# Size selection of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Northeast Atlantic bottom trawl fishery with a newly developed double steel grid system

Roger B. Larsen[1*&], Bent Herrmann[1,2*], Manu Sistiaga[2*], Eduardo Grimaldo[2*], Ivan Tatone[1], Jesse Brinkhof[1]

[1] The Arctic University of Norway, UiT, Breivika, N-9037 Tromsø, Norway
[2] SINTEF Fisheries and Aquaculture, Brattørkaia 17C, N-7010 Trondheim, Norway
[&]Corresponding author. Tel.: +4777644536
E-mail address: roger.larsen@uit.no (Roger B. Larsen)
*Equal authorship

## Abstract

In recent years, Norwegian fishermen have reported problems with fish accumulation in front of the mandatory sorting grids (Sort-X, Sort-V, and Flexigrid). These problems are associated with high fish entry rates and low water flow through the grid sections. In this study, we replaced the lifting panel in the original design of a sorting grid section (Sort-V) by another steel grid ("lower grid") in order to improve water flow and increase sorting area. Two different inclination angles of this new additional "lower grid" were tested. The results demonstrated that both the lower grid and the main grid contributed to the release of cod and haddock. However, the release efficiency of the lower grid was low compared to that of the main grid. A larger proportion of fish contacted at least one of the grids with the lower grid set at 40° compared to at 35°. The new double grid was found to release significantly more haddock between 38 and 50 cm long than the mandatory Flexigrid. For cod, the sorting system was at least as good as the Flexigrid at releasing undersized fish. Thus, the new double grid system represents a potential alternative to the Flexigrid. Although the Sort-V single grid releases significantly more undersized cod and haddock than the new double grid system, it also releases a significantly higher proportion of the targeted commercial sizes.

*Keywords:* Sorting grid; Selectivity; Trawl; Cod; Haddock; Water flow

## 1. Introduction

Rigid sorting grids in combination with diamond mesh codends have been mandatory in the Barents Sea demersal cod (*Gadus morhua*) and haddock (*Melanogramus aeglefinus*) fishery since 1997. In 2011, the minimum mesh size of the diamond mesh codend was changed from 135 to 130 mm and this remains the minimum mesh size for the fleet today. Fishermen are allowed to use three different grid systems in the fishery, all of them with a minimum bar spacing of 55 mm: the Sort-X, which is a three-section system that is composed of two steel grids and a canvas section (Larsen and Isaksen, 1993); the Flexigrid, which is a double flexible grid section composed of two grids made of plastic (i.e., bars made from fibre-glass) and rubber (Sistiaga et al., 2016; www.fiskeridir.no); and the Sort-V, which is a single steel grid section (Jørgensen et al. 2006; Herrmann et al. 2013a). The Sort-X system is considered outdated by fishermen and only the Sort-V system and the Flexigrid are actively used in the fishery today (Fig. 1).

FIG. 1

The current stock size of Northeast Arctic cod is estimated to be around 3,200,000 tons (www.imr.no), which is at the top of the levels registered in recent decades. A direct consequence of this stock size is that the trawlers fishing in the Barents Sea often encounter densities of fish that make ordinary fishing operations challenging. Specifically, the grid systems applied in the Barents Sea today experience capacity problems that render more acute when the densities of fish entering the section are high (i.e., >10 tons/hour). The causing mechanism is that fish often seem to stop just in front of the grid and keep a somewhat stationary position up to several minutes before being size sorted in the section and pass it in the direction of the codend. This phenomena leads to fish accumulation at the entrance of the grid section, which combined with high entrance rates can result in that the grid section gets blocked (or clogged) by fish, loses its sorting ability and finally breaks in some cases (Grimaldo et al., 2015; Sistiaga et al., 2016). Therefore, a key to eliminate or at least significantly reduce this risk for grid clogging is to ensure that the fish does not stop and accumulate in front of the grid section before being size sorted by it. Reduction in water flow both in front of and inside grid sections is assumed to be one of the key factors that encourages and makes it possible for fish to halt and keep a stationary position in front of the grid section. Therefore, in an attempt to solve this issue, the Norwegian authorities, research institutes, and fishermen are testing alternative gear and grid designs that increase the water flow through the grid sections and facilitate the continuous flow of fish into the grid section and towards the codend. One of the measures proposed by the Norwegian authorities was the removal of the lifting panel from the grid section, which is believed to substantially reduce water flow through the section. Grimaldo et al. (2015) evaluated the importance of the lifting panel in a Sort-V section to see if its removal affected the selective performance of the section. The results showed that the lifting panel has a significant effect on the sorting ability of the Sort-V grid section and therefore it should not be removed. Therefore, the present study examines an alternative design where the lifting panel was not eliminated but substituted by an additional grid that would potentially increase water flow through the section, provide an additional sorting process and at the same time lift the fish towards the main grid. The study aims at first instance at answering the following research questions:

- Do fish stop in front of the grids in the new section, and if not, how fast do they pass through the section?
- To what extent is the water flow maintained through the new section?

In addition to carrying fish through the section and towards the codend effectively, a potential alternative grid section should perform at least as good as the existing grid sections at releasing undersized fish and retaining commercial size fish. However, for a sorting grid to be effective regarding size selection, fish need to have enough time in the grid zone to orientate itself correctly towards the grid for an exposure to a size selection process. Therefore, as increasing the water flow may have negative effect on the size selection, it is essential to examine the size selectivity performance of the new grid section with respect to the main target species in the fishery. Thus, the next research questions to be answered would be:

- Do fish have enough time in the grid section to orientate itself correctly towards the two grids for an effective size selection process?
- To what extent do cod and haddock escape through the new additional grid and through the main grid in the double grid design?
- Does this new grid design provide size selection for cod and haddock comparable to the grid designs used in the fishery today?

## 2. Materials and Methods

### *2.1 Vessel, area, time, and fishing gear*

The experimental fishing was carried out on board the research vessel (R/V) “Helmer Hanssen” (63.8 m LOA and 4080 HP) from 27th February to 7th March, 2015. The fishing grounds chosen for the tests were located off the coast of Finnmark and Troms (Northern Norway) at 71°30’ N –27°30’ E and

70°30’ N – 17°20’ E. At this time of the year the area is suitable for size selectivity studies under rather high fish entry rates.

We used an Alfredo No. 3 Euronet trawl built entirely of 155 mm polyethylene (PE) netting. This trawl design is commonly used in commercial Norwegian fisheries. The trawl had a headline of 36.5 m, a fishing line of 19.2 m, and 454 meshes in circumference and was constructed entirely in 155 mm nominal mesh size (nms). The trawl was rigged with a set of Injector Scorpion bottom trawl doors (7.5 $m^2$ and 2800 kg each), 60 m sweeps, and 111.2 m ground gear. The ground gear had a conventional 19.2 m long rock-hopper in the center that was built with Ø 53 cm rubber discs attached to the fishing line of the trawl and five Ø 53 cm steel bobbins distributed on a 46 m × 19 mm chain along each side of the trawl. The headline was equipped with 170 × Ø 20 cm plastic floats. The trawl gear was monitored using Scanmar (Scanmar AS, Åsgårdstrand, Norway) acoustic sensors placed at the trawl doors, headline, and codend. With the given rig details, we achieved ca. 130 m door spread, ca. 14.5 m fishing line spread, and a ca. 5 m headline height at towing speeds of 3.5–4.0 knots, and a depth that ranged between 250 and 320 m.

We built a 4-panel netting section with two steel grids inserted into it. This grid section was made of 138 mm nms Euroline Premium PE netting (single Ø 8.0 mm twine), was 26 meshes long (the section was 18.5 meshes shorter than the mandatory Sort-V steel grid section), and had 104 meshes in circumference. All four selvedges in the grid section were strengthened with Ø 36 mm Danline PE rope. The original Sort-V system is equipped with a 60 mm PE lifting panel and its main function is to guide fish closer to the grid face (Fig 1). The lifting panel was replaced by a one-half standard steel grid (Sort-V type) with 55 mm bar spacing, hereafter called $grid_1$ (outer dimensions: length 835 mm × width 1234 mm). $Grid_1$ was initially fixed to maintain an inclination angle of approximately 35°, but later this angle was increased to approximately 40°. The aft section of $grid_1$ was made from square mesh 80 mm nms Euroline Premium PE netting (single Ø 3.0 mm twine). The main grid in the section, hereafter called $grid_2$, was a standard steel grid (Sort-V type) with 55 mm bar spacing (outer dimensions: length 1650 mm × width 1234 mm). The square mesh guiding panel behind $grid_2$ was also made of 80 mm Euroline Premium PE netting (single Ø 3.0 mm twine). The length of the guiding panel was approximately one-half that used in the standard mandatory Sort-V sorting grid section (Fig. 2).

FIG. 2

We built a transition diamond mesh section to connect the 2-panel trawl belly to the 4-panel grid section. This transition section was made from 138 mm nms Euroline Premium PE netting (single Ø 8.0 mm twine) and was 35.5 meshes long (Fig. 3).

We used two small-mesh grid covers (GCs) to collect separately the fish escaping through $\text{grid}_1$ and $\text{grid}_2$, respectively. $\text{Grid}_2$ was covered with a GC made of 52 mm (full mesh size) Euroline Premium PE netting (single Ø 2.4 mm twine) and had a total length of ca. 25 m (Larsen and Isaksen, 1993). The entire GC was reinforced with double 155 mm Euroline Premium PE netting (single Ø 4.0 mm twine), and 7 × Ø 20 cm plastic floats were added along the mid-seam to ensure its expansion. $\text{Grid}_1$ was covered with a GC made of 42 mm polyamide (PA) netting of Ø 1.0 mm in the front part and 52 mm PE netting (single Ø 2.2 mm twine) in the aft part. This cover had a total length of approximately 15 m. Despite the use of PA with relative thin twines we added ca. 15 kg of chains along the mid-seam of this cover to ensure (upside-down) inflation. GCs were installed following the standard procedures described by Larsen and Isaksen (1993) and Wileman et al. (1996) (Fig. 3).

