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Predicting size selection of cod (*Gadus morhua*) in square mesh codends for demersal seining: A simulation-based approach

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ABSTRACT

Demersal seining is an important fishing method to harvest cod (*Gadus morhua*) in Norwegian fisheries. Knowledge about size selectivity of cod in this type of fishing gear is therefore of importance for managing the exploitation of cod resources. However, limited data exist on the size selection of cod in the square mesh codends mostly applied in this fishery. By using knowledge of fish morphology and the computer-based simulation method FISHSELECT, we investigated the potential for size selection of cod in square mesh codends for demersal seining. We were able to explain and understand existing experimental selectivity results and predict the effect of design changes in the codend. The results showed that the currently applied codend designs are adequate to ensure low catches of cod below the minimum size for this fishery, but they also indicated that a considerable part of the size selection may occur through slack meshes. Thus, it is likely that part of the codend mesh selection may occur when the gear is at the surface.

1. Introduction

Cod (*Gadus morhua*) is the most important species in the Norwegian white fish fishery when measured in both tonnes landed and in value (www.råfisklaget.no). About 20% of the Norwegian cod quota is caught by demersal seining, i.e. the Norwegian style fly dragging of a seine net. Most of the Norwegian demersal seine fishing targeting cod is conducted north of 64°N. This fishing method has been increasingly favoured over the last decades at the expense of e.g. gillnetting and longlining. Many of the seine vessels operate in coastal areas, including fjords, while larger vessels also target fish in deeper waters. Especially within the last 15–20 years, vessel size, main engine power and gear size has increased (Digre et al., 2010). Studies on bottom trawls (Engås and Godø, 1989; Ingolfsson and Jørgensen, 2006) showed that a relatively large fraction of small and undersized cod, haddock (*Melanogrammus aeglefinus*) and saithe (*Pollachius virens*) escape below the fishing line. Modern demersal seines towed by larger vessels are in the northern fisheries usually equipped with a weighted netting skirt to prevent escapement below the ordinary fishing line. Therefore, these seine nets are likely to experience entry of more small fish than before, making the size selection in the codend increasingly important.

Demersal seining in Norwegian fishery targeting cod and other demersal fish is practiced by deploying two long seine ropes connected to the wing tips of the seine net in one end and the winches of the vessel on the other end. The length of the seine ropes is restricted to 2000 m each, when fishing inside the four nautical mile limit. The seine net has a typical headline and fishing line length of 123 m and a maximum circumference of 156 m stretched in the mouth when used inside the four nautical mile limit. The seine ropes, made of up to Ø60 mm combination rope (polyethylene with a steel core) weighting more than 2 kg/m, are placed on the seabed in a quadrilateral pattern in order to encircle the targeted fish (Sainsbury, 1996). Once the ropes and the net have reached the seabed the vessel starts moving forward at a speed of 1–1.5 knots. As a result of the vessel movement the seine ropes are moving towards each other and herd the fish into the centre of the encircled area; the collecting phase. At some instance the net will start moving along the seabed when pulled by the seine ropes. When the distance between the ropes has decreased to a certain level the rope drums are activated in order to close the wings fast and to force the last fraction of collected fish into the codend; the closing

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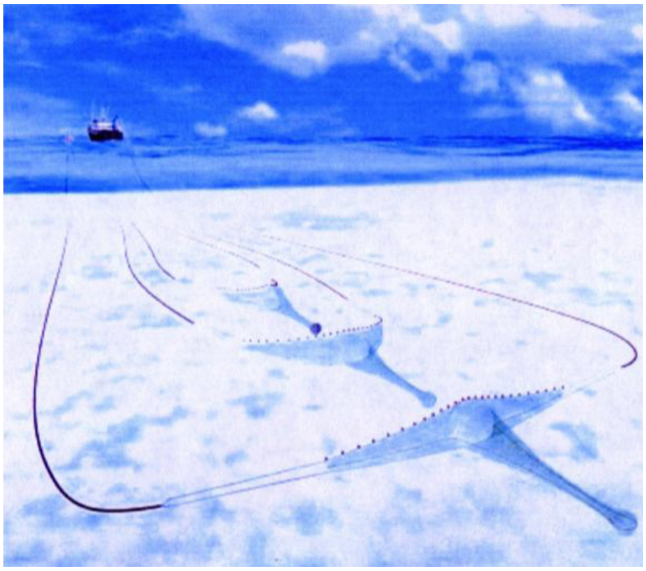

Fig. 1. Principles of a demersal seine in a fly dragging operation (not scaled), showing the collecting and closing phases. (The full process in the Norwegian operation is: drop a drift buoy attached to the start of first (port) rope, deployment of port rope, deployment of the seine net (and stretch out wing ends), deployment of the starboard rope, returning to drift buoy (start point), pick up buoy and first rope, adjust rope lengths and start the fishing operation). ©Crown copyright 2004.

phase. This fly dragging principle of demersal seining is shown in Fig. 1.

Recent underwater observations (conducted by the sixth author) has confirmed that fish starts entering the funnel of the net as soon as the seine net is sat in motion during the collecting phase, but the majority of those fish herded by the ropes enters the belly and codend sections in the latter stage of the closing phase. The actual fishing time, i.e. the collecting and closing phase, may be as short as 15 min. The good initial physical condition of seine net caught fish is often explained by the relatively low towing speed and short fishing time. For this reason, the demersal seine is the commonly used gear to catch live cod for capture based aquaculture (Dreyer at al., 2008).

The size of seine net, total lengths and dimensions of the seine ropes vary depending on the size of the vessel. Mandatory codends used in fishing areas north of 64°N must have a minimum mesh size of 130 mm or 125 mm depending on whether they are constructed in diamond meshes or square meshes. The regulations require that only the 125 mm square mesh codend should be used in specific areas to protect the undersized haddock along the coast (Norwegian Fisheries Directorate, 2010). Most of the demersal seine fishery north of 64°N is in fact carried out using this type of codend. The reason for demanding the use of a square mesh codend for this fishery is that this type of codend increases the potential escaping area for the fish compared to an ordinary diamond mesh codend. Due to the longitudinal tensions, the meshes in a diamond mesh codend have small openness except for the area just in front of the catch bulk (Herrmann et al., 2007a). Whereas, in a square mesh codend the tension while fishing is distributed along the mesh bars enabling these meshes to keep open and stable along the whole codend (Robertson and Stewart, 1988; Krag et al., 2011; Herrmann et al., 2007a). Since the fish spends little time in the back part of the codend while the gear is at the seabed it is considered of particular importance for demersal seining that undersized fish have a fair chance to escape along the entire codend. For the final phase of the fishing operation the codend is brought next to the vessel and the catch is then either pumped or lifted on board in batches of approximately 500–800 kg in a procedure known as "sacking". When "sacking", an adequate portion of fish is released from the aft of the square mesh codend into an attached short diamond mesh section, termed the fish-lift. The entrance to the fish-lift is by regulation closed during fishing and only opens during the sacking operations. The fish-lift may contribute to the size selection during the last stage of the fishing operation (Fig. 2). On vessels using a pump to bring the catch on board, a hose is connected to the

