters $\mathrm{L50}_2$ 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 (lengths with 5% to 95% probabilities of being retained, respectively), in 5% increments.

Evaluating the ability of a model to describe the data sufficiently is based on the corresponding *P*-value, which expresses the likelihood of obtaining 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 for modeling the size selection data, this *P*-value should not be below 0.05 (Wileman et al. 1996). In cases of a poor fit, the residuals were inspected to determine whether this was due to structural problems in modeling the experimental data using the different selection curves or to overdispersion in the data (Wileman et al. 1996). Selection of the best model among the five considered in (1) was based on comparing the Akaike information criterion (AIC) values for the models. The model selected was the one with the lowest AIC value (Akaike 1974). Furthermore, based on Wagenmakers and Farrell (2004), we estimated the relative likelihood L_i for each of the other *i* models compared with the model with the lowest AIC value ($\mathrm{AIC}_{\min}$):

$$L_i = \exp\left(-\frac{\mathrm{AIC}_i - \mathrm{AIC}_{\min}}{2}\right) \tag{2}$$

Once the specific size selection model was identified for a particular species and cod end, bootstrapping was used to estimate the confidence limits for the average size selection. We used the software tool SELNET (Herrmann et al. 2012) for the size selection analysis and 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 cod end were used to define a group of hauls. To account for between-haul variation, an outer bootstrap resampleing with replacement from the group of hauls was included in the procedure. Within each resampled haul, the data for each length class were 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, 1,000 bootstrap repetitions were conducted to estimate the Efron percentile 95% confidence limits (Herrmann et al. 2012).

*Simulating the selective potential of the diamond-mesh cod end based on fish morphology.—*Several studies have demonstrated that not only mesh size but also the openness of the meshes in diamond-mesh cod ends affects net selectivity (Herrmann 2005a, 2005b; Herrmann and O'Neill 2005; Herrmann et al. 2007; O'Neill and Herrmann 2007; Herrmann et al. 2009). During trawling, the cod end meshes are stretched by hydrodynamic drag forces that act primarily on the accumulated catch in the aft end of the cod end (Herrmann 2005b; Herrmann et al. 2006), where the mesh opening is unlikely to exceed 75 degrees. The same mesh state can be expected during the closing phase of the Danish seine fishing process, when the diamond-mesh netting is stretched and under tension due to pulling by the seine ropes. Therefore, it is unlikely that fish trying to escape through the cod end meshes during the closing phase will be able to deform the netting and thus a diamond shape with an opening that does not exceed 75 degrees is maintained. However, when the cod end is at the surface it is without tension and the meshes can be both wide open (up to 90 degrees) and slack, which could enable fish trying to escape the possibility of distorting the mesh shape to fit their cross-sectional shape (Herrmann et al. 2016).

FISHSELECT is a framework of methods, tools, and software developed to determine whether 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 estimation of the size selectivity for a certain species by comparing the morphological characteristics of the fish with the shape and size of the mesh. FISHSELECT enables one to simulate both the situation in which the mesh shape cannot be deformed by fish trying to escape through it (a stiff mesh state) and the situation with slack meshes, in which the mesh can be fully deformed (a soft mesh state). Therefore, the FISHSELECT methodology was used to estimate the size selective potential of the diamond-mesh cod end used during the experimental fishing. Applying FISHSELECT in this way requires (1) a morphological model describing the cross sections of importance for size selection of the species and (2) a model describing how and to what extent the fish cross sections can be squeezed when trying to pass through a mesh. The methodology has previously been used to investigate size selectivity for numerous species and fisheries (Frandsen et al. 2010; Herrmann et al. 2012, 2013b, 2016; Krag et al. 2011, 2014; Sistiaga et al. 2011; Tokac et al. 2016). The FISHSELECT models necessary to study Atlantic Cod and Haddock size selectivity in diamond-mesh cod ends were already available through the studies by Herrmann et al. (2009) and Krag et al. (2011) and were adapted to the present study. Unfortunately, no FISHSELECT models are available for Witch Flounder.

Based on the FISHSELECT models for Atlantic Cod and Haddock (Herrmann et al. 2009; Krag et al. 2011), we simulated size selection in stiff diamond meshes with a mesh size identical to that in the cod end used in the experimental fishing. Mesh opening angles between 15 and 90 degrees, in 5-degree increments, were tested to establish the potential size selection in the cod end and its dependence on the opening angle in the meshes. In addition, we simulated potential size selection in slack meshes 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.