The 4-panel diamond mesh codend used during the experiments was made from Euroline Premium PE netting (Polar Gold) with 138 mm nms meshes and Ø 8 mm single twine. The codend was 120 meshes long and had 80 meshes of circumference. All four selvedges were strengthened with Ø 36 mm Danline PE ropes. In total, seven round-straps (Ø 24 mm PE) were attached around the codend at intervals of 1.2 m. The codend was blinded by a 14 m long inner net constructed of 52 mm nms Euroline Premium PE netting (single Ø 2.2 mm twine) (Fig. 3).

FIG. 3

All cod and haddock from the codend and the GCs were measured to the nearest cm. Underwater video observations were made to monitor the correct configuration of the grids and to obtain information about fish behavior inside the grid section. For the underwater recordings we used a GoPro Hero 4 black edition HD camera system. To provide appropriate illumination for this camera, two Metalsub FL 1255 halogen lamps (white light, 1500 lumen and 3200 K) were connected to a Metalsub FX 1209 dual battery pack (http://www.metalsub.nl/). The camera unit with lights was fixed 2 m in front of the grid (facing backwards). Because artificial light can affect fish behavior, these hauls were excluded from the selectivity analyses.

To measure water flow inside the grid section, two Scanmar flow meters were placed in the middle of a rectangular steel frame (1120 mm × 1000 mm) in the center and three-quarters of the way down from the top, respectively. We used four separate hauls for these flow measurements and they were made both in front of the grid section and behind the grid section and with and without the GCs. To monitor the actual inclination angle of $grid_2$, we used a Scanmar grid sensor fixed in the middle of this grid and the tows were inspected with Go-Pro cameras.

### *2.2 Modeling size selection in the double grid system*

Sistiaga et al. (2010) successfully described size selection of cod and haddock by a 55-mm Sort-V sorting grid using a model that accounted for the fact that not all fish necessarily made contact with the grid in a way that provided them with a size dependent probability to escape through it. Herrmann et al. (2013b) showed later that this model could also describe the size selection of redfish, one of the main bycatch species in the fishery, for a 55-mm Sort-V sorting grid. This model is known in the literature as *CLogit* (Herrmann et al., 2013b):

$$CLogit(l, C, L50, SR) = 1 - C \times \left(1 - Logit(l, C, L50, SR)\right) = 1 - \frac{C}{1 + exp\left(\frac{ln(9)}{SR} \times (l - L50)\right)} \quad (1)$$

Only the fish contacting the grid have a size dependent probability of escaping through it. In the *CLogit* model, the parameter *C* quantifies the length independent probability that a fish entering the grid zone will also make contact with it in a way that provides it with a length dependent probability of escaping through the grid. Thus, *C* has a value between 0.0 and 1.0, where 1.0 would mean that every fish entering the grid zone would make contact with the grid. In contrast, a value of 0.3 would mean that only 30% of the fish entering the grid zone would make contact with it. For a fish making contact with the grid, the *CLogit* model assumes a traditional *Logit* size selection model (Wileman et al., 1996) defined by the parameters L50 and SR (L50 is the length at which a fish has a 50% chance of being retained by the gear, whereas SR is the selection range defined as the difference in fish length between 75% and 25% chance of being retained, i.e. L75-L25). Sistiaga et al. (2016) extended this model to describe the size selection of cod and haddock in a double grid system, the Flexigrid. Larsen et al. (2016) applied the same double grid size selection model to estimate the size selection of redfish for the double grid system used in present study. Thus, we applied the following model (2) to describe the size selection of cod and haddock in the double grid system:

$$\begin{aligned} e_1(l) &= 1.0 - CLogit(l, C_1, L50_1, SR_1) \\ e_2(l) &= \left(1.0 - CLogit(l, C_2, L50_2, SR_2)\right) \times \left(1.0 - e_1(l)\right) \\ r_{comb}(l) &= 1.0 - e_1(l) - e_2(l) \end{aligned} \qquad (2)$$

For a fish of length $l$ that enters the double grid section, $e_1(l)$ models the length dependent probability for it to escape through $\text{grid}_1$ (the lower grid) and $e_2(l)$ models the probability for it to escape through $\text{grid}_2$ (the upper grid). If the fish does not escape through one of the two grids it is retained in the codend, for which the probability is described by $r_{comb}(l)$. $C_1$ quantifies the fraction of fish entering the gear that makes contact with the first grid and is subject to a size dependent probability of escapement through it. For those fish, $L50_1$ and $SR_1$ are the contact selectivity parameters assuming a *Logit* size selection model. For the fish that reach the zone of the second grid, meaning that they have not previously escaped through the first grid, $C_2$ quantifies the fraction of fish that makes contact with it and consequently is subject to a size dependent probability of escapement through this grid. For those fish, $L50_2$ and $SR_2$ are the contact selectivity parameters assuming a *Logit* size selection model. Thus, according to equation (2) the size selectivity in the double grid system is fully described by the six parameters $C_1$, $L50_1$, $SR_1$, $C_2$, $L50_2$, and $SR_2$. The selection properties of the individual grids, $\text{grid}_1$ (lower grid) and $\text{grid}_2$ (upper grid), are described by the parameters $(C_1, L50_1, SR_1)$ and $(C_2, L50_2, SR_2)$, respectively, following the *CLogit* size selection model (1). The probability that a fish entering the grid section will make contact with at least one of the two grids, $C_{comb}$, can be expressed by:

$$C_{comb} = C_1 + C_2 - C_1 \times C_2 \quad (3)$$

The overall selectivity parameters for the whole grid section (first and second grid combined: $L50_{comb}$ and $SR_{comb}$) were estimated based on (2) using the numerical method described in Sistiaga et al. (2010).

### *2.3 Estimation of selection parameters for the double grid model*

The values of the parameters for the overall selection model (2) (i.e., $C_1$, $L50_1$, $SR_1$, $C_2$, $L50_2$, and $SR_2$) were obtained using a maximum likelihood estimation method. The method was applied pooled over hauls $j$ (1 to $m$), separately for cod and haddock, and separately for the two grid riggings investigated) by minimizing:

$$-\sum_l \sum_{j=1}^{m} \left\{ n_{GC1,l,j} \times ln\left(e_1(l)\right) + n_{GC2,l,j} \times ln\left(e_2(l)\right) + n_{C,l,j} \times ln\left(r_{comb}(l)\right) \right\} \qquad (4)$$

where $n_{GC1,l,j}$, $n_{GC2,l,j}$, and $n_{C,l,j}$ denote the number of fish lengths collected in haul *j* with length *l* in the cover for the first grid, the cover for the second grid, and the blinded codend, respectively (Fig. 3). When estimating the size selection parameters $C_1$, $L50_1$, $SR_1$, $C_2$, $L50_2$, and $SR_2$, the values of the parameters are not constrained, meaning that they are not bound in value to each other. However, because the bar spacing in the two grids is identical, it could be expected that the size selection for those fish making contact with $grid_1$ would be similar to the size selection of the fish making contact with $grid_2$. Thus, the main difference in the performance of the two grids is expected to be due to potential differences in grid contact probability between the two grids ($L50_1 \approx L50_2$ and $SR_1 \approx SR_2$, while $C_1$ and $C_2$ can have different values).

We first used a constrained version of model (2), in which $L50_1 = L50_2$ and $SR_1 = SR_2$, to describe the size selection in the double grid system. We used the unconstrained version of the model only if this constrained version of the model failed to describe the experimental data sufficiently well. The diagnosis of goodness of fit of the models used was based on the p-value, model deviance versus degrees of freedom, and finally inspection of the model curves' ability to reflect the trends in the data.

The maximum likelihood estimation using Equation (4) with (2) requires aggregation of the experimental data over hauls. This results in stronger data to estimate the average size selectivity at the expense of not considering explicit variation in selectivity between hauls (Fryer, 1991). To account correctly for the effect of between-haul variation in the uncertainty of the size selectivity parameters estimated, we estimated the Efron percentile confidence intervals using a double bootstrap method with 1000 bootstrap iterations (Efron, 1982; Chernick, 2007). The method was applied both for the estimated parameters in equation (2) and the curves for $e_1(l)$, $e_2(l)$, and $r_{comb}(l)$. We used the software tool SELNET (Herrmann et al., 2012) to carry out all selectivity data analyses.

Based on the *CLogit* model and inserting the values of the selection parameters for the first grid ($C_1$, $L50_1$, $SR_1$) and the second grid ($C_2$, $L50_2$, $SR_2$), we obtained the size selection curves for the two grids for stand-alone deployments. By incorporating this estimation into the bootstrapping procedure described above, we also obtained 95% confidence limits for the grid's stand-alone size selection curves. As we are also interested in the difference in contact probability between the two grids, we incorporated an explicit estimation of $\Delta C = C_2 - C_1$ into the bootstrap procedure.

To infer whether the two selection curves were significantly different, we checked the 95% confidence limits of the curves for length classes without overlap. For the estimated selectivity parameters we used a similar approach and inspected whether or not the confidence limits of the estimated values being compared overlapped.

## 3. Results

### *3.1 Observations of gear and fish*

When using the covered codend method in a selectivity study, there is always some uncertainty related to the use of the covers and their potential influence on the performance of the gear. Therefore, we investigated whether the GCs affected the water flow through the grid section. The results showed that the GCs indeed reduced the water flow inside the grid section by approximately 25% (from 3.5 to 2.7 knots). With the GCs removed, flow measurements were made in front of the grid section and aft of the grid section. Measurements taken at 1/2 and 1/4 of the grid section's height were 13% and 57% lower behind the grids than in front of the grids.