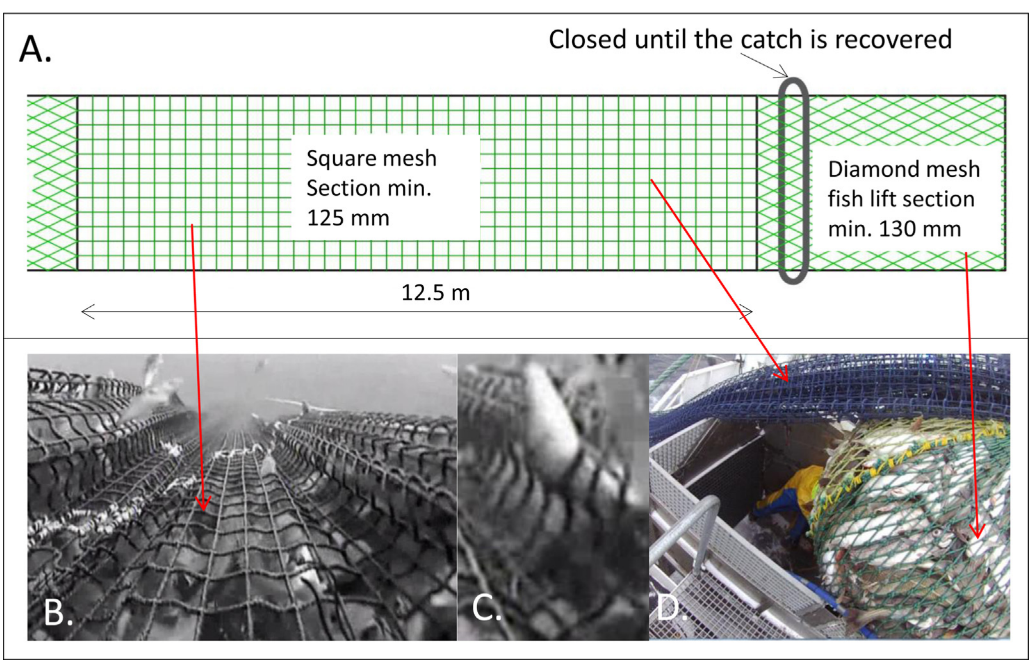

Fig. 2. Square mesh codend used in commercial demersal seine fishing to target cod. (A) Outline of the codend design with a main section of 125 mm (minimum mesh size) and a diamond mesh section of 130 mm (minimum mesh size) that is used as fish-lift. A binding strap ensures that fish cannot enter the fish-lift section before the process of lifting the fish on board has begun. (B) Snapshot from an underwater recording showing both fully open and partly open square meshes occurring during this part of the fishing process. (C) Snapshot from an underwater recording showing a fish escaping through a codend square mesh while it bends outwards the tensionless circumferential mesh bars. (D) Fish-lift and aft end of the square mesh section of the codend during the "sacking" operation.

Fig. 3. Collage of photos taken during the "sacking" operation. The photos show how the fish-lift is operated by releasing part of the catch into it while the remaining part of the catch is kept in the square mesh section of the codend at the surface. Several of the photos show that the catch remaining in the square mesh section is surrounded by tensionless square meshes. Further, there is evidence that escapement at the surface does occur.

aft end of the codend. For practical reasons only portions up to 1000–1500 kg are pumped into the sorting and processing area at a time. Therefore, independent on whether the catch is pumped or sacked on board the remaining catch will spend substantial time at the surface surrounded by tensionless meshes.

Depending on the catch volume, the number of sacks necessary to take the catch onboard can be high, especially when catches reach 20 tonnes or more. During the sacking operations the part of the square mesh codend holding the rest of the catch bulk remains at the surface with slack square meshes. The fish in a demersal seine codend does not normally experience fatigue because they are not forced to swim for a long period in their attempt to escape the gear, as compared to e.g. the fish captured by a trawl. Therefore, it is likely that the fish in general has the sufficient energy to attempt escaping at the surface (Fig. 3).

The minimum target size for cod in Norway north of 64°N is currently 44 cm. Thus the gear used to harvest cod in these waters should ensure low risk to retain cod below the minimum size, especially if small cod would be highly represented on the fishing grounds. Therefore it is important to have quantitative information on the size selectivity of cod in the square mesh codends commonly applied in the Norwegian demersal seine fishery. It is relevant to know to what extent the design or the operational conditions of the gear may affect the size selectivity of cod in these codends. It is unclear to which extent surface selection of cod may contribute to the overall size selection in the codend. In particular, it has not been investigated to which extent the slack meshes at the surface represent an escape possibility for bigger cod that did not have a chance to escape at depth or during haul back, when the codend meshes hold some tension due to hydrodynamic forces. However, limited published information exists regarding size selection of cod in square mesh codends of relevance to the Norwegian demersal seine fishery. In fact, we only found one study on the size selection of cod in a square mesh codend with a mesh size of 120 mm (Isaksen and Larsen, 1988).

Because of the knowledge gaps identified above, the present study investigates which codend mesh states of the currently compulsory 125 mm square mesh would ensure the release of undersized cod.

Size selectivity studies for active fishing gears in Norwegian waters have to a great extent been conducted at sea as a direct co-operation with the industry following a trial and error procedure and solely based on experimental fishing (Kvamme and Isaksen, 2004; Jørgensen et al., 2006). Apart from being costly, time consuming and experimentally complicated for demersal seining, sea trials are limited with regard to the amount of different gear designs that can be tested. Considering these challenges we applied the FISHSELECT methodology (Herrmann et al., 2009) to investigate and predict the size selective properties of different square mesh codends relevant to the Norwegian demersal seine fishery targeting cod. Further, we try to explain and understand the limited experimental size selectivity results available from this fishery.

2. Materials and methods

2.1. The FISHSELECT methodology and basic cod data

FISHSELECT is a framework of methods, tools, and software developed to determine if a fish is able to penetrate a certain mesh in an active fishing gear. Through computer simulation, 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. The methodology is thoroughly described in Herrmann et al. (2009) for a case study on trawl selectivity of cod. It has since been applied to investigate size selectivity of haddock in the North Sea (Krag et al., 2011), nephrops (*Nephrops norvegicus*) (Frandsen et al., 2010) and krill (*Euphausia superba*) (Krag et al., 2014). The FISHSELECT methodology has also been applied to study and predict the size selectivity of different species in Norwegian bottom trawl fishery north of 64°: cod and haddock (Sistiaga et al., 2011); redfish (*Sebastes* spp.) (Herrmann et al., 2012, 2013d); greenland halibut (*Reinhardtius hippoglossoides*) (Herrmann et al., 2013b). The morphological data and basic FISHSELECT models necessary to study cod size selectivity in the Norwegian demersal seine square mesh codends was already available through the bottom trawl study by Sistiaga et al. (2011), and was adapted to this study.