Understanding the experimentally obtained size selection based on fish morphology.—Of further interest was whether the experimental size selection data for both Atlantic Cod and Haddock obtained from the sea trials could be understood based on the FISHSELECT simulations described above. Specifically, information on the extent of escapement through slack and undistorted meshes was required. Accordingly, we explored whether 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: (1) stiff diamond meshes with opening angles between 15 and 75 degrees, as could be expected during the collection phase; (2) 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 may be wide open; (3) 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 at the surface, where some of the meshes might be slack; and (4) 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 at the surface, where some of the meshes might be wide open or slack. For each scenario, the combination of mesh opening 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 procedure, we used the selection curves (with confidence intervals and retention lengths) obtained from the analysis of the sea trial data. We then used the simulated retention data for the different mesh openings and states from FISHSELECT. For each of the four scenarios, we estimated the contributions needed from the different retention data to obtain combined selection curves that fitted the experimentally obtained values L05–L95 the best. This procedure is identical to the one used in Herrmann et al. (2013b), which contains detailed information on the technical aspects of the method. The simulation scenarios that were able to reproduce the entire size selection curve accurately based on the experimental fishing enabled us to estimate how much each mesh state contributed to the cod end size selection process, thereby providing the ability to describe how and when the size selection process occurs.

Predicting size selectivity in different diamond-mesh cod ends.—To explore the potential consequences of making design changes to the currently legislated cod end, we simulated the size selection of a number of other mesh sizes using FISHSELECT, following the procedure described above. Based on the level of contribution found for each mesh state for the experimental cod end, we could predict size selection for Danish seining with cod ends of other mesh sizes. Based on this, we assumed that the contribution would be similar for cod ends with other mesh sizes. This procedure is identical to the one used by Krag et al. (2014) to predict size selection for krill *Euphausia superba* in a range of cod ends with varying mesh sizes. In this study, we used the procedure described in Krag et al. (2014) to predict the cod end size selection of Atlantic Cod and Haddock in Danish seining using diamond-mesh cod ends with mesh sizes between 90 and 150 mm in 5-mm increments.

Comparing the predicted cod end size selectivity for Danish seines with that of trawls with similar cod ends.—In Danish 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 of diamond-mesh cod ends when used for Danish seining with the size selectivity of similar cod ends when used in demersal trawling. The predictions made herein for Atlantic Cod and Haddock in Danish seines were compared with previous results for similar cod ends 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 summarized in Madsen (2007) for double-twined diamond-mesh cod ends. For Haddock, we used the model for size selection in demersal trawl cod ends provided in Fryer et al. (2016) to predict size selection in 4-mm double-twined diamond-mesh cod ends with 100 open meshes in the circumference. This specification conforms to the cod end that we used in the Danish seine experiment. Using the model provided by Fryer et al. (2016), we made predictions for cod ends with mesh sizes ranging from 90 to 150 mm in 5-mm increments.

In addition to the selectivity parameter (L50) that we used to compare selectivity in trawls and seines, SR values could have been compared. However, the values for demersal trawls provided in Madsen (2007) and those obtained by the model in Fryer et al. (2016) 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 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 the extent to which differences in SR values are due to differences in selectivity between the two fishing methods as opposed to differences in estimation methods. Since L50 values will not be affected to the same extent by the different estimation methods, we chose to make the comparison based on those values alone.

RESULTS

Size Selection Obtained from Sea Trials

A total of nine valid hauls were carried out during the sea trials. Table 1 summarizes the catch data for Atlantic Cod, Haddock, and Witch Flounder in these hauls. Altogether, lengths were obtained from 7,307 Atlantic Cod, 6,901 Haddock, and 5,462 Witch Flounder, and these form the basis for the size selectivity analysis.

For all three species, the average size selectivity was best described by the DLogit model. This is especially clear when one inspects the relative likelihoods for the other models (Table 2). This result could indicate that size selection in a diamond-mesh cod end involves more than one size selection process when such a cod end is used in Danish seining.

The size selection curves for all three species are described and quantified in Figure 3 and Table 3, respectively. For Haddock, the *P*-value <0.05 could indicate problems in describing the experimental data, but since inspection of the deviance residuals did not show any patterns we considered it a case of overdispersion in the data and are confident in using

TABLE 1. Catch data from individual hauls of three species using Danish seining.

