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Combination of a sorting grid and a square mesh panel to optimize size selection in the North-East Arctic cod (*Gadus morhua*) and redfish (*Sebastes* spp.) trawl fisheries

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Sorting grids and square mesh panels are the two most-applied technical devices to supplement codend size- and species-selection in demersal trawls. In the Barents Sea gadoid fishery, the compulsory size-selectivity system comprises a mesh section with a sorting grid followed by a diamond mesh codend. We tested the size-selective performance of a new sorting section that comprised a sorting grid combined with a square mesh panel as a potential alternative for the grid sections currently in use. The new sorting section was shorter and therefore more maneuverable than the existing sorting grid sections. The investigation was carried out on cod and the bycatch species redfish. The grid was found to contribute to the largest proportion of fish release, and the release through the square mesh panel was low. But, the results showed that the grid was successful at guiding fish not escaping through the grid to a second selection process in the panel. However, the square mesh panel did not result on the intended release efficiency except for the smallest sizes of fish, most likely because the guiding angle of the grid and the square meshes in the panel used did not provide a suitable escape path for the desired size range of fish. Therefore, optimizing the mesh size/shape in the panel and/or the guiding angle for the grid potentially could lead to the desired selectivity pattern in the new sorting section.

Keywords: bottom trawl, fish behaviour, grid size selection, size selectivity.

Introduction

In many demersal trawl fisheries, size, and/or species selection in the codend has been found to be suboptimal. Therefore, in many of these fisheries, codend selection is supplemented by an additional selection device installed before, or in, the codend. Square mesh panels (Broadhurst, 2000; Catchpole and Revill, 2008; Alzorriz *et al.*, 2016; Brčić *et al.*, 2016) and sorting grids (Larsen and Isaksen, 1993; Sistiaga *et al.*, 2010; Herrmann *et al.*, 2013; Lövgren *et al.*, 2016) are the two most-broadly applied technical devices to supplement codend selection. In the Barents Sea, for example, the selectivity of a 130-mm diamond mesh codend is supplemented by the compulsory use of a sorting grid section installed before the codend. Fishermen can use three different grid section designs and all grids need to have a minimum bar spacing of 55 mm. The first grid section design introduced in the fishery, the Sort-X (Larsen and Isaksen, 1993), is rarely used by

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fishers. This design is composed of two steel grids and a canvas section that make it heavy (ca. 300 kg) (Figure 1), difficult to maneuver, and dangerous to use, especially in bad weather. The other two grid systems, one made with two grids known as Flexigrid (Sistiaga *et al.*, 2016) and the other a single steel grid system called Sort-V (Jørgensen *et al.*, 2006), are both lighter and easier to handle (Figure 1). The choice between the systems is usually the personal preference of the skipper.

Sorting grids have been compulsory in the Barents Sea gadoid fishery since 1997 and even though there has been improvement in their design, both fishermen and the authorities are constantly looking for designs that can make the grid section more efficient regarding size selectivity and easier to manoeuvre (lighter and smaller). In this study, we tested the size-selective performance of a new fish-sorting design that combined a sorting grid and square mesh panel as a potential alternative design. In this new design, the sorting grid was installed upside down compared to the Sort-V section and the top panel was substituted by a square mesh panel. The potential advantage of this design is hypothesized to be improved fish sorting efficiency. With traditional sorting grid designs, fish are required to make contact with the grid(s) to have a chance to escape. However, some fish may respond with avoidance behaviour to the grid(s), and therefore, only a fraction of the fish is size-sorted. This fraction is quantified by the grid contact parameter in selectivity studies (Sistiaga *et al.*, 2010; Larsen *et al.*, 2016). In the new grid system, a steel grid was installed in the lower panel to act as the first sorting mechanism. Fish that respond to the grid with an avoidance response are guiding upwards towards the second sorting device that consists of a square mesh panel. In this sense, the new design combines the most commonly applied sorting devices in trawls into one system, where the second device is meant to sort at least part of those fish that avoid the first device. The main hypothesis was that this combination would improve the sorting efficiency compared to traditional grid systems that cannot provide an additional sorting opportunity for fish.

Some studies have proven that guiding fish towards a square mesh panel increases its sorting efficiency significantly (e.g. Herrmann *et al.*, 2014). Given that the section has only one grid and does not require any additional lifting panel, it is substantially shorter than the traditional Flexigrid and Sort-V sections, which makes it more manoeuvrable and less likely to suffer from reduced water flow (Gjøsund, 2012).