2.2. Mesh penetration modelling

Since square meshes are especially relevant for demersal seine codends (Fig. 2), it is particularly important to find an accurate way of modelling the size selectivity of cod through this type of codend netting. The model needs to consider both the shape and the potential distortion of the mesh as well as the compression of the fish when it tries to escape. In this study, we used the cross section compression model determined by Sistiaga et al. (2011) for the North-east Arctic cod. A cross section compression model defines how and to what extent the cross section of a fish of a certain length can be compressed when the fish attempts to escape through a mesh. Regarding the shape and physical behaviour of the codend meshes we need to consider two different situations: (i) during the fishing process the codend is towed and therefore only tensionless circumferential mesh bars can potentially be distorted by a cod trying to escape through it; (ii) during the sacking operations the codend meshes hold no tension and a cod trying to escape through a mesh can fully distort the mesh shape. To model the meshes in situation (i) Krag et al. (2011) developed a model for round fish species which was based on approximating the shape of the distorted mesh by a hexagonal shape. This model assumes that if the square mesh codend is not fully circumferentially opened, meaning that the distance between the longitudinal mesh bars is shorter than the length of the mesh bars, a round fish attempting

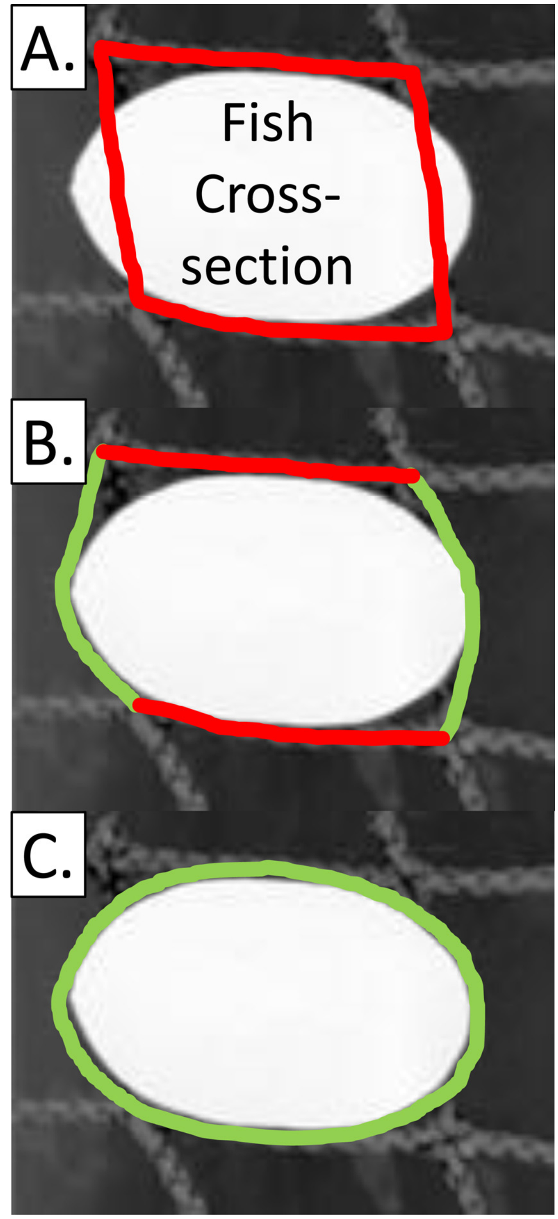

Fig. 4. The three different mesh state scenarios considered to simulate size selectivity in the square meshes of demersal seine codends. (A) "stiff mesh state" where we assume that cod cannot deform the mesh in any way. (B) "semi-soft mesh state" where we assume that cod can deform tensionless mesh bars outwards in a way that they become hexagonal like meshes. (C) "Soft mesh state" where we assume that cod can deform the mesh shape fully to take shape after its own cross section.

to escape can distort the mesh into a hexagonal-like shape. The meshes in this state are defined to be in a semi-soft state (Fig. 4B). In situation (ii), the slack mesh scenario, it is assumed that a cod trying to escape can fully distort the shape of the mesh in the escape attempt. This state is referred to as the soft mesh state (Fig 4C). Further, we also considered the possibility of fish not being able to distort the mesh bars at all, not even tensionless bars. In this situation the partly open square meshes can, in regard to size selection, be modelled as rectangular meshes. This mesh scenario is referred to as the stiff mesh state (Fig. 4A). Fig. 4 illustrates the three mesh states which are considered for the square meshes in the FISHSELECT simulations of the size selectivity through the demersal seine codends.

For the diamond meshes in the fish-lift (Fig. 2A) we considered the scenario of cod being able to distort the meshes fully (the soft mesh state) and the scenario of cod not being able to distort the meshes at all (the stiff mesh state).

For the square meshes we defined mesh openness as the circumferential distance between mesh bars to the mesh bar length. Thus, a fully open square mesh where the bars would be fully stretched would have an openness of 100%. While a square mesh where the circumferential distance between the two mesh bars was 0.7 of the length of the mesh bars would have an openness of 70%. For the diamond meshes, the openness was defined as the ratio between the circumferential distance between the knots and the axial distance between the other two knots in the mesh. Thus, a diamond having an opening angle of 90° would have an openness of 100%. While a similar mesh with an opening angle of 53° would have an openness of 50%.

In this study, we considered the semi-soft and the stiff mesh state models for simulating the size selection of cod through square meshes with tension in the mesh bars along the codend. Thus, it is necessary to investigate if these partly opened square meshes are present in the codend during parts of the fishing process where fish actually attempts to escape. In particular it is important to assess how closed the meshes might be since this sets limits for the hexagonal-like and rectangular-like shapes to be considered while a cod attempts to escape. Underwater recordings (Fig. 2B) showed not only that partially open meshes are present in the codend but also that there are meshes with openness down to ≈50%. Thus, in the simulations carried out we considered mesh openness between 50% and 100%.

The slack mesh selectivity (soft mesh state) can potentially occur during any of the phases of the fishing process, especially during the sacking operation (Fig. 3). It can be simulated using the soft mesh penetration model implemented in the FISHSELECT software (Fig. 4; Herrmann et al., 2009 for further details).

2.3. Simulating the selective potential of the square mesh codend

To examine the size selective potential in the currently legislated square mesh codend (Fig. 2) we simulated the size selection of cod through the codend meshes with openness from 50% to 100% using FISHSELECT and the cod morphology data from Sistiaga et al. (2011). For the 125 mm square meshes we considered the three different mesh state scenarios: soft, semi-soft and stiff. For the 130 mm diamond meshes in the fish-lift we considered both the soft and the stiff mesh states. The simulations were conducted following the standard FISHSELECT procedure (see Herrmann et al. (2009) for details). First, based on the morphology data reported in Sistiaga et al. (2011), which describe the cross sectional shape and size of cod with different length, we generated a virtual population of 5000 cod with lengths uniformly distributed between 20 and 100 cm. Then, we defined different hexagonal shaped meshes by using the FISHSELECT software tool. These meshes represent 125 mm square meshes in a semi-soft state with openness between 50 and 100%. Similarly, we defined different rectangular meshes representing partly open square meshes in the stiff mesh state. For the soft mesh state only one 125 mm mesh was generated since the fish for this scenario is assumed to be able to distort the mesh shape fully. In addition to the square meshes, different diamond meshes of 130 mm with different openness (50–100%) were generated to enable simulating the stiff mesh state in the fish-lift. Finally, a single 130 mm mesh was generated to represent the soft mesh state scenario for the fish-lift.