Haul	Length span (cm)	Number recovered in cod end	Number recovered in cover	Sampling rate in cod end	Sampling rate in cover
			Atlantic Cod		
1	15–71	81	270	1.0000	1.0000
2	16–90	155	938	1.0000	0.3007
3	16–112	104	886	1.0000	1.0000
4	12–90	174	527	1.0000	1.0000
5	15–86	322	643	1.0000	0.3093
6	15–110	424	625	1.0000	0.1791
7	17–90	159	777	1.0000	0.8000
8	18–74	80	129	1.0000	1.0000
9	14–85	147	866	1.0000	0.1920
			Haddock		
1	18–52	30	673	1.0000	0.3443
2	16–66	378	683	1.0000	0.1164
3	17–62	72	550	1.0000	1.0000
4	20–57	20	504	1.0000	1.0000
5	19–72	768	663	0.7021	0.1723
6	17–75	361	711	1.0000	0.1384
7	17–62	20	506	1.0000	1.0000
8	19–50	18	121	1.0000	1.0000
9	18–65	201	622	1.0000	0.2928
			Witch Flounder		
1	17–49	774	660	1.0000	0.2589
2	31–46	17	4	1.0000	1.0000
3	29–43	8	4	1.0000	1.0000
4	20–44	718	630	0.7499	0.3419
5	33–43	9	0	1.0000	1.0000
6	29–46	13	1	1.0000	1.0000
7	21–49	632	702	1.0000	0.6530
8	19–49	630	628	0.5568	0.4600
9	29–45	31	1	1.0000	1.0000

TABLE 2. AIC values obtained for the five different models fitted to the experimental selectivity data. Models with the lowest AIC values are denoted by bold italics. The relative likelihood denotes how probable the model is relative to the model with the lowest AIC.

Species	Model	AIC value	Relative likelihood (%)
Atlantic Cod	Logit	6,322.30	8.16×10^{-13}
	Probit	6,266.67	0.98
	Gompertz	6,281.87	4.91×10^{-4}
	Richard	6,264.26	3.27
	DLogit	***6,257.42***	***100.00***
Haddock	Logit	7,638.62	3.46×10^{-66}
	Probit	7,510.10	2.80×10^{-38}
	Gompertz	7,335.40	2.41
	Richard	7,350.32	1.39×10^{-3}
	DLogit	***7,327.95***	***100.00***
Witch Flounder	Logit	9,132.42	4.44×10^{-25}
	Probit	9,198.86	1.66×10^{-39}
	Gompertz	9,520.37	2.54×10^{-109}
	Richard	9,022.72	0.29
	DLogit	***9,011.06***	***100.00***

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 Figure 3.

Figure 3 and Table 3 demonstrate very low retention probability at the minimum conservation reference sizes (MCRSs; previously known as the minimum landing sizes [MLSs]) of 30 and 27 cm for Atlantic Cod and Haddock in this fishery (EU Regulation 850/98). There is no MLS for Witch Flounder in this fishery; however, there is a minimum market size of approximately 27 cm. The results demonstrate a low retention probability for Witch Flounder up to 34 cm (Figure 3; Table 3). Combined with the fact that most of the fish caught in the fished population are below 34 cm in length, this leads to an inefficient fishery for Witch Flounder with the legislated cod end, as tested in the sea trials.

Simulating the Selective Potential of the Diamond-Mesh Cod End Based on Fish Morphology

The potential size selection curves using the experimental cod end for Atlantic Cod and Haddock based on different mesh situations (opening angle and mesh state) are depicted in Figure 4. The fish lengths for which full retention is obtained (~0.95) seem to match the fish lengths that are predicted to occur for slack-mesh selection for both Atlantic Cod and Haddock (Figure 4). Furthermore, the 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 Atlantic Cod and Haddock.