$\text{Grid}_2$ in the new double steel grid section was rigged in exactly the same manner as in a standard 4-panel Sort-V section (Grimaldo et al., 2014). Underwater video recordings and measurements of water flow indicated a stronger water flow through the 4-panel grid section than a conventional 2-panel Sort-V section (Fig. 4). This stronger water flow can help reduce blockages (clogging) and allow fish to better flow towards the codend after passing the area for potential escape through the grids. All video inspections inside the grid section showed that fish encountered the grids at a higher speed than previously observed in the rest of the mandatory grid systems. None cod or haddock was observed stopping in front of the grid section for more than a few seconds. Moreover, one could observe cod and haddock passing through the section without having the chance to correctly orient themselves towards the bars of the grids and escape. Thus, although the strong water flow had a positive effect on making the fish pass through the grid section and reduced the risk of clogging, it also affected grid contact negatively and consequently impacted the overall performance of the grid system. The video sequences showed how cod (Fig. 5a) and haddock (Fig. 6a) could pass through the section without contacting either of the grids (i.e., sliding over/under them).

FIGS. 4, 5 & 6

In the video sequences (snapshots) selected from the underwater recordings, we observed three different possible outcomes for cod and haddock: the fish flows through the section towards the codend without contacting any of the grids (Fig. 5a and 6a); the fish contacts and escapes through $grid_1$ (Fig. 5b and 6b); and the fish escapes through $grid_2$ (Fig. 5c and 6c). Both species had problems contacting the grids, especially $grid_1$, as they often passed through the full section relatively quickly. The pictures in Figure 6c illustrate how a haddock slid along $grid_1$ and was unable to achieve contact, but when it reached the escape zone of $grid_2$ it successfully contacted the grid and escaped through it. Haddock showed much more active escape behavior in the new grid section than cod and were therefore more successful at achieving contact. In addition, the sizes of cod captured in the trials were larger than those of haddock, which can be explained by fewer cod observed escaping through the grids in the underwater recordings.

### *3.2 Selectivity analyses*

Size selectivity data was collected for cod and haddock in 19 hauls. Eight hauls were carried out with $grid_1$ at a low angle (35°) and 11 hauls were conducted with $grid_1$ at a higher angle (40°). For haddock all hauls were included in the selectivity analysis. For cod one of the hauls was omitted from the analysis with $grid_1$ at a higher angle because this haul contained very few cod. In total, 3272 cod were length measured, in the hauls included in the selectivity analyses carried out on this species. In total, 7055 haddock were length measured. Table 1 summarizes the results of the analysis based on the constrained model presented in sections 2.2–2.3, and Figures 7 and 8 show plots of the escapement through $grid_1$, through $grid_2$, and the combined size selection.

TABLE 1

FIG. 7

FIG. 8

The results in Table 1 show that the constrained model described in (1) can describe the experimental data for the size selection of cod and haddock in the double grid system sufficiently well, as all *p*-values are > 0.05. For both inclination angles in which $grid_1$ was fixed, it is likely that the deviation between the model fitted and the experimental rates is a coincidence. The plots in Figures 7 and 8 further support this, as the curves modelled in all cases seem to reflect the trends in the experimental points without any systematic patterns in the deviations. Based on these results, we are confident in applying model (2) to describe the size selection of cod and haddock in the double grid system used in this study. Several observations can be made based on the estimated selection parameters in Table 1:

i) Of the fish entering the grid section, a higher fraction made contact with $grid_2$ (the main grid) compared to $grid_1$. The mean estimated values for $C_2$ were much higher than those estimated for $C_1$, and the differences between these two parameters were significant for both grid set-ups we tested.
ii) Between 57 and 66% of the cod and haddock entering the grid section made contact with at least one of the two grids.
iii) For three out of the four cases (all except cod with $grid_1$ at low angle), $C_{combined}$ was estimated to be significantly below 100%.
iv) For the combined size selection of both grids, using a higher angle for $grid_1$ led to an increase in size of fish sorted out, as the estimated $L50_{comb}$ was higher for the high grid angle set up than for the low grid angle set up. However, this effect was not statistically significant because the confidence bands of $L50_{comb}$ for the two cases overlapped.

Based on the *CLogit* model and the estimated parameter values (Table 1), Figure 9 plots the estimated stand-alone size selection curves of the lower ($grid_1$) and the upper grid ($grid_2$), respectively. For haddock, the release efficiency was higher for the second grid compared to the first grid, as the retention probability for a large size span was significantly higher for the first grid. The same tendency occurred for cod, although the difference was only significant for the design with the 40° angle for $grid_1$.

FIG. 9

Figure 10 provides a direct comparison between the low and high grid angle set up of $grid_1$ for the combined size selection. For both cod and haddock, L50 was higher when the grid angle for $grid_1$ was high. However, overlapping confidence intervals show that the difference is not significant.

FIG. 10

The new double grid and the Flexigrid has some similarities as both systems comprises two separate grids. The combined size selection for cod and haddock in the new double grid system compared to that previously estimated for a 55-mm Flexigrid (Sistiaga et al., 2016) is shown in Figure 11. The comparison was made for the high angle of $grid_1$ because this setup resulted in the most desired selectivity pattern for the fishery due to less capture of fish below minimum landing size (MLS). For cod, the comparison was made with two different results for the Flexigrid. The comparisons indicate that the use of the new double grid system would result in greater size selection on cod than that obtained using the Flexigrid. However, the difference was significant only for few length classes in one of the comparisons (Fig. 11). The new double grid was found to release significantly more haddock between 38 and 50 cm long compared to the Flexigrid (the lower graph in Fig. 11). The vertical lines represent the MLS for cod (44 cm) and haddock (40 cm).

FIG. 11

The combined size selection for cod and haddock in the new double grid system was also compared to size selection results previously estimated for a 55-mm Sort-V grid (Sistiaga et al., 2010). Data for cod were also compared to Sort-V results presented in Grimaldo et al. (2015). For both species, the size selection results obtained with the new double grid system were not as good as those obtained with the Sort-V steel grid system (Fig. 12). Specifically, the double grid system appeared to be significantly less efficient at releasing undersized cod and haddock, likely because fewer cod and haddock made contact with the grids during their passage through the section of the new double grid system. The premise is supported by the vertical difference in the horizontal part far left on the grid sections size selectivity curves (Fig. 12). This difference is particularly profound for haddock. Another important point to consider when interpreting the results is that the new double grid system is significantly more efficient at retaining cod and haddock above the minimum size than the Sort-V.

FIG. 12

## 4. Discussion

We tested a new grid section equipped with two steel grids to address current selectivity problems in the Northeast Arctic cod and haddock fishery. The grid section tested was a 4-panel construction with the same design as the Sort-V section tested by Grimaldo et al. (2015), except the lifting panel was replaced with a second steel grid in this new design. The aim of this design was to increase the fish sorting area by adding a new grid ($grid_1$) while simultaneously improving water flow in the section. The results showed that the new design did improve water flow inside the grid section, which in the past has been shown to contribute to reduced risk of blockage in the section (Sistiaga et al., 2016). The effect of this was also clear from the underwater recordings showing no cod or haddock halting in front of the grid section for more than a few seconds. Therefore, we assume that the new design will have lower risk for grid clogging than the designs currently used in this fishery.

A relatively high proportion of fish (34–37%) was estimated to pass through the new grid section without contacting any of the grids, thus these fish were not subject to a size selection process. This effect with the new double steel grid section was apparently related to the replacement of the lifting panel with a steel grid ($grid_1$). First, because of its size and weight, $grid_1$ pressed the section's lower panel down. This created a bigger opening under $grid_2$ (main grid) than that observed when using a lifting panel made of PE netting. Second, the greater porosity of $grid_1$ with respect to a PE lifting panel significantly improved the water flow in the lowest part of the grid section. This strong water flow was negatively correlated with the swimming ability of fish and consequently lowered the chances for the individual fish to orient themselves to attempt escape through the grids. Underwater video recordings consistently showed that many fish entering the grid area passed through the section without contacting any of the grids. These observations are well supported by the contact values estimated for $grid_1$ and $grid_2$ and the estimated combined contact values for the system ($C_{combined}$), which were estimated to be no higher than 63.47% for cod and 66.39% for haddock. Further, the upper confidence limit of three out of the four combined contact estimates were significantly lower than 100 (all cases except cod with low angle of $grid_1$), which indicates that fish pass through the section without contacting any of the grids.

When considering the performance of the lower grid ($grid_1$) and the upper grid ($grid_2$) independently, the estimates for $C_1$ were always lower than those for $C_2$. These differences, which were significant for haddock, show that the performance of $grid_2$ is more important for the overall performance of the grid system than the performance of $grid_1$. This is reasonable because the selective surface of $grid_2$ is twice as large as that of $grid_1$. The estimates obtained for $C_1$ and $C_2$ also reveal that cod was better at contacting the lower grid ($grid_1$) than haddock and that haddock was better at contacting the upper grid ($grid_2$) than cod. This result is in accordance with the well documented behavioral difference between cod and haddock: most cod pass through the trawl gear close to the lower panel of the trawl, whereas haddock tend to swim closer to the upper panel of the trawl (e.g., Engås et al., 1998; Ferro et al., 2007). These behavioral patterns were also confirmed during our video observations. During the trials, we tested two different angles for $grid_1$ in an attempt to improve grid contact (Fig. 1a). The results showed very little improvement in the overall retention of small fish when the grid angle was increased from 35 and 40°.

The size selectivity of the new double steel grid system was compared to previous results obtained for the only mandatory grid system in the fishery that is composed of two grids (i.e., the Flexigrid). The new double grid was found to release significantly more haddock 38–50 cm long than the Flexigrid. For cod, the new double grid system was found to be at least as efficient as the Flexigrid at releasing undersized fish. Thus, the performance of the new double grid system represents a potential future alternative to the Flexigrid.