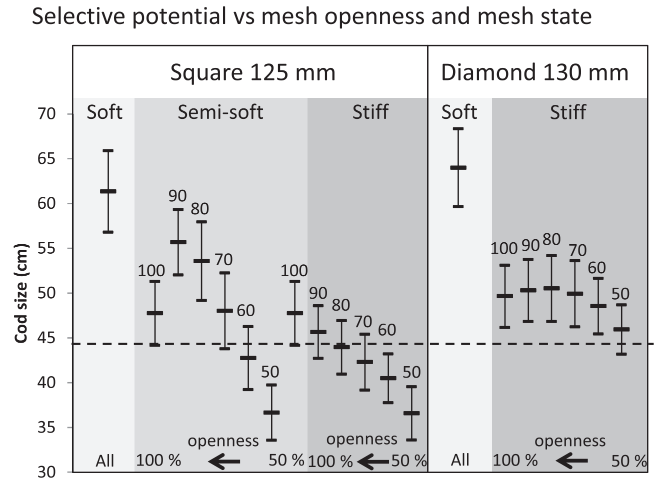

Fig. 5. Selective potential for both the 125 mm square mesh section and the 130 mm diamond mesh fish-lift section in the legislated demersal seine codend (Fig. 2). The vertical bars represent the selective range for each situation. The lower cross bar represents the 5% retention probability (L05), the middle cross bar the 50% retention probability (L50) and the top cross bar the 95% retention probability (L95). The label above each vertical bar shows the mesh openness, which is also represented on the *x*-axis of the plot. The *y*-axis represents the length of the fish and the horizontal stippled line illustrates the minimum target size for cod (44 cm). For the square mesh section all three mesh states are considered; soft, semi-soft and stiff states. For the fish-lift we considered both the soft and stiff mesh state scenarios.

Table 1
Results from fitting a Richard selection curve to the selection data collected by Isaksen and Larsen (1988) for cod. The values in brackets show the 95% confidence limits. L50, SR and δ are the selection parameters for the Richard curve (see Wileman et al., 1996 or Wienbeck et al., 2014 for details). SP is the split parameter for the entry sharing of fish between the two legs of the trouser gear (see Herrmann et. al, 2007b for details). DOF are the degree of freedom. L05... L95 denote the length of cod having 5%... 95% of probability of being retained.

L50 (cm)	57.33 (54.52–85.65)
SR (cm)	6.61 (5.37–32.43)
$1/\delta$	0.0231 (0.0193–100)
SP	0.500 (0.4044–0.8603)
P-Value	0.5889
Deviance	3.73
DOF	5
L05 (cm)	43.48 (39.44–53.66)
L10 (cm)	47.65 (44.14–59.44)
L15 (cm)	50.09 (46.88–63.69)
L20 (cm)	51.82 (48.69–66.80)
L25 (cm)	53.16 (50.09–70.31)
L30 (cm)	54.26 (51.30–73.61)
L35 (cm)	55.18 (52.34–76.61)
L40 (cm)	55.99 (53.18–79.57)
L45 (cm)	56.70 (53.85–82.57)
L55 (cm)	57.90 (55.08–88.87)
L60 (cm)	58.43 (55.61–92.29)
L65 (cm)	58.91 (56.11–96.15)
L70 (cm)	59.35 (56.58–100.56)
L75 (cm)	59.77 (57.10–105.58)
L80 (cm)	60.16 (57.49–110.38)
L85 (cm)	60.52 (57.83–116.91)
L90 (cm)	60.87 (58.36–123.78)
L95 (cm)	61.21 (58.71–137.68)

In the next step of the FISHSELECT procedure, we simulated whether or not each of the 5000 virtually generated cod could pass through the defined meshes using the cod compression model from Sistiaga et al. (2011). The applied compression model simulates how much the cross section of a cod can be compressed when it attempts to escape through a mesh. This procedure led to a set of simulated "covered codend retention data" (Wileman et al., 1996) for each of the meshes defined. Each of these simulated retention data sets was then analysed as covered codend data assuming a standard logit selection curve (Wileman et al., 1996). This analysis was conducted using the software tool SELNET (Herrmann et al., 2012). Each of the retention curves was represented by L05, L25, L50, L75 and L95, which is the size of a cod having respectively 5%, 25%, 50%, 75% and 95% probability of being retained by the mesh given that the fish attempted to escape through it. By plotting L05, L50 and L95 for the range of mesh openness considered likely to occur during fishing for both the square and the diamond meshes, we obtained a global picture of the selective potential of the currently legislated square mesh codend. These estimations was applied to judge the risk of catching cod below the minimum size and to assess the risk of losing cod of target size.

2.4. Understanding the size selection process in a historically tested square mesh codend

Isaksen and Larsen (1988) collected size selectivity data for a demersal seine square mesh codend using the trouser trawl sampling method (paired gear data) (Wileman et al., 1996; Herrmann et al., 2007b). The codend they applied had a mesh size of 120.1 mm and was made of 3 mm single twine nylon. Even though thicker and stiffer polyethylene twine materials are in use today, we still expect the results obtained with this old codend could help us gain some insight on the size selection processes that occur in the square mesh codends used today. We were interested in whether the experimental results obtained with this historical codend could be understood based on FISHSELECT simulations. Specifically, we needed information on the extent of escapement through slack meshes (soft mesh state), through distortion of partly opened meshes (semi-soft mesh state) and through non-distorted meshes (stiff mesh state). Accordingly, we explored if the experimental size selection curve based on the data collected by Isaksen and Larsen (1988) could be replicated by simulation scenarios with mesh states: stiff, semi-soft, soft or combinations of them. Since the fish-lift mesh size (110.1 mm) was smaller than that of the square mesh main section in the codend, it is not necessary to consider the fish-lift in the FISHSELECT simulations. We considered the following scenarios: (i) stiff square meshes with varying openness between 50% and 100%; (ii) semi-soft square meshes with varying openness between 50% and 100%; (iii) soft square meshes; (iv) a combination of a soft square mesh and semi-soft square meshes with varying mesh openness between 50% and 100%. For each of the scenarios we obtained the combination of varying openness that best was able to reproduce the experimental size selection curve of the historical codend.

To carry out the above outlined procedure we first re-analysed the historical size selection data from Isaksen and Larsen (1988) using the selectivity analysis tool SELNET (Herrmann et al., 2012). From the re-analysis we obtained the selection curve with confidence intervals and the retention lengths L05–L95 in steps of 5, which quantify the length of a cod with respectively 5–95% probability of being retained in the codend. For the 120.1 mm square mesh we simulated retention curves for different mesh openness's and the different mesh states using FISHSELECT following the approach described in Section 2.3. For each of the scenarios (i)–(iv) we estimated the contributions needed from the different retention curves to obtain combined selection curves that fitted the experimentally obtained values L05. . . L95. This procedure is identical to the one applied in Herrmann et al. (2013b) which contains detailed information on the technical aspects of the method.