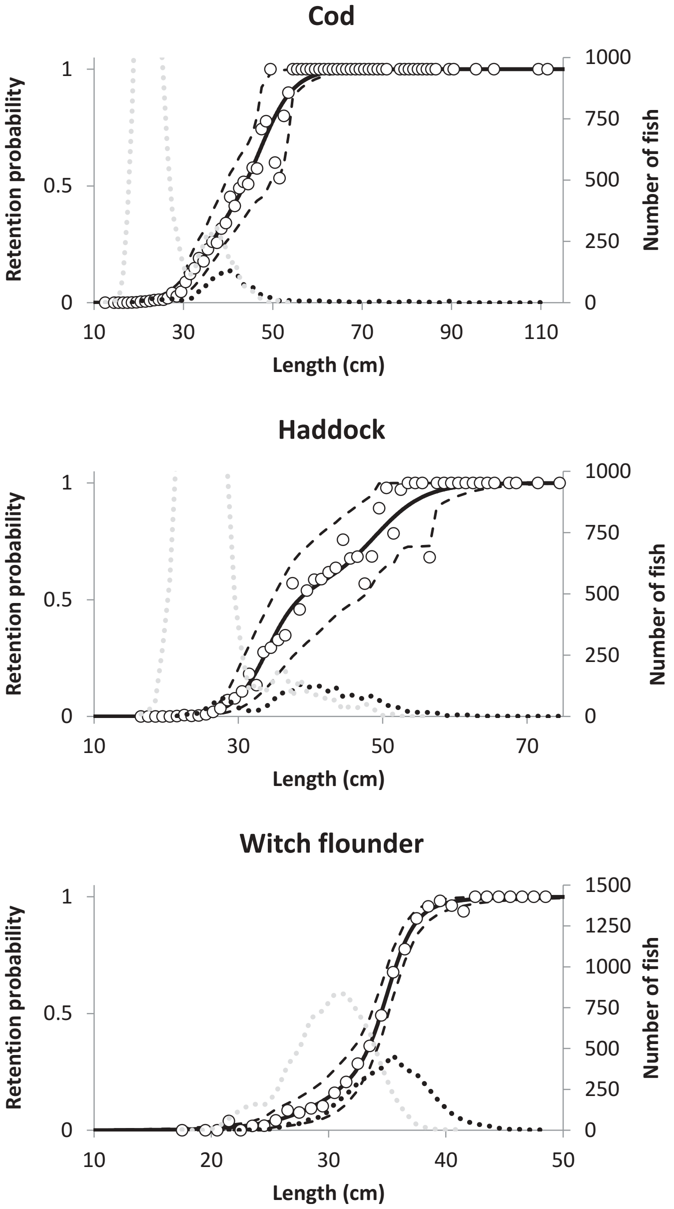

FIGURE 3. Size selection curves (probability of retention in the cod end or cover as a function of fish length) for three species. Circles represent the experimental retention rates; black lines represent the modelled size selections; dashed lines represent the 95% confidence limits for the estimated size selection curves; black dotted lines represent the population retained in the cod end; and gray dotted lines represent the populations collected in the cod end cover.

Understanding the Size Selection Process in the Experimental Diamond-Mesh Cod End

Following the indications obtained in Figure 4 regarding the ability to reproduce the experimentally obtained size selection curves for Atlantic Cod and Haddock based on FISHSELECT simulations, we applied the procedure described in the Methods

TABLE 3. Results from fitting the double logistic model to the experimental data for Atlantic Cod, Haddock, and Witch Flounder. See text for definitions of parameters. The values in parentheses are 95% confidence intervals.

Parameter[a]	Atlantic Cod	Haddock	Witch Flounder
C_1	0.65 (0.24–0.92)	0.46 (0.18–0.83)	0.64 (0.32–0.95)
$L50_1$	47.49 (42.73–53.96)	48.93 (40.76–57.04)	35.06 (34.24–37.69)
SR_1	8.20 (0.10–10.94)	7.64 (0.10–10.03)	2.46 (1.25–3.68)
$L50_2$	34.63 (29.99–39.80)	33.92 (29.49–38.65)	31.49 (24.47–34.50)
SR_2	6.57 (0.10–9.56)	4.91 (2.08–7.07)	6.58 (0.10–9.76)
L05	28.96 (26.51–31.27)	28.72 (27.05–31.07)	26.04 (24.22–29.96)
L10	31.52 (29.42–33.87)	30.52 (28.33–33.16)	28.58 (25.65–31.49)
L15	33.29 (30.64–36.10)	31.69 (29.19–34.62)	30.23 (27.67–32.33)
L20	34.79 (31.68–37.86)	32.63 (29.86–35.84)	31.41 (29.28–32.95)
L25	36.22 (32.96–39.68)	33.46 (30.53–37.26)	32.26 (30.44–33.45)
L30	37.68 (34.26–41.26)	34.27 (31.19–38.98)	32.89 (31.37–33.85)
L35	39.20 (35.70–42.74)	35.08 (31.94–40.90)	33.38 (32.23–34.25)
L40	40.73 (36.97–44.64)	35.98 (32.59–42.67)	33.79 (32.80–34.57)
L45	42.20 (38.14–47.23)	37.02 (33.55–44.35)	34.15 (33.28–34.88)
L50	43.56 (39.41–48.69)	38.38 (34.34–46.91)	34.48 (33.67–35.16)
L55	44.79 (40.64–51.87)	40.32 (35.04–48.38)	34.79 (34.03–35.55)
L60	45.95 (42.14–52.84)	42.76 (36.01–49.42)	35.09 (34.36–35.76)
L65	47.06 (43.49–53.42)	44.93 (37.09–52.27)	35.40 (34.69–36.07)
L70	48.17 (44.86–53.50)	46.71 (38.39–52.92)	35.72 (35.00–36.42)
L75	49.33 (45.68–53.56)	48.28 (40.42–56.95)	36.07 (35.31–36.80)
L80	50.58 (46.39–53.60)	49.89 (42.79–57.00)	36.46 (35.71–37.26)
L85	52.03 (46.62–53.77)	51.41 (44.69–57.04)	36.95 (36.17–37.87)
L90	53.89 (47.12–55.29)	53.35 (46.61–57.49)	37.62 (36.76–38.86)
L95	56.80 (47.96–58.59)	56.21 (48.54–60.79)	38.82 (37.75–41.04)
P-value	0.9991	0.0103	0.7377
Deviance	40.87	74.79	21.08
df	73	49	26

[a] Measured in centimeters except for C_1 and summary statistics.

to investigate this in more detail. This was investigated for each of the four scenarios (Figure 5).