Comparison of the selectivity results obtained with the new double grid system with the selectivity results obtained previously for the Sort-V grid system showed that the Sort-V system grid releases significantly more undersized cod and haddock than the new double grid system. However, the Sort-V also releases a significantly higher proportion of fish above the minimum landing size (MLS). The effectiveness of a grid can be measured as both its ability to release undersized fish and its ability to retain fish above the MLS. No grid is able to deliver a knife edge selection curve with an *L50* right on the MLS and a *SR* of 0 cm. Therefore, the aim is to achieve a grid design that provides a good balance between retaining as few fish below the MLS as possible and as many fish above the MLS as possible. When comparing the new grid section to the compulsory Sort-V and Flexigrid systems, it appears that its performance falls between the two legal grids used by fishermen.

The practical functioning of the new double steel grid section, its operation did not add any additional challenge compared to operation of a traditional Sort-V section. The dimensions of the new grid section were the same as that of the Sort-V section, and the additional weight due to the insertion of grid$_1$ in the section was barely noticeable in the operation process on board our research trawler.

Larsen et al. (2016) recently reported the size selective performance of the new double grid section for an important bycatch species (*Sebastes* spp.). They also found that the Sort-V grid was more effective at releasing undersized fish than the new double steel grid system, but that the new system was more efficient at retaining redfish of commercial sizes. These results are therefore somehow in line with those reported here for cod and haddock. No results for size selection of redfish are available for the Flexigrid.

Considering that the release efficiency for undersized fish is at least as good as one of the two systems currently used, and better than the Sort-V to retain the targeted sizes, we consider the new double grid design to be an acceptable alternative regarding its size selectivity to the existing systems.

Regarding the lower efficiency for releasing undersized fish compared to the Sort-V, one should also consider that these grids are used in combination with a codend of minimum 130 mm mesh size which subsequently will be able release a large proportion of the undersized fish retained after passing the grid section.

## Acknowledgements

We thank the crew of the RV "Helmer Hansen" and MSc student Ixai Salvo for their valuable assistance on board. We like to express sincere thanks to the two anonymous reviewers whose comments helped us to improve this manuscript. We are grateful for the financial support from the Directorate of Fisheries, the Research Council of Norway (RCN) (RCN project 243627 (*"Managing trawl catches by improving the hydrodynamic performance of sorting grid sections and codends"*), and the University of Tromsø for making it possible to carry out the trials.

## References

Chernick, M.R., 2007. Bootstrap Methods: A guide for practitioners and researchers, second edition. Wiley series in probability and statistics. Wiley, New York.

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

Engås, A., Jørgensen, T., West, C.W., 1998. A species-selective trawl for demersal gadoid fisheries. ICES J. Mar. Sci. 55, 835–845.

Ferro, R.S.T., Jones, E.G., Kynoch, R.J., Fryer, R.J., Buckett, B.-E., 2007. Separating species using a horizontal panel in the Scottish North Sea whitefish fishery. ICES J. Mar. Sci. 64, 1543–1550.

Fryer, R.J., 1991. A model of between-haul variation in selectivity. ICES J. Mar. Sci. 48, 281–290.

Grimaldo, E., Sistiaga, M., Herrmann, B., Gjøsund, S.H., Jørgensen, T., 2015. Effect of the lifting panel on selectivity of a compulsory grid section (Sort-V) used by the demersal trawler fleet in the Barents Sea cod fishery. Fish. Res. 170, 158–165.

Herrmann, B., Sistiaga, M., Larsen, R.B., Nielsen, K.N., Grimaldo, E., 2013a. Understanding sorting grid and codend size selectivity of Greenland halibut (*Reinhardtius hippoglossoides*). Fish. Res. 146, 59‑ 73.Herrmann, B., Sistiaga, M., Larsen, R.B., and Nielsen, K.N., 2013b. Size selectivity of redfish (*Sebastes* spp.) in the Northeast Atlantic using grid-based selection systems for trawls. Aquat. Living Resour. 26. 109–120.

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (Sebastes spp.) in North Atlantic trawl codends. J. Nor. Atlan. Fish. Sci. 44, 1-13.

Jørgensen, T., Ingo` lfsson, O.A., Graham, N., Isaksen, B., 2006. Size selection of cod by rigid grids—is anything gained compared to diamond mesh codends only? Fish. Res. 79, 337–348.

Larsen, R.B., Isaksen, B., 1993. Size selectivity of rigid sorting grids in bottom trawls for Atlantic cod (*Gadus morhua*) and haddock (*Melangorammus aeglefinus*). ICES Mar. Sci. Symp. 196, 178‑182.

Larsen, R.B., Herrmann, B., Sistiaga, M., Grimaldo, E., Tatone, I., Onandia, I., 2016. Size selection of redfish (Sebastes spp.) in a double grid system: Quantifying escapement through individual grids and comparison to former grid trials. Fisheries Research 183, 385-395.

Sistiaga, M., Brinkhof, J., Herrmann, B., Grimaldo, E., Langård, L., Lilleng, D., 2016. Size selective performance of two flexible sorting grid designs in theNortheast Arctic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) fishery. Fish. Res. 183, 340-351.

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R.B., 2010. Assessment of dual selection in grid based selectivity systems. Fish. Res. 105, 187-199.

Wileman, D. A., Ferro, R. S. T., Fonteyne, R., and Millar, R. B. (Eds.), 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Cooperative Research Report No. 215.

Fig. 1: Sorting grids that are mandatory in the Norwegian Sea (North of 62°N) and the Barents Sea trawl fisheries: (a) Sort-X, (b) Sort-V, and (c) Flexigrid. The figure illustrates cod and haddock are in the aft of the trawl often observed swimming in the towing direction.

Fig. 2: a) Sketch of the double grid section used during the experiments. The two different angles tested for grid$_1$ are illustrated. b) Dimensions of the two grids inserted in the section, grid$_1$ (left) and grid$_2$ (right). c) Picture showing a side view of the section. d) Picture taken from inside the section that illustrates the installation of grid$_1$ and grid$_2$.

Fig. 3: Sketch of the set-up used to collect selectivity data.

Fig. 4: a) Picture of the original 2-panel Sort-V section taken in a flume tank (Hirtshals, Denmark), where white arrows mark the position of the lifting panel. The white circle illustrates the lack of space between grid$_2$ and the lower panel in the section. b) Picture of the double grid section tested in this study taken in the flume tank. The white circle illustrates that the grid does not press the section's lower panel and reduce the entrance to the codend in the same way as the original Sort-V grid design does (a). c) Picture of the double grid section tested in this study as observed during the sea trials. The white ellipse shows that there is an opening between grid$_2$ and the lower panel (grid$_1$) in the section.

Fig. 5: Underwater sequences that illustrate a) cod not contacting either of the two grids, b) cod contacting and escaping through grid$_1$, and c) cod contacting and escaping through grid$_2$.

Fig. 6: Underwater sequences that illustrate a) haddock not contacting either of the two grids, b) haddock contacting and escaping through grid$_1$, and c) haddock contacting and escaping through grid$_2$.

Fig. 7: Selectivity results for cod. Panels a, b, and c show respectively the escapement from grid$_1$, escapement from grid$_2$, and the retention of the grid section when grid$_1$ was configured at a low angle (35$^{o}$). Panels d, e, and f show respectively the escapement from grid$_1$, escapement from grid$_2$, and the retention of the grid section when grid$_1$ was configured at a high angle (40$^{o}$). Circle-marks represent the experimental rates, and the thick black curve represents the modelled rate. The stippled curves represent 95% confidence limits for the modelled rate. The grey curve represents the size distribution of cod in the respective compartments GC$_1$, GC$_2$, and CC (Fig. 2).

Fig. 8: Selectivity results for haddock. Panels a, b, and c show respectively the escapement through grid$_1$, escapement through grid$_2$, and the retention of the grid section when grid$_1$ was configured at a low angle (35$^{o}$). Panels d, e, and f show respectively the escapement from grid$_1$, escapement from grid$_2$, and the retention of the grid section when grid$_1$ was configured at a high angle (40$^{o}$). Circle-marks represent the experimental rates, and the thick black curve represents the modelled rate. The stippled curves represent 95% confidence limits for the modelled rate. The grey curve represents the size distribution of cod in the respective compartments GC$_1$, GC$_2$, and CC (Fig. 2).

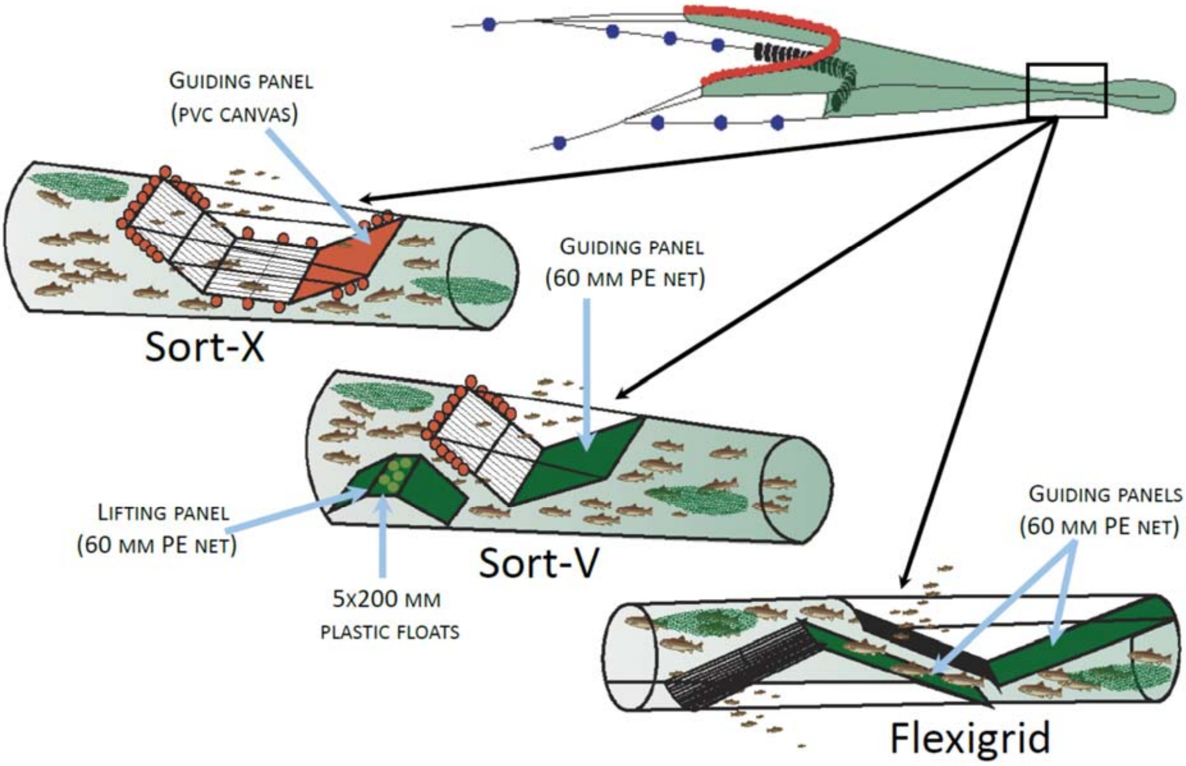
Fig. 9: Size selection for grid$_1$ and grid$_2$ conditioned that the fish enters the grid zone. Grid$_1$: grey curve. Grid$_2$: black curve. Combined for both grids: white circle marks. Stippled curves represent 95% confidence limits.