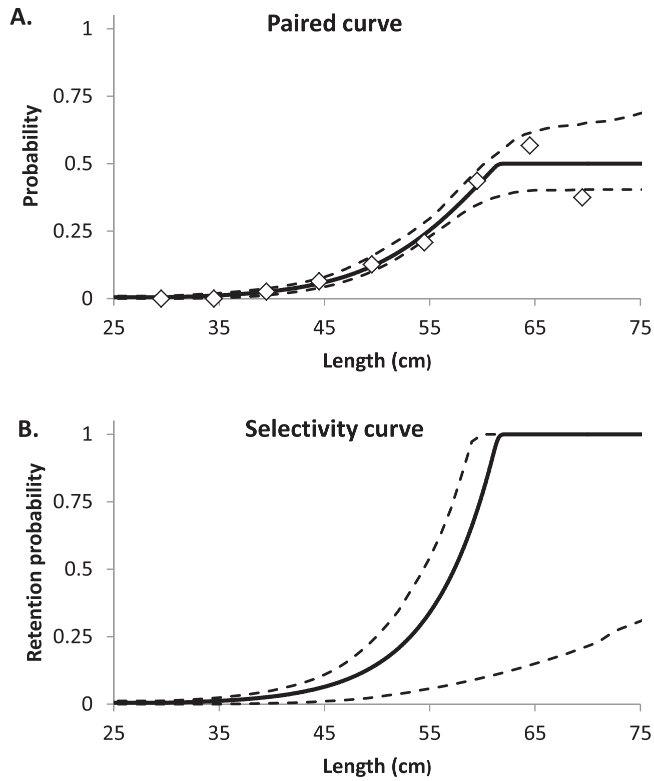

Fig. 6. Experimental size selection curves (Richard curves) obtained from re-analysing the demersal seine data collected by Isaksen and Larsen (1988). (A) Experimental retention rates (diamond marks) and the estimated paired curve. (B) The selectivity curve estimated. The stippled curves represent the 95% confidence bands for the estimated curves (full curves).

2.5. Design guides for predicting size selectivity in different square mesh codends

To explore the potential consequences of making design changes to the currently legislated codend, we simulated the size selection for a number of other mesh sizes using FISHSELECT following the procedure described in Section 2.3. We were interested in the size selection in the square mesh section and in the diamond mesh fish-lift. We considered the mesh state scenarios: soft, semi-soft and stiff to obtain a global overview of potential consequences of design changes on size selection of cod. Based on the results obtained we produced a number of design guides consisting of iso-curves for L05, L25, L50, L75 or L95 that quantify the sizes of cod which has a specific probability of being retained by a mesh depending on the mesh size and openness (consult Herrmann et al., 2009 for more information on design guides). Each design guide covers mesh sizes in the range 100–200 mm.

3. Results

3.1. Size selective potential of the mandatory square mesh codend

The size selective potential (Fig. 5) of the mandatory square mesh codend is quantified, based on the procedure described in Section 2.3. The size selective potential of the three mesh state scenarios are quantified for the square mesh (125 mm) main section. The figure also quantifies the selective potential of the fish-lift (130 mm diamond meshes) considering both the soft and stiff mesh

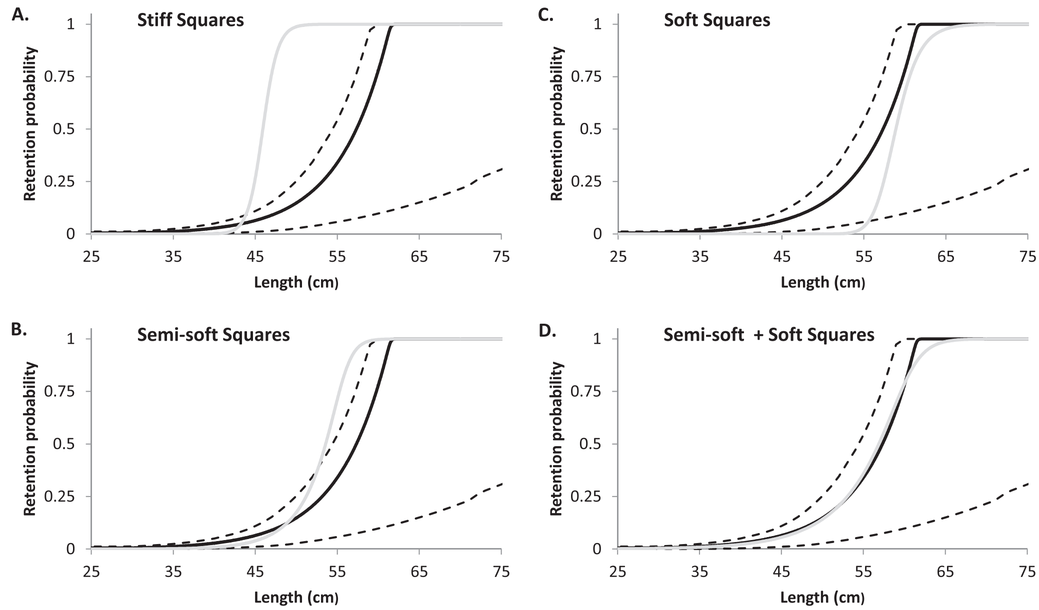

Fig. 7. Best possible fits of simulated size selectivity curves (grey curves) to experimental size selection curve (black curve) based on Isaksen and Larsen (1988). Each simulated curve assumes a different mesh state scenario. (A) 100% stiff mesh state. (B) Semi-soft mesh state. (C) Soft mesh state. (D) A combination of semi-soft and soft meshes. The stippled curves in each plot represent the 95% confidence limits for the experimental size selection curve.

scenarios. Each of the vertical bars in the figure shows the selective range from 5% to 95% retention probability with the middle cross bar representing the 50% retention probability. The *y*-axis in the figure shows the corresponding cod length. The dashed horizontal line represents the minimum legal catch size for cod (44 cm).

If slack mesh selectivity occurs (soft mesh state), then this could potentially result in release of cod far above the minimum size as this mesh state is predicted not to retain cod below 57 cm (Fig. 5). In addition, if semi-soft mesh selectivity with mesh openness of 80–90% occurs, cod well above 44 cm could be released. However, the meshes also need to have an openness of at least 70% to avoid retaining some undersized cod. Moreover, if cod would not be able distort even tensionless mesh bars (stiff mesh state), the square meshes would need to be fully open to avoid the risk of retaining undersized cod. If the diamond meshes were slack/soft or well open in the fish-lift, it could lead to after-selection at the surface where the entrance to the fish-lift is open.

From the above observations it is evident that the selective potential of the codend is highly dependent on the contribution of the different mesh states during the fishing process.

Table 2
Contribution of respectively the semi-soft mesh state with different mesh openness and the soft mesh state to best simulate the experimental size selection curve (data from Isaksen and Larsen, 1988). The contributions shown for the simulation are based on a combination of meshes in the semi-soft and soft state (Fig. 7D). The Table shows that 63% of the meshes are in the soft state while the remaining 37% are in the semi-soft state with openness varying between 50% and 100%.