It is evident that the first two scenarios were not able to reproduce the experimentally obtained size selection curves for either Atlantic Cod or Haddock since part of the simulated curves are outside the confidence limits for the experimental curve (Figure 5). In scenario 3, part of the simulated size selection curve for Atlantic Cod was still outside the confidence limits for the experimental curve, though the simulated curve for Haddock reflected the experimental curve quite well. However, the simulated curves in scenario 4 accurately reproduced the experimentally obtained size selection for both Atlantic Cod and Haddock. Based on these results, it is highly likely that slack meshes play an important role in size selection in diamond-mesh cod ends in Danish seining. Specifically, it is likely that the mesh state conditions in scenario 4 are the most representative of the Danish seine fishing process and that further investigations should be 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 cod end is at the surface (Table 4). If we assume that the widest open meshes (opening angle >75 degrees) only occur at the surface, the results in Table 4 imply that 46% and 34% of Atlantic 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 Figure 5).

Predicting Size Selectivity in Different Diamond-Mesh Cod Ends

The predictions for Atlantic Cod and Haddock size selection in cod ends with alternative mesh sizes can be used to

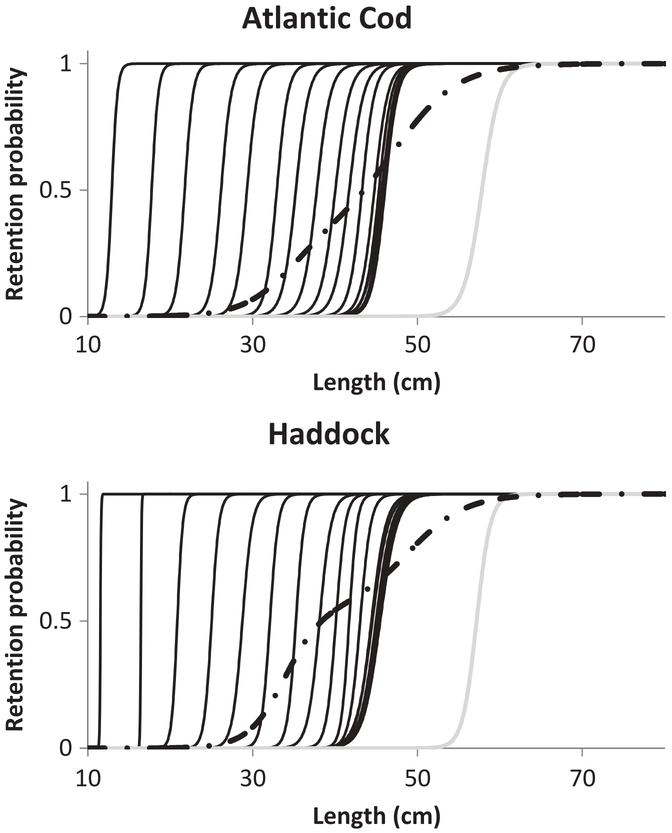

FIGURE 4. Experimental size selection curves (dotted–dashed lines) and FISHSELECT predicted curves for different mesh states; black lines depict stiff mesh states with angles of the opening ranging from 15 to 90 degrees (left to right) and a soft mesh state (gray lines).

TABLE 4. Estimated contributions to catch for the different mesh states. The simulations were based on (1) a stiff mesh state with the angle of the opening (OA) ranging from 15 to 90 degrees and (2) a soft mesh state.

	Contribution (%)	
Mesh state mode	Atlantic 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

estimate the consequences if a cod end of a different mesh size were used in the fishery (Figure 6; Table 5). Such an objective could be motivated based on the poor retention efficiency of the targeted Witch Flounder sizes (Figure 3). If we attempt to match the MCRS for Atlantic Cod and Haddock (30 and 27 cm, respectively) with the L25 values for the cod end size selection, as suggested by Reeves et al. (1992), we predict that it would be appropriate to reduce the cod end mesh size to 105 mm (Table 5).

Comparing the Danish Seine Cod End Size Selectivity with That of Trawls

The predicted cod end size selectivity for Danish seine cod ends of different mesh sizes (Figure 6; Table 5) were compared with the size selectivity in similar cod ends used in demersal trawl fisheries following the procedure described in the Methods. Figure 7 summarises the results of this comparison.

From Figure 7 it is clear that the predicted L50 values for the cod end size selectivity of Atlantic Cod are generally higher for Danish seining than for demersal trawling. For Haddock, however, the L50 values obtained for the two different fishing processes seem to match nearly perfectly across the entire range of cod end mesh sizes investigated.