The investigation was carried out for North-East Arctic cod (*Gadus morhua L.*) and redfish (*Sebastes* spp.), which are the main target and bycatch species, respectively, in the Barents Sea fishery (Yaragina *et al.*, 2011). On average, approximately 70% of the North-East Arctic cod in this fishery are caught with demersal trawls, highlighting the potential importance of this new gear for the fishery. Two species of redfish have traditionally been harvested in the Barents Sea: the beaked redfish (*Sebastes mentella*) and the golden redfish (*Sebastes marinus*). The stock of golden redfish is considered to be below sustainable levels and direct fishing for this species is not permitted (ICES, 2016). Beaked redfish can be commercially harvested (Planque and Nedreaas, 2015), however, directed fishing for this species is normally carried out with pelagic trawls and therefore, to avoid incidental catches of golden redfish as high release as possible of redfish from bottom trawls is desired.

The objective of this study was to investigate if a new sorting design can improve trawl selectivity compared to the grid-only systems currently in use. Specifically, we aimed to answer the following questions.

- To what extent do the grid and square mesh panel each contribute to the combined size selection in the sorting system?
- How well do the grid and the square mesh panel perform individually regarding size selectivity compared to the combined sorting system?
- How do cod and redfish behave in the new combined sorting system?
- How does the new combined sorting system perform compared to the size selectivity of the grid-alone systems currently in use?

Material and methods

Research vessel, study area, and gear set-up

The experimental fishing was conducted on board the research vessel "Helmer Hanssen" (63.8 m LOA and 4080 HP) in a fishing area outside the coast of Finnmark (North of Norway) between 70°29'–70°52'N and 30°08'–31°44'E. All data included in the study were collected from the 6th to the 15th of March 2017.

The Alfredo No. 3 two-panel Euronete trawl used in the experiments was built entirely of 155 mm nominal mesh size (nms) polyethylene (PE) netting (single Ø 4 mm braided knotted twine). The trawl had a headline measuring 36.5 m, a fishing line measuring 19.2 m, and a 454 mesh fishing circle. It was rigged with a set of bottom trawl doors (Injector Scorpion type, 8 m^2, 3 200 kg each), 60 m sweeps, and 111 m ground gear. The sides of

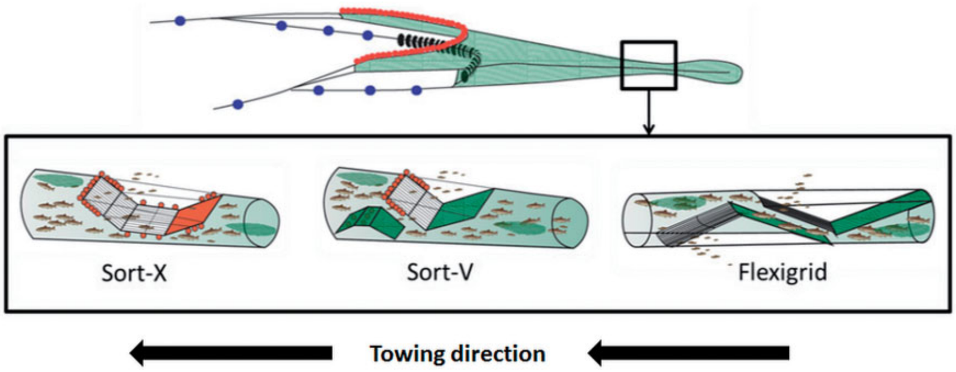

Figure 1. Legal grids for the North-East Arctic gadoid trawl fisheries.

the ground gear had five 53 cm (diameter) steel bobbins equally distributed on a 46 m chain (diameter = 19 mm), and the centre of the ground gear had a 19 m long rockhopper (with 53 cm rubber discs) that was attached to the fishing line of the trawl.

The new sorting design comprised a four-panel mesh section made of 138-mm nms Euroline Premium PE knotted netting (Polar Gold) (single Ø 8 mm braided twine). It was 29.5 meshes long (~ 4.6 m) and measured 80 meshes in circumference (~ Ø 1.2 m). All four selvedges were strengthened by 30 mm Danline PE ropes. A standard 55 mm bar spacing sorting grid, Sort-V type (1 650 mm high × 1 234 mm wide), was attached inside the section with an inclination angle of 23° ± 2° (Figure 2). The square mesh panel, comprising single Ø 8 mm braided knotless ultracross netting, was 50-meshes long (~3.5 m) and 17 meshes wide (~ 1.2 m) (Figure 2). The average mesh size in the panel was 144.30 ± 2.43 mm (mean ± SD), from 40 measurements taken with an ICES gauge (Westhoff *et al*., 1962).