Mesh state	Mesh openness (%)	Contribution (%)
Semi	50	0
Soft	55	4
	60	0
	65	1
	70	2
	75	2
	80	5
	85	17
	90	0
	95	3
	100	3
Soft	–	63

3.2. Understanding the size selection process in the historical square mesh codend

Following the procedure described in Section 2.4, we re-analysed the paired-gear selection data collected by Isaksen and Larsen (1988). The analysis revealed that the data could be described sufficiently well by a Richard curve (Wileman et al., 1996;

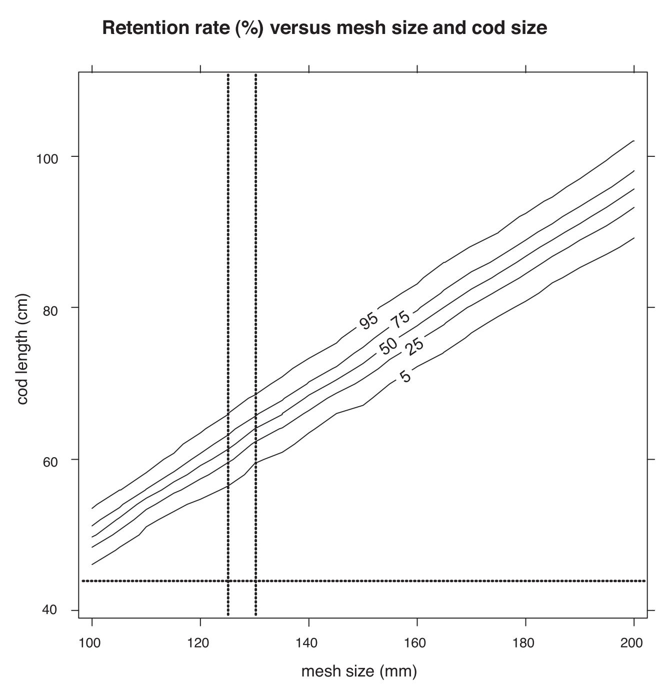

Fig. 8. Design guide for the soft mesh state. It quantifies the retention probability for different mesh sizes (*x*-axis) and different lengths of cod (*y*-axis). The iso-curves represent different levels of retention probability respectively at 5, 25, 50, 75 and 95%. The vertical lines in the plot represent the minimum mesh sizes at 125 mm and 130 mm for respectively the square mesh section and for the fish-lift. The soft mesh state design guide is applicable for both square and diamond meshes since the initial mesh shape has no effect on the retention probability for this mesh state scenario.

Wienbeck et al., 2014). Fig. 6 plots the fit of the Richard curve versus the experimental data and the selection curve. Table 1 summarises the results of the analysis.

The experimental data can be described by the Richard curve since the *p*-value is above 0.05 (Table 1). The choice of the model is further supported by the deviance being similar to the degrees of freedom. Consult Wileman et al. (1996) or Herrmann et al. (2013c) for further details on how to interpret these fit statistics. The selection parameters for the Richard curve, L50 and SR (= L75 − L25), were estimated to be 57.3 cm and 6.6 cm respectively. The L50 is significantly and far above the 44 cm minimum legal size for cod with the lower confidence limit at 54.5 cm (Table 1). The size of a cod with 10% retention probability (L10) is estimated to be 47.7 cm with a lower confidence limit at 44.1 cm matching the minimum size. Hence a mesh size of 120 mm should ensure low catching probability for undersized cod at least for the material type applied in the historical codend.

We investigated to what extent it is possible to reproduce the size selection curve from the historical codend based on FISHSELECT simulations while assuming different mesh state scenarios (Fig. 7).

In the first scenario we assumed that the fish was not able to distort the meshes during the escape attempt (stiff mesh state). Fig. 7A shows the best fit (grey curve) to the experimental curve (black curve). It is clear from the plot that a pure stiff mesh scenario can by no means explain the historical results since the best fitted curve is left compared to the confidence interval of the experimental curve. For the next scenario we assumed that the cod could distort the circumferential mesh bars (semi-soft mesh state). Fig. 7B shows that this scenario is a better fit to the experimental curve than the stiff mesh scenario. However, the semi-soft mesh scenario is not able to fully explain the upper part of the experimental selection curve since it has a significantly higher retention probability for cod sizes between 53 and 58 cm (Fig. 7B). Thus, this scenario cannot fully explain the experimentally obtained results. The third scenario considered assumed that all the cod could fully distort the meshes when trying to escape through (soft mesh state). It is clear that this scenario matches the upper part of the experimental selection curve but that it leads to a selection curve that has a retention probability significantly lower for cod below 56 cm compared to the experimental curve (Fig. 7C). Based on the results presented in Fig. 7A–C it seems likely that a combination of semi-soft and soft meshes could potentially explain the historical experimental size selection. Fig. 7D shows that this is actually case. Hence, a combination of semi-soft mesh and soft mesh penetration is a possible explanation for size selection of cod in the square mesh demersal seine codend, at least for the design used by Isaksen and Larsen (1988). The contributions of respectively soft mesh selectivity and semi-soft mesh states for the simulated curve are shown in Table 2.

According to our predictions, a large proportion of the size selection in this type of codends occurs through slack meshes (more than 60% according to Table 2). The remaining 37% is caused by semi-soft meshes with openness between 50% and 100% and with the contribution of meshes with openness ≤70% predicted to be less than 10%. So at least for the historical square mesh codend it seems that size selectivity occurs mainly through slack meshes and a lower proportion through semi-soft meshes. For the currently applied codend materials, which are often stiffer and with thicker twine diameter (up to 7 mm), the situation might be slightly displaced towards meshes with less distortion.

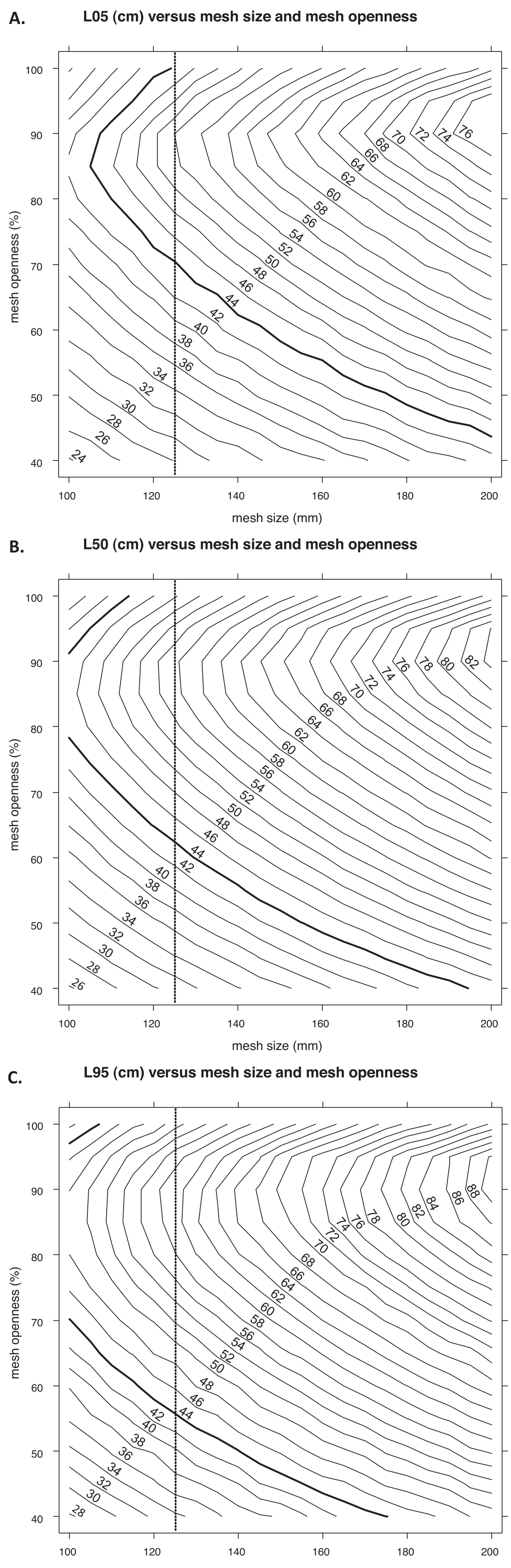

Fig. 9. Design guides for the semi-soft square mesh scenario (Fig. 4B). They quantify the size selective potential for square meshes of different size (*x*-axis) and mesh openness (*y*-axis) assuming a semi-soft mesh state. The vertical line in the plot represents the minimum mesh size at 125 mm. The thick curve in the plots represents the minimum target size for cod in the fishery. (A) Iso-curves for L05 (length of cod having 5% probability of being retained given that it attempts to escape through the mesh). (B) Iso-curves for L50 (length of cod having 50% probability of being retained given that it attempts to escape through the mesh). (C) iso-curves for L95 (length of cod having 95% probability of being retained given that it attempts to escape through the mesh).