DISCUSSION

In this study we used the covered cod end method to investigate the size selectivity of a 120-mm diamond-mesh cod end in the Danish seine fishery for Atlantic Cod, Haddock, and Witch Flounder. Selectivity for all three species was best described by the double logistic model, indicating that more than one process affects cod end size selectivity. This dual-selectivity pattern for a diamond-mesh cod end is different from that typically observed with similar cod ends 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 whether the double logistic model would have been better at describing their diamond-mesh cod end size selectivity data than the single logistic model they applied. Therefore, we cannot definitively rule out that a similar double logistic size selection pattern could occur in demersal trawling using diamond-mesh cod ends. Based on this, we can only speculate on the reason for the double logistic size selection that we observed for the Danish seine fishing and not about size selection in a similar cod end when used in a demersal trawl fishery.

The experimental fishing was conducted using a cover with kites without supporting hoops. Such covers can lead to masking

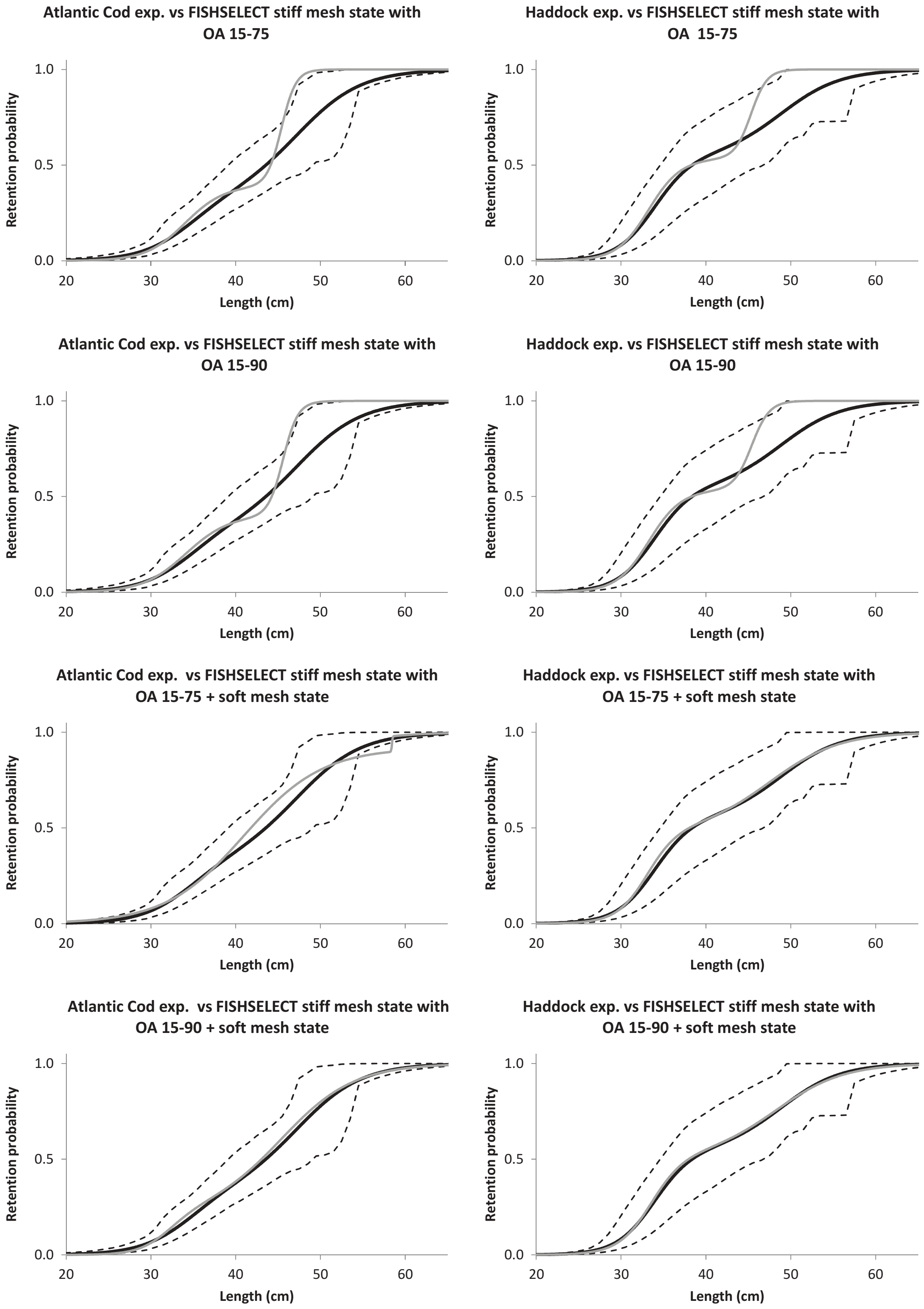

FIGURE 5. Experimental size selection curves (solid black lines) with confidence limits (dotted lines) versus best-fit FISHSELECT simulations (gray lines) under four different scenarios: (1) a stiff mesh state with mesh opening angles (OAs) in the range 15–75 degrees (first row); (2) a stiff mesh state with OAs in the range 15–90 degrees (second row); (3) a stiff mesh state with OAs in the range 15–75 degrees and a soft mesh state (third row); and (4) a stiff mesh state with OAs in the range 15–90 degrees and a soft mesh state (fourth row).