Fig. 10: Retention for both grids combined. For grid$_1$ with low angle (35$^{o}$): black. For grid$_1$ with high angle (40$^{o}$): grey.

Fig. 11: Comparison of the double grid retention probability (black) with the retention probability for the Flexigrid system (grey). From top, Flexigrid results from trials at Hopen (Hopen Island) for cod, Bjørnøya (Bear Island) for cod, and Bjørnøya for haddock. Stippled curves represent 95% confidence limits and vertical lines are minimum landing sizes for cod (44 cm) and haddock (40 cm).

Fig. 12: Comparison of the double grid retention probability (black) with the retention probability for the Sort-V grid system: grey curve (from Sistiaga et al., 2010), white circles (from Grimaldo et al., 2015). Stippled curves represent 95% confidence limits and vertical lines are minimum landing sizes for cod (44 cm) and haddock (40 cm).

FIG. 1



GUIDING PANEL
(PVC CANVAS)
Sort-X
GUIDING PANEL
(60 MM PE NET)
LIFTING PANEL
(60 MM PE NET)
5X200 MM
PLASTIC FLOATS
Sort-V
GUIDING PANELS
(60 MM PE NET)
Flexigrid

FIG. 2

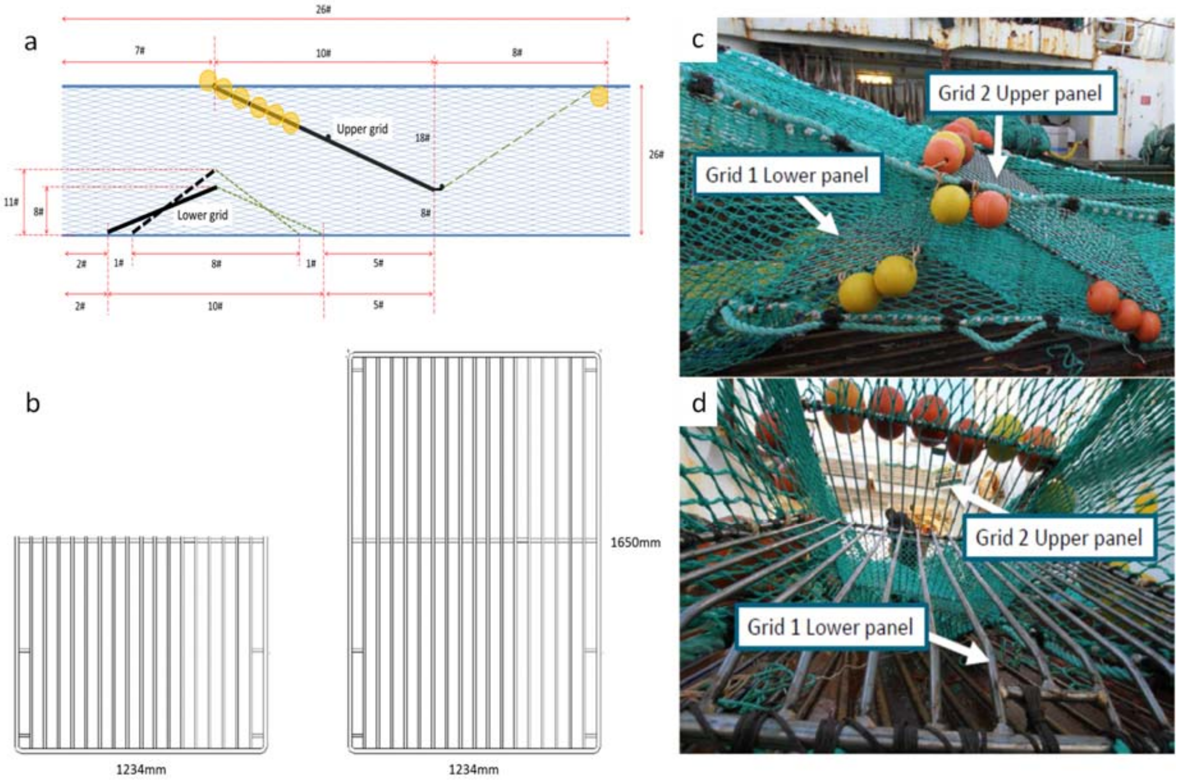

a
26#
7#
10#
8#
Upper grid
18#
26#
11#
8#
Lower grid
8#
2#
1#
8#
1#
5#
2#
10#
5#
b
1650mm
1234mm
1234mm
c
Grid 2 Upper panel
Grid 1 Lower panel
d
Grid 2 Upper panel
Grid 1 Lower panel

FIG. 3

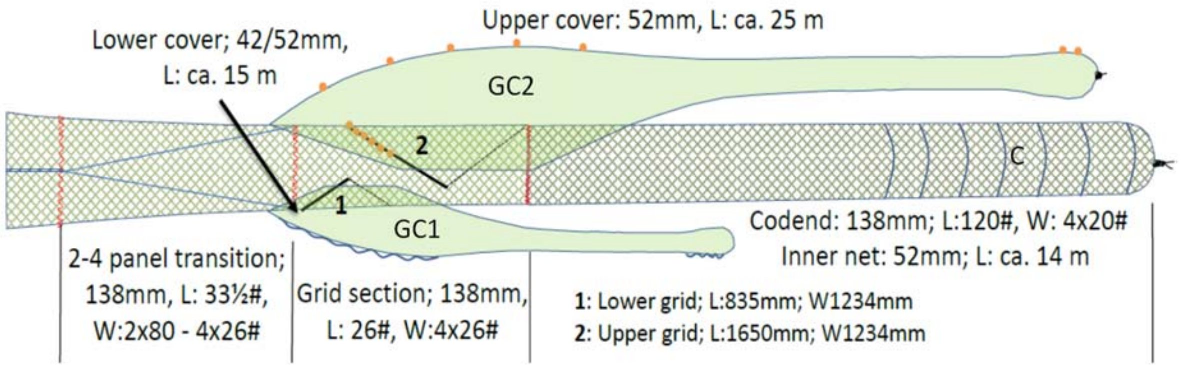

Upper cover: 52mm, L: ca. 25 m
Lower cover; 42/52mm,
L: ca. 15 m
GC2
2
1
GC1
C
Codend: 138mm; L:120#, W: 4x20#
Inner net: 52mm; L: ca. 14 m
2-4 panel transition;
138mm, L: 33½#,
W:2x80 - 4x26#
Grid section; 138mm,
L: 26#, W:4x26#
1: Lower grid; L:835mm; W1234mm
2: Upper grid; L:1650mm; W1234mm