To attach the four-panel sorting section to the trawl belly we constructed a transition section. The section, which was 35.5 mesh long, was built with 138 mm nms Euroline Premium PE knotted netting (single Ø 8.0 mm braided twine). A four-panel diamond-mesh codend was then attached after the sorting section. It was made from 138 mm nms Euroline Premium PE knotted netting (Polar Gold) (single Ø 8-mm braided twine). The codend was 40 meshes long (~6.2 m) and had 80 meshes of circumference (~Ø 1 m). All four codend selvedges were strengthened by 30 mm Danline PE ropes. The round straps were placed every 1.20 m apart and had a length of 6.9 m, which limited the expansion of the codend to 2.20 m at that point.

The purpose of the trials was to evaluate the size selection in the sorting section. Therefore, the codend was blinded by an inner net of 52 mm nms Euroline Premium PE knotted netting (Ø 2.2 mm single twine) with 300 meshes around. The number of meshes in the inner net ensured low meshes opening to retain fish. The use of round straps, which limited the expansion of the codend, also contributed to the low mesh opening.

We applied the Covered-gear method (Wileman *et al*., 1996) and used two identical covers to collect all fish escaping through the grid (grid cover) and the square mesh panel (panel cover) (Figure 3). The front part of the covers was made of square meshes of Dyneema netting (knotless 210/54 braided twine). The purpose of this netting was twofold: (i) to ensure that the water flow outside the trawl did not push the cover against the square mesh panel or the grid outlet; and (ii) to create enough water flow through the meshes to push the fish entering the covers to the cover codend. The back part of the covers comprised of Polyamid PA diamond mesh netting (2.5-mm Ø knotted braided twine). The average mesh size of the covers was estimated from

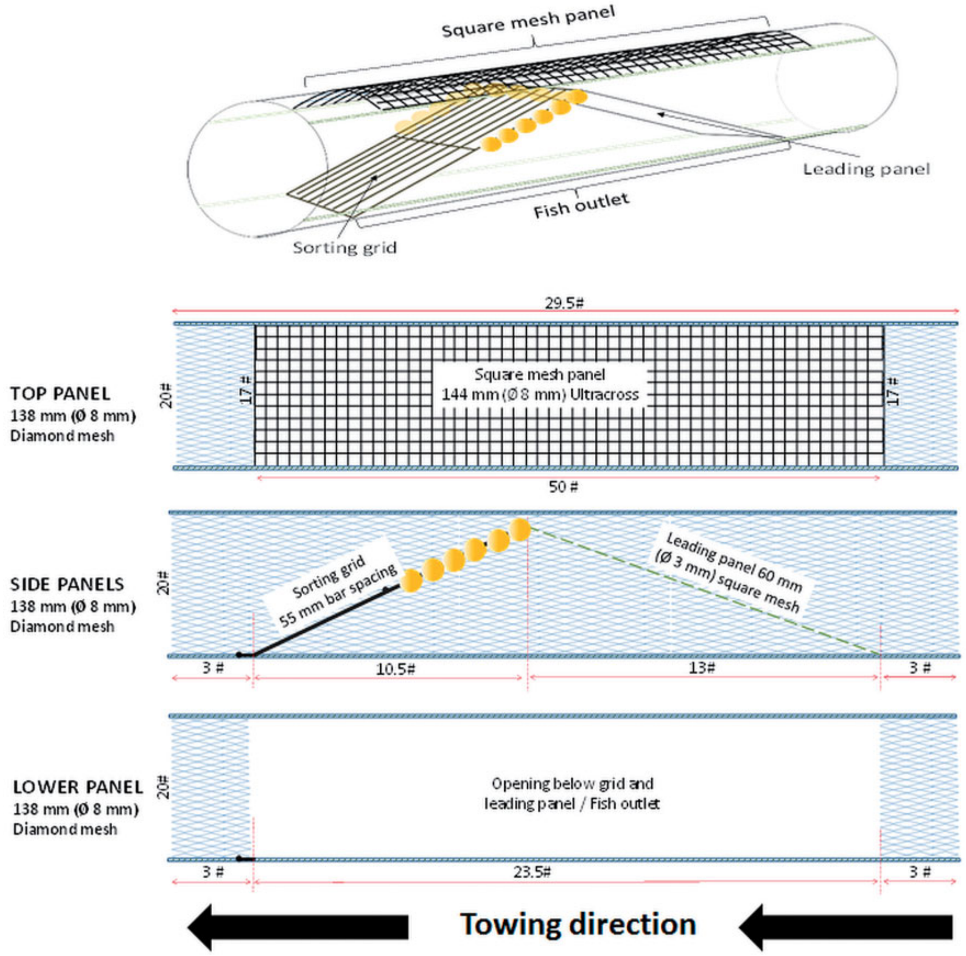

Figure 2. Schematic representation of the experimental grid section with the top square mesh panel used in the sea trials.