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3.3. *Design guides for predicting size selectivity in different square mesh codends*

In this section, we explored the potential consequences of making design changes to the square mesh codend used in the Norwegian demersal seine fishery (Fig. 2). Using the simulation tools in FISHSELECT and following the procedure described in Section 2.5, we predicted changes to size selectivity by varying mesh size. In addition to changes in the mesh size of the main square mesh part of the codend, we also considered mesh size changes in the fish-lift. The predictions included soft/slack mesh penetration and semi-soft mesh penetration since these were found to be important for the size selection in the historical codend. However, since the codend materials used today are often stiffer, and because we wanted to assess a theoretical lower limit for the size selection, we also covered the case of stiff mesh penetration in this section.

Fig. 8 plots a design guide for the soft/slack mesh scenario for codend mesh sizes between 100 and 200 mm. Since the initial mesh shape does not affect the predictions in the case of soft mesh penetration, these results are valid both for the square mesh part of the codend and the diamond fish-lift.

The first vertical line in Fig. 8 marks the current minimum mesh size for the square mesh part of the codend and the second for the fish-lift. The horizontal line marks the minimum target size for cod. Fig. 8 shows that the current mesh size in its slack form ensures negligible retention levels for cod below the minimum size. This discovery is in line with the result from Fig. 5. However, cod considerably above the minimum size would also be able to escape. Further, the larger mesh size required for the fish-lift enables escapement of even bigger cod. Hence, cod that are still active when released into the fish-lift (with slack mesh state) may contribute to additional surface escapement because of the larger mesh size (Fig. 3).

Fig. 9 quantifies the predicted size selection for square meshes in semi-soft state.

Fig. 9A–C quantifies the dependency of respectively L05, L50 and L95 on mesh size and openness. The iso-curve in bold represents the minimum legal size of cod for the fishery (44 cm). The vertical lines represent the current minimum mesh size. For instance to match L05 (5% retention probability) with the minimum target size requires an openness above 72% for a mesh size of 125 mm, whereas for a mesh size of 140 mm the openness required would be above 62% (Fig. 9A). Fig 9B–C provides similar information for L50 and L95.

Based on Fig. 9, it is possible to predict the consequences of changing mesh size in a situation where cod can distort the tensionless circumferential meshes in the square mesh codend (semi-soft state). Based on the results obtained for the historical square mesh codend, this type of mesh state is likely to play a role also for the codends applied in the fishery today. However, today's use of stiffer materials makes it relevant with similar predictions for the stiff mesh state (Fig. 10).

A comparison of the plots in Fig. 10 with its homologous plots in Fig. 9 reveals that the retention probabilities are in general higher for the stiff meshes, except when the meshes are fully open. Fig. 10A illustrates the importance of keeping the meshes fully open when the fish is not able to distort the codend mesh bars. The L05 value for fully open meshes (100%) matches the minimum legal sized cod at 44 cm for the current legal mesh size. However, for a mesh size of 125 mm L05 decreases considerably with decreasing openness.

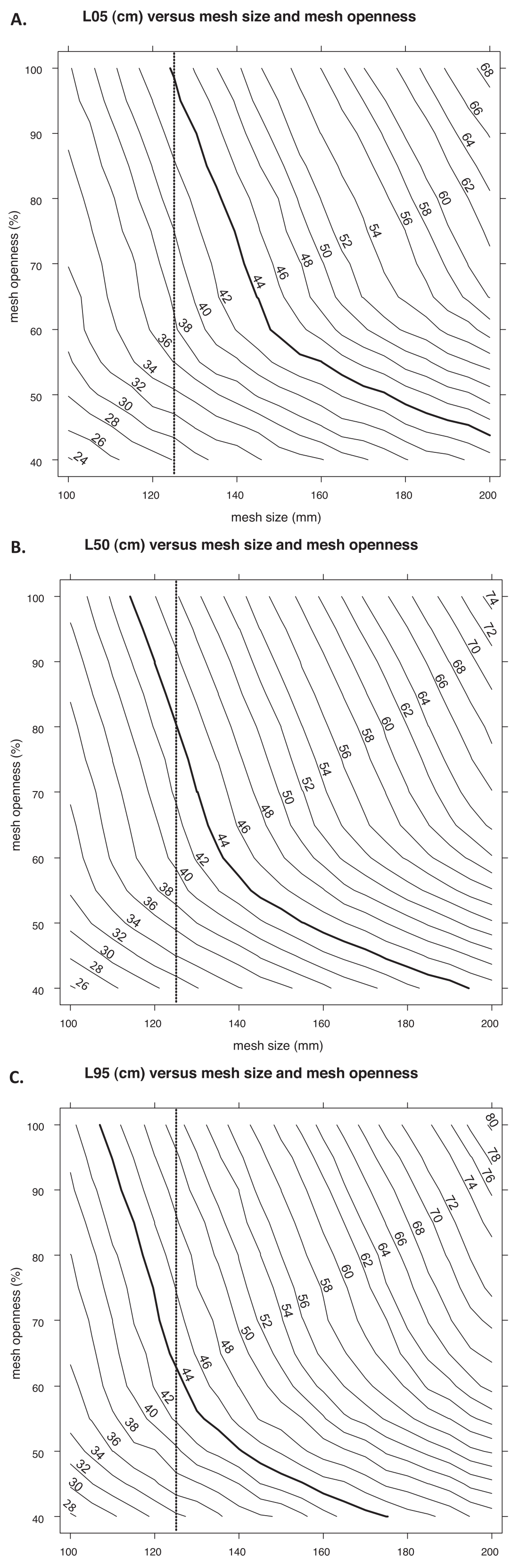

Fig. 10. Design guides for the stiff square mesh scenario (Fig. 4A). They quantify the size selective potential for square meshes of different size (*x*-axis) and mesh openness (*y*-axis) assuming a stiff mesh state. The vertical line in the plot represents the minimum mesh size at 125 mm. The thick curve in the plots represents the minimum target size of cod for the fishery. (A) Iso-curves for L05 (length of cod having 5% probability of being retained given that it attempts to escape through the mesh). (B) Iso-curves for L50 (length of cod having 50% probability of being retained given that it attempts to escape through the mesh). (C) Iso-curves for L95 (length of cod having 95% probability of being retained given that it attempts to escape through the mesh).

For example, L05 is only about 39 cm if the openness is 70% and only 33 cm for an openness of 50%. A similar tendency is found for respectively L50 (Fig. 10B) and L95 (Fig. 10C).