FIG. 4

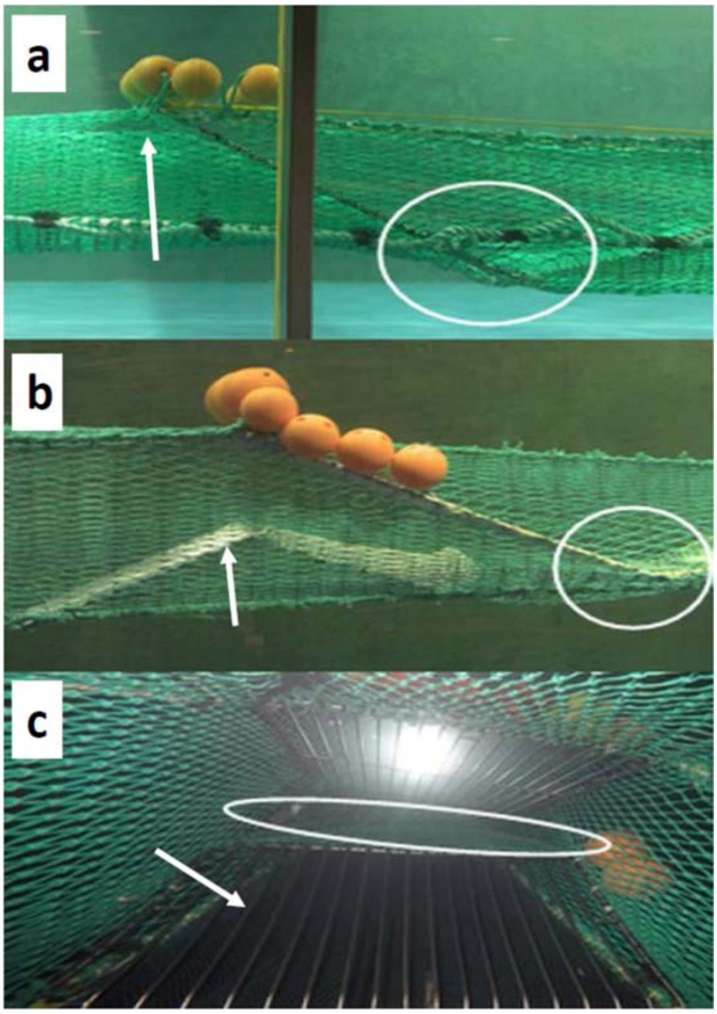


FIG. 5

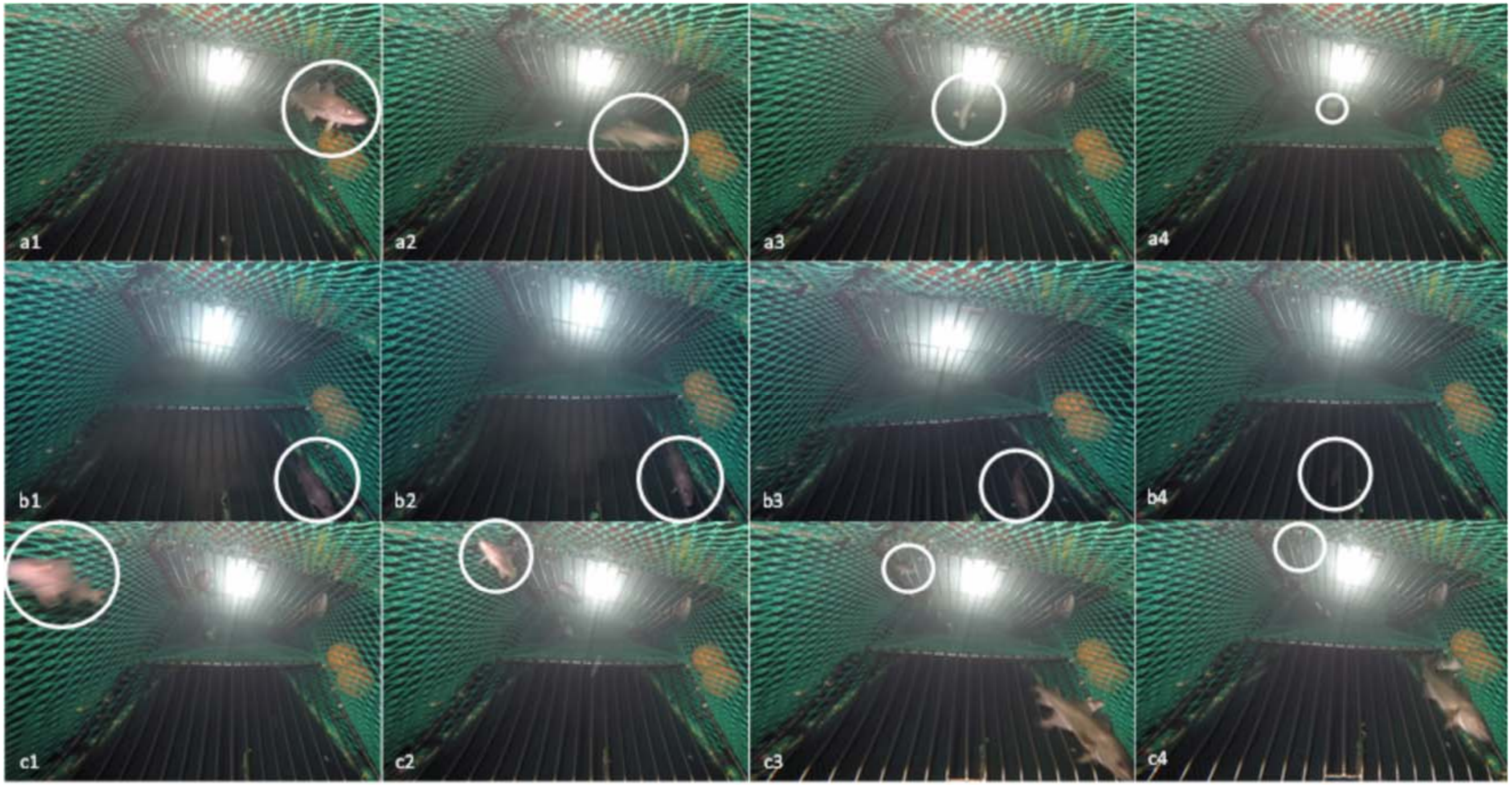


FIG. 6

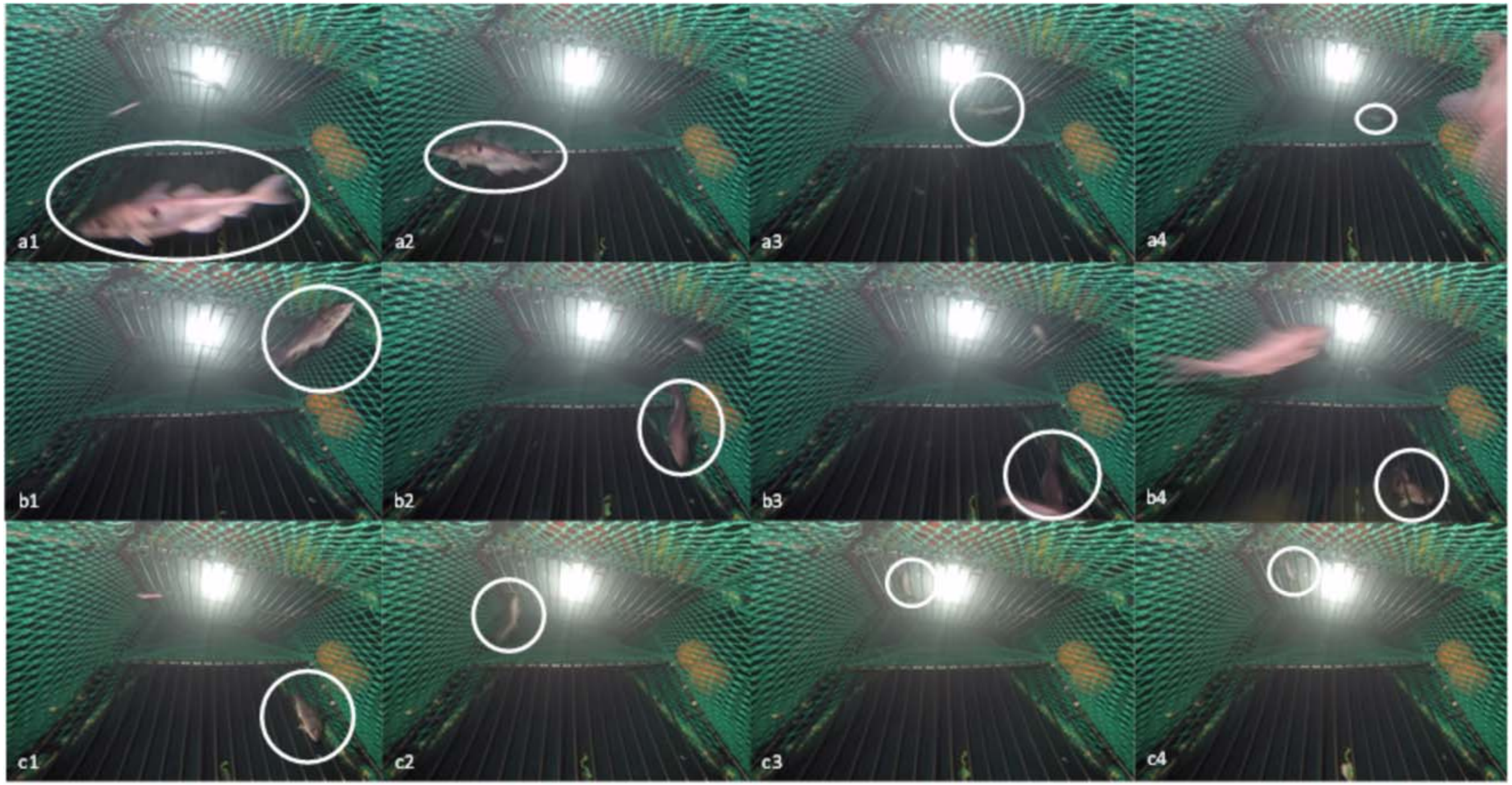


FIG. 7

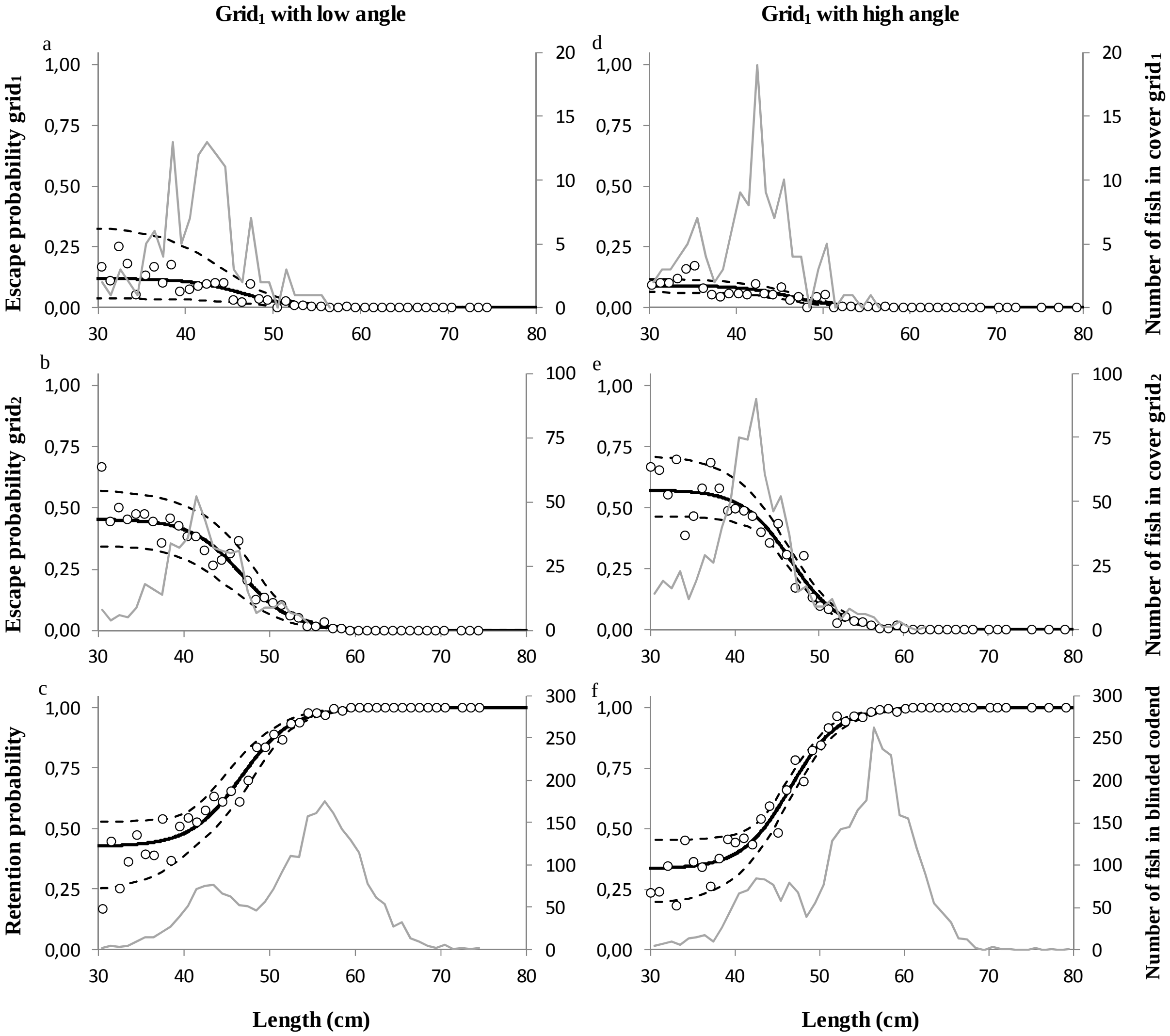
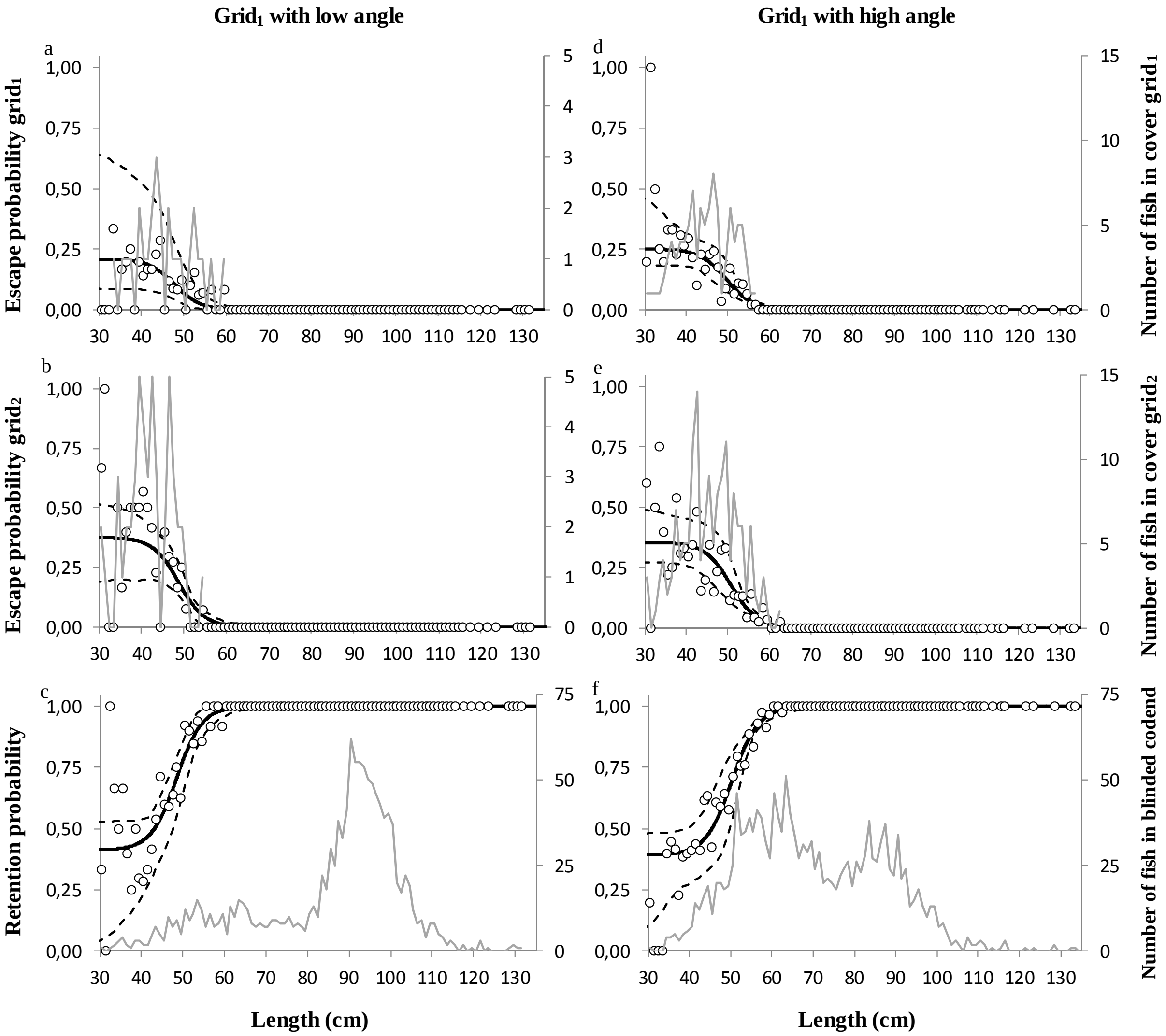

Grid$_1$ with low angle
Grid$_1$ with high angle
a
b
c
d
e
f
Escape probability grid$_1$
Escape probability grid$_2$
Retention probability
Number of fish in cover grid$_1$
Number of fish in cover grid$_2$
Number of fish in blinded codend
Length (cm)
Length (cm)
1,00
0,75
0,50
0,25
0,00
20
15
10
5
0
100
75
50
25
300
250
200
150
100
50
30
40
50