TABLE 5. FISHSELECT predictions of cod end size selection using the mesh state contributions estimated for the experimental fishing trials (Table 4). The abbreviations L05, L25, L50, L75, and L95 denote the lengths (cm) of fish predicted to have 5, 25, 50, 75, and 95% probabilities of being retained by the cod end.

	Atlantic Cod					Haddock				
Mesh size (mm)	L05	L25	L50	L75	L95	L05	L25	L50	L75	L95
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

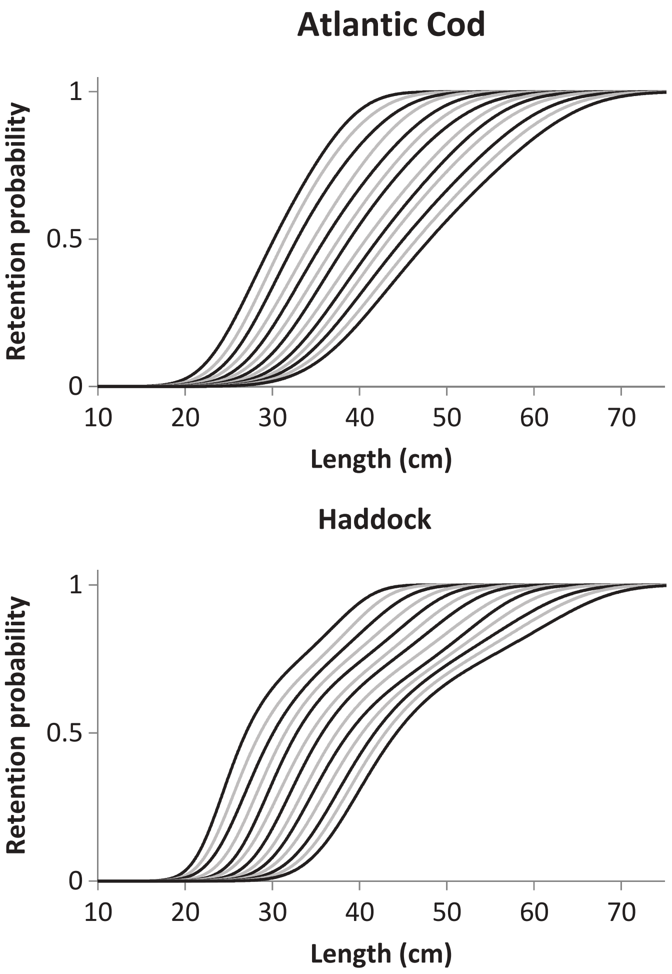

FIGURE 6. Prediction of size selection in cod ends with mesh sizes between 90 and 150 mm. The black lines represent mesh sizes of 90, 100, 110, 120, 130, 140, and 150 mm (left to right), the gray lines mesh sizes of 95, 105, 115, 125, 135, and 145 mm.