When the diamond meshes in the fish-lift are under tension, they act like stiff diamond meshes for cod trying to escape. Fig. 11 shows predictions for stiff diamond meshes similar to those shown in Figs. 9 and 10 for the square meshes in the main part of the codend. A stiff 125 mm diamond mesh with openness above 53% for example, would enable the escape of nearly all undersized cod.

4. Discussion

We investigated the size selection of cod in square mesh codends with relevance for Norwegian demersal seine fishing. Limited scientific work is published on this gear in general and in particular on its selectivity. We applied for the first time the fish morphology and simulation-based method FISHSELECT to investigate size selection in demersal seines. We investigated the size selectivity in the mandatory codend for this fishery (Fig. 2) to conclude that the 125 mm square meshes ensure low retention probability of undersized cod as long as they are fully open or the cod attempting to escape are able to distort the tensionless mesh bars in the partially opened meshes. We also studied the selective properties of the 130 mm diamond mesh fish-lift, which the cod is released into during the process of taking the catch onboard, to learn that it can potentially lead to an after-selection process at the surface for some sizes of the cod if the meshes are sufficiently open or slack.

Based on FISHSELECT simulations, we were able to explain the size selection curve for the only published study on square mesh codends for the Norwegian demersal seine fishery (Isaksen and Larsen, 1988). Soft/slack mesh escapement seemed to play an important role for the selection process in the codend. Consequently, one could speculate at which stage of the fishing process the selection may occur and what would be the survival rate of those escaping fish. The codends used in the fishery today are made of stiffer and thicker twine and it can therefore be questioned if soft/slack mesh escapement plays as big a role today as it did 25 years ago. Therefore, it would be beneficial to carry out selectivity experiments with the types of codends used in the fishery today (e.g. square mesh codends).

If cod as indicated from underwater recordings (Fig. 2) can distort tensionless square meshes (semi-soft state), then the design used today would enable the escapement of all cod below the target size (44 cm) as long as the mesh openness is at least 70%. However, this mesh configuration can also lead to considerable escapement of cod far above the minimum size if the meshes in the codend become slack as they might do during the sacking operation (Fig. 3). 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; Herrmann et al., 2013a). In particular, Herrmann et al. (2013a) reported that about 30% of the cod entering the codend during the fishing process made their first escape attempt after the haul back operation had begun. Because the fish in a demersal seine is expected to have spent less time in contact with the gear than in a demersal trawl, both fishermen and scientists claim that when taken onboard the fish harvested with demersal seines is less exhausted (see for instance Dreyer et al., 2008). Since seine caught fish hold a good physiological state as they reach the surface, late escapement might be even

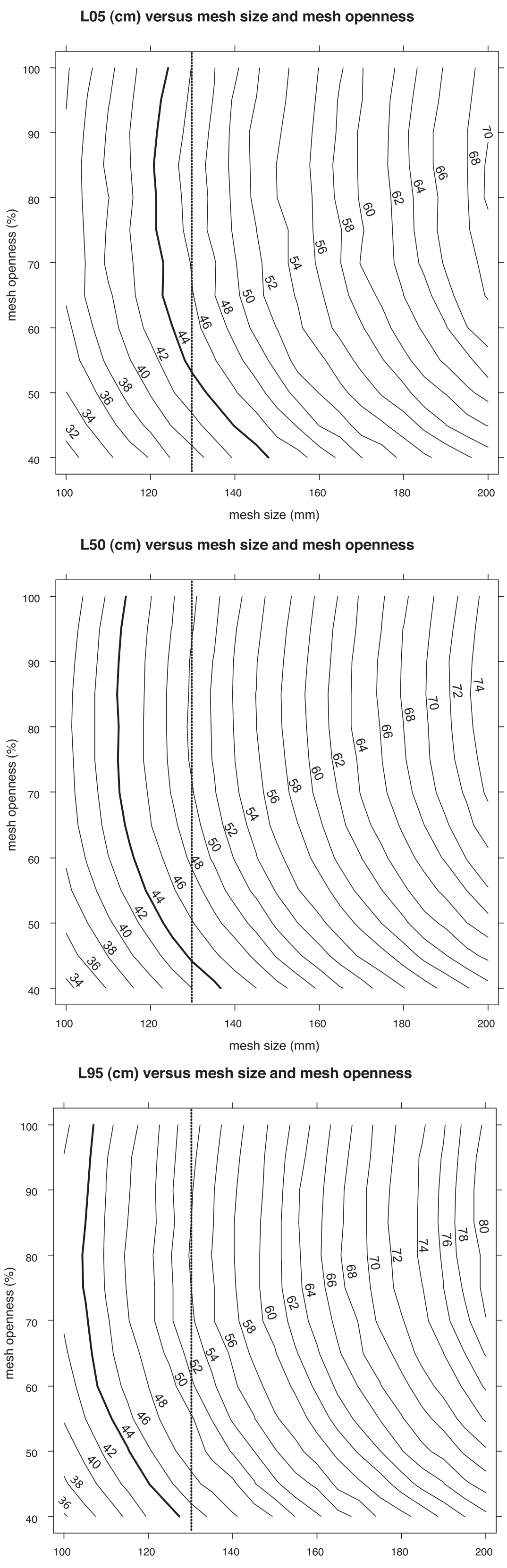

Fig. 11. Design guides for the stiff diamond mesh scenario. They quantify the size selective potential for diamond meshes of different size (*x*-axis) and mesh openness (*y*-axis) assuming a stiff mesh state. The vertical line in the plot represents the minimum mesh size for the fish-lift at 130 mm. The thick curve in the plots represents the minimum target size of cod for the fishery. (A) Iso-curves for L05 (length of cod having 5% probability of being retained given that it attempts to escape through the mesh). (B) Iso-curves for L50 (length of cod having 50% probability of being retained given that it attempts to escape through the mesh). (C) Iso-curves for L95 (length of cod having 95% probability of being retained given that it attempts to escape through the mesh).

more prominent for demersal seines than it is for demersal trawls. The design guides (Figs. 8–11) produced in the current study enable the exploration of the consequences of making design changes to the codends used in the demersal seine fishery. These design guides are tools that facilitate a quick first judgement that could aid on decision making for both fisheries managers and fishermen. We believe this approach could also be relevant and be applied to seine fisheries other than the Norwegian cod demersal seine fisheries.

Keeping in mind the evident technological improvements and capacities on vessels and gears since the Isaksen and Larsen (1988) data were collected, it is important to encourage the industry and the science community to update data on the selection characteristics of modern demersal seines. The Norwegian demersal seine fleet today consists of more than 300 vessels in a size range of 15–40 m, and the variations of dimensions on gear (seine ropes and net), hauling operations and catch handling varies accordingly. The fishing method has over the last 5 decades changed from a historical typical gear for the catch of plaice (*Pleuronectas platessa*) on smooth sandy grounds (i.e. using the original Danish seine principle) to become very efficient for species like cod, haddock, saithe and the deep water species greenland halibut. Due to structural changes inside the Norwegian fisheries it is expected that larger proportions of the national quotas for the most important commercial species of bottom fish will be caught by demersal seines in the future. Especially the use of heavy ropes (up to 2.2 kg/m) and modern types of groundgears (i.e. a flexible netting panel weighted with chains and combination wire) to avoid fish escapement below the fishing line, may lead to the entry of more small fish given they are present in the population making codend size selection increasingly important.

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