60
70
80

FIG. 8



Grid$_1$ with low angle
Grid$_1$ with high angle
a
b
c
d
e
f
Escape probability grid$_1$
Escape probability grid$_2$
Retention probability
Number of fish in cover grid$_1$
Number of fish in cover grid$_2$
Number of fish in blinded codend
1,00
0,75
0,50
0,25
0,00
0
1
2
3
4
5
10
15
25
50
75
30
40
50
60
70
80
90
100
110
120
130
Length (cm)
Length (cm)

FIG. 9

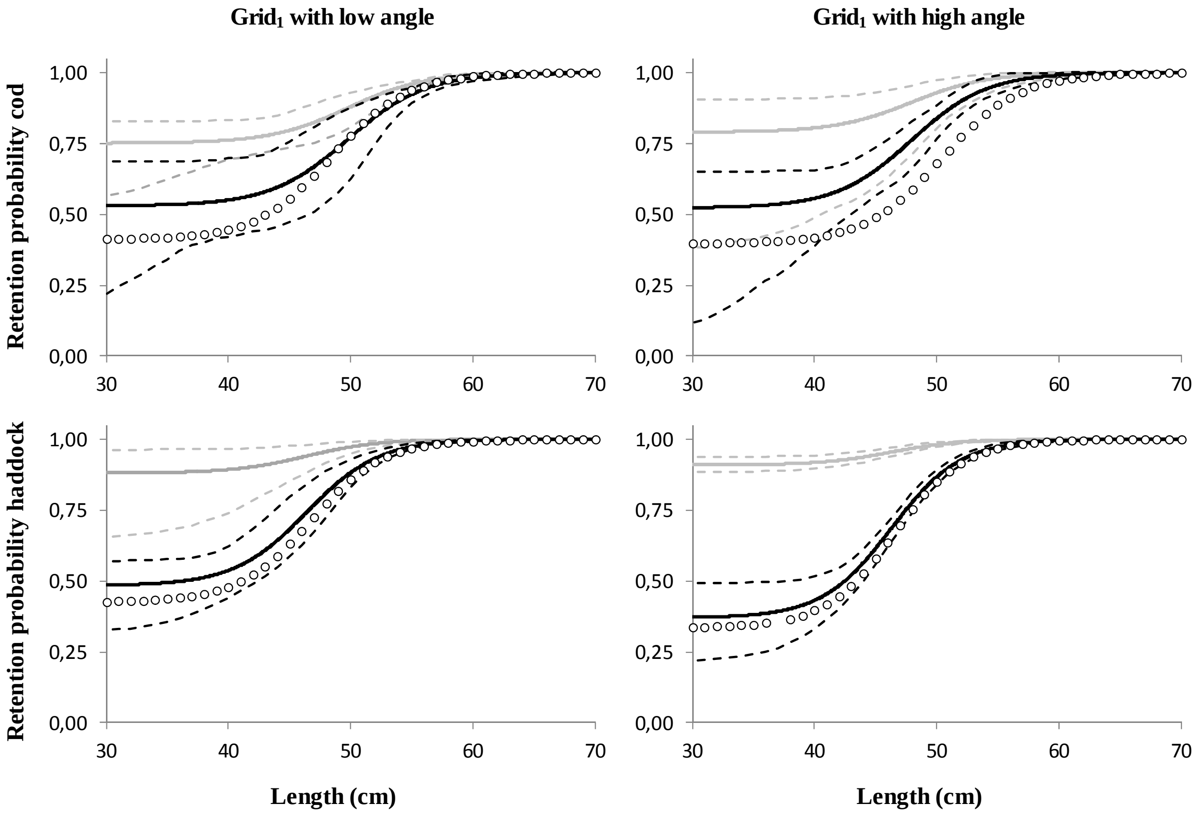

Grid$_1$ with low angle
Grid$_1$ with high angle
Retention probability cod
Retention probability haddock
1,00
0,75
0,50
0,25
0,00
30
40
50
60
70
Length (cm)
Length (cm)