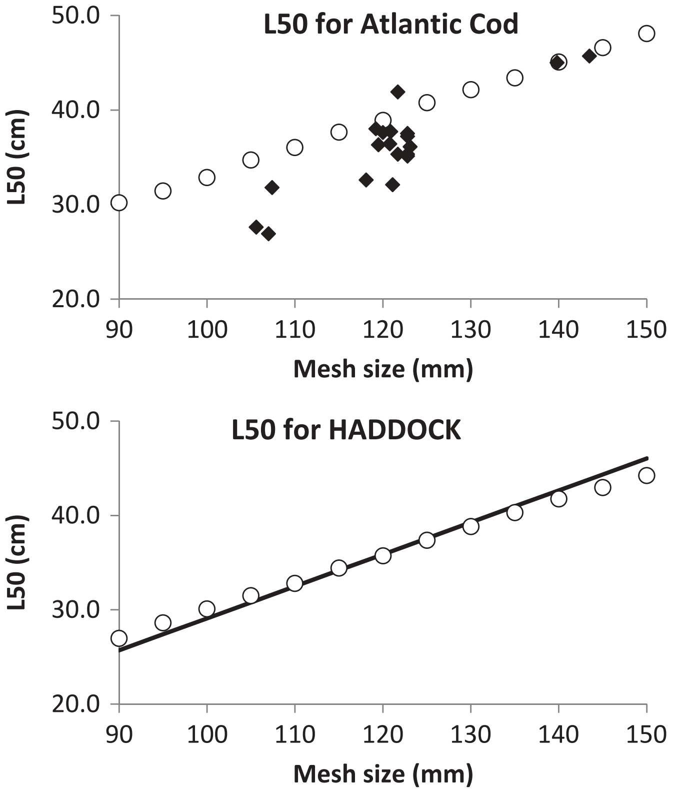

FIGURE 7. Comparisons of the FISHSELECT-based predictions for Danish seine cod end size selectivity (circles) with historical results for trawl size selectivity in similar cod ends. The comparisons are in terms of L50 for cod ends with mesh sizes of 90 to 150 mm. For Atlantic Cod (top panel), the comparisons are with the 4-mm double-twined cod end selectivity results (diamonds) summarized in Madsen (2007). For Haddock, the comparisons are with the results (black line) obtained by using the model in Fryer et al. (2016) for cod ends with 4-mm double-twined and 100 open meshes in the circumference.

between the cod end and cover, thus 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 cod end size selection that we obtained requires that there be wide-open meshes, another indication that cod end size selection would have been biased by a masking cover. Additionally, the comparison made with trawl selectivity results for similar cod ends does not indicate that our experimental seine results were biased due to masking. Based on this, we assume that our results have not been affected by cover masking, although we cannot entirely rule it out.

The size selectivity estimates that we obtained are based on experimental hauls carried out by a commercial fishing vessel following normal commercial fishing practices. The only exception was the additional handling of the cover during the final part of the fishing operation. Therefore, we assume that the estimated size selection is representative of the size selectivity of the cod end in commercial use. However, caution should be taken since our fishing trial was based on only 9 hauls and these hauls reflect the average size selection of the cod end when employed by the commercial fleet. Furthermore, due to the small number of hauls the amount of fish caught was limited, which leads to uncertainties in the estimated size selection curves. However, such uncertainties are reflected in the confidence bands around the size selection curves and the parameters that are provided along with the results. Therefore, as long as these confidence bands are considered when drawing conclusions, the limited number of fish in this study should not be a problem.

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

With towed fishing gears, late escapement through cod end meshes is a known phenomenon, as various demersal trawl selectivity studies have reported (Grimaldo et al. 2009; Herrmann et al. 2013a). In particular, Herrmann et al. (2013a) reported that about 30% of the Atlantic Cod in the cod end made their first escape attempt after the haulback operation had begun. Because the fish in a Danish seine are expected to have spent less time in contact with the gear than those 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 or slack-mesh escapement during the last stages of the fishing process, especially at the surface, could therefore play an important role in the size selection process when diamond-mesh cod ends are used for Danish seining. Since the swim bladders of physoclistous fishes like Atlantic Cod and Haddock cannot adapt instantaneously to changes in hydrostatic pressure, these species might suffer considerable trauma during the haulback process. Consequently, the survival rate is expected to be lower if fish escape during the later stages of fishing (Herrmann et al. 2013a).

By using fish morphology and the computer-based simulation method FISHSELECT, we investigated the potential for size selection of Atlantic Cod and Haddock in diamond-mesh cod ends in Danish seining. In this way, we were able to estimate and predict selectivity for Atlantic Cod and Haddock with different mesh sizes. This is the first time that this has been attempted, and it could be a useful tool for predicting the size selectivity of other net configurations and optimizing 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 Atlantic Cod and Haddock in this fishery, the results obtained show that the cod end used in the sea trials (mesh size, 129 mm) results in a very small retention probability for undersized fish for both species (Figure 3). Although there is no MLS for Witch Flounder in this fishery, there is a minimum market size of approximately 27 cm. The results demonstrate a low retention probability for Witch Flounder up to 34 cm (Figure 3; Table 3). Combined with the fact that most of the fish caught in the fished population are below 34 cm, this leads to an inefficient fishery for Witch Flounder with the legislated cod end, as determined in the sea trials. For Witch Flounder, this would support the use of a smaller cod end mesh size than legally allowed.

Danish seining is quite different from trawling. During trawling, the trawl is towed at the same speed over the seabed and 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 widely spread in the setting phase to completely closed at the end of the collecting and closing phases. However, the netting used for constructing trawls and seines, and to some extent the construction of the gears, is relative similar. In Danish and EU waters, the gear regulations pertaining to seining are the same as those for trawling. Therefore, we compared our predicted cod end size selectivity with the size selectivity of similar cod ends used for demersal trawling. For Atlantic Cod, this comparison indicates that the size selection is lower for demersal trawling since most L50 values were lower for such trawling. For Haddock, the L50 values obtained were nearly identical for the two fishing processes. The results of these comparisons therefore could mean that the difference in cod end selectivity between Danish seining and demersal trawling is species dependent.

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