FIG. 10

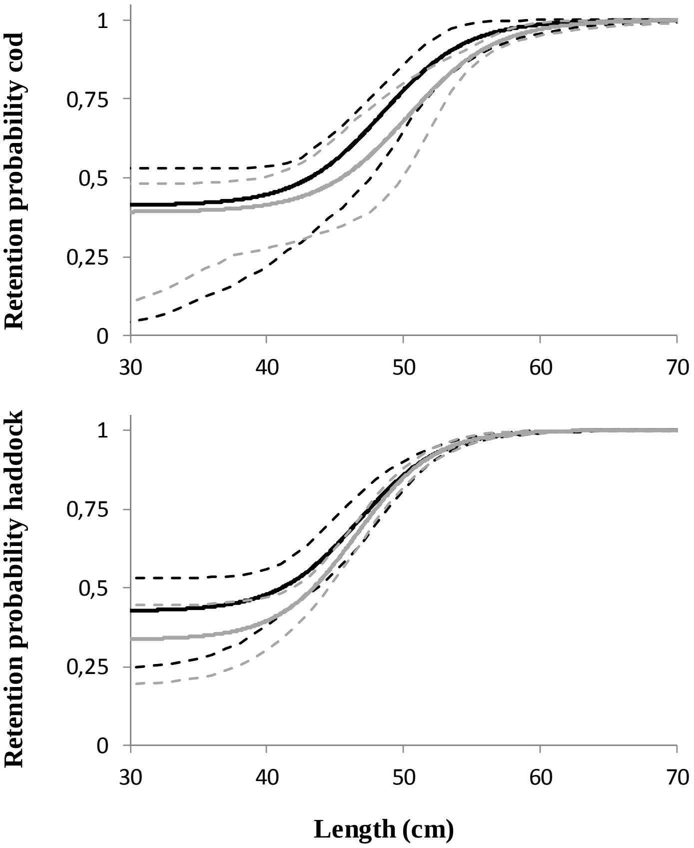

Retention probability cod
1
0,75
0,5
0,25
0
30
40
50
60
70
Retention probability haddock
1
0,75
0,5
0,25
0
30
40
50
60
70
Length (cm)

FIG. 11

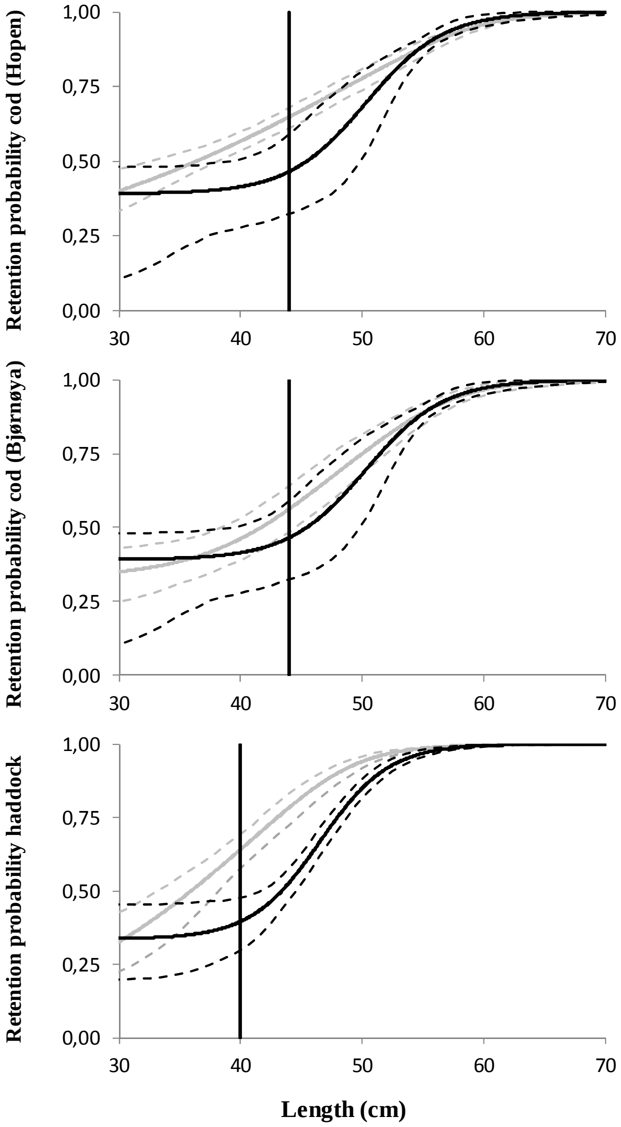
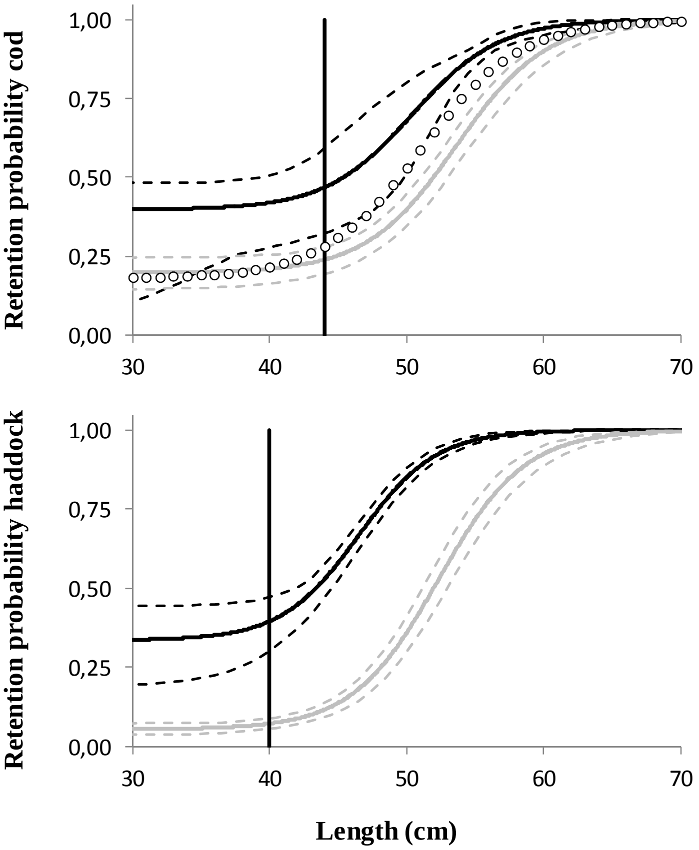

Retention probability cod (Hopen)
1,00
0,75
0,50
0,25
0,00
30
40
50
60
70
Retention probability cod (Bjørnøya)
1,00
0,75
0,50
0,25
0,00
30
40
50
60
70
Retention probability haddock
1,00
0,75
0,50
0,25
0,00
30
40
50
60
70
Length (cm)

FIG. 12



Retention probability cod
1,00
0,75
0,50
0,25
0,00
30
40
50
60
70
Retention probability haddock
1,00
0,75
0,50
0,25
0,00
30
40
50
60
70
Length (cm)

Table 1: Selectivity results and fit statistics for the constrained model. Values in () are 95% confidence interval. *: not defined.

| | Cod | | Haddock | |
|---|---|---|---|---|
| | Low angle ($35^o$) | High angle ($40^o$) | Low angle ($35^o$) | High angle ($40^o$) |
| number hauls | 8 | 10 | 8 | 11 |
| n escaped first grid | 27 | 99 | 121 | 121 |
| n escaped second grid | 50 | 154 | 479 | 780 |
| n retained | 1282 | 1660 | 2454 | 3100 |
| $L50_{combined}$ (cm) | 43.12 (* - 47.59) | 45.58 (39.51-49.86) | 41.07 (*-43.67) | 43.39 (41.67-44.57) |
| $SR_{combined}$ (cm) | *(*-15.65) | *(*-21.09) | *(*-11.59) | *(*-13.58) |
| $L50_1 = L50_2$ (cm) | 47.95 (41.51-50.53) | 49.25 (39.88-52.19) | 46.40 (42.91-48.47) | 46.29 (44.71-47.89) |
| $SR_1 = SR_2$ (cm) | 6.78 (2.91-10.88) | 7.40 (4.14-12.62) | 6.51 (4.90-8.33) | 6.21 (5.01-7.31) |
| $C_1$ (%) | 21.02 (8.91-65.79) | 26.24(18.65-52.86) | 11.95 (3.67-32.97) | 9.11 (6.29-11.84) |
| $C_2$ (%) | 47.75 (35.55-100) | 50.48 (37.18-97.89) | 51.64 (43.55-68.70) | 63.02 (50.76-78.65) |
| $\Delta C$ (%) | 26.73 (-10.65-46.98) | 22.09 (6.84-37.34) | 39.69 (20.04-54.11) | 53.92 (41.08-68.75) |
| $C_{combined}$ (%) | 58.73 (47.09-100) | 63.47 (52.05-99.12) | 57.42 (47.20-75.92) | 66.39 (54.56-80.62) |
| p-value | 1.0000 | 1.0000 | 0.9930 | 0.8500 |
| deviance | 50.70 | 58.15 | 55.53 | 72.51 |
| DOF | 184 | 172 | 84 | 86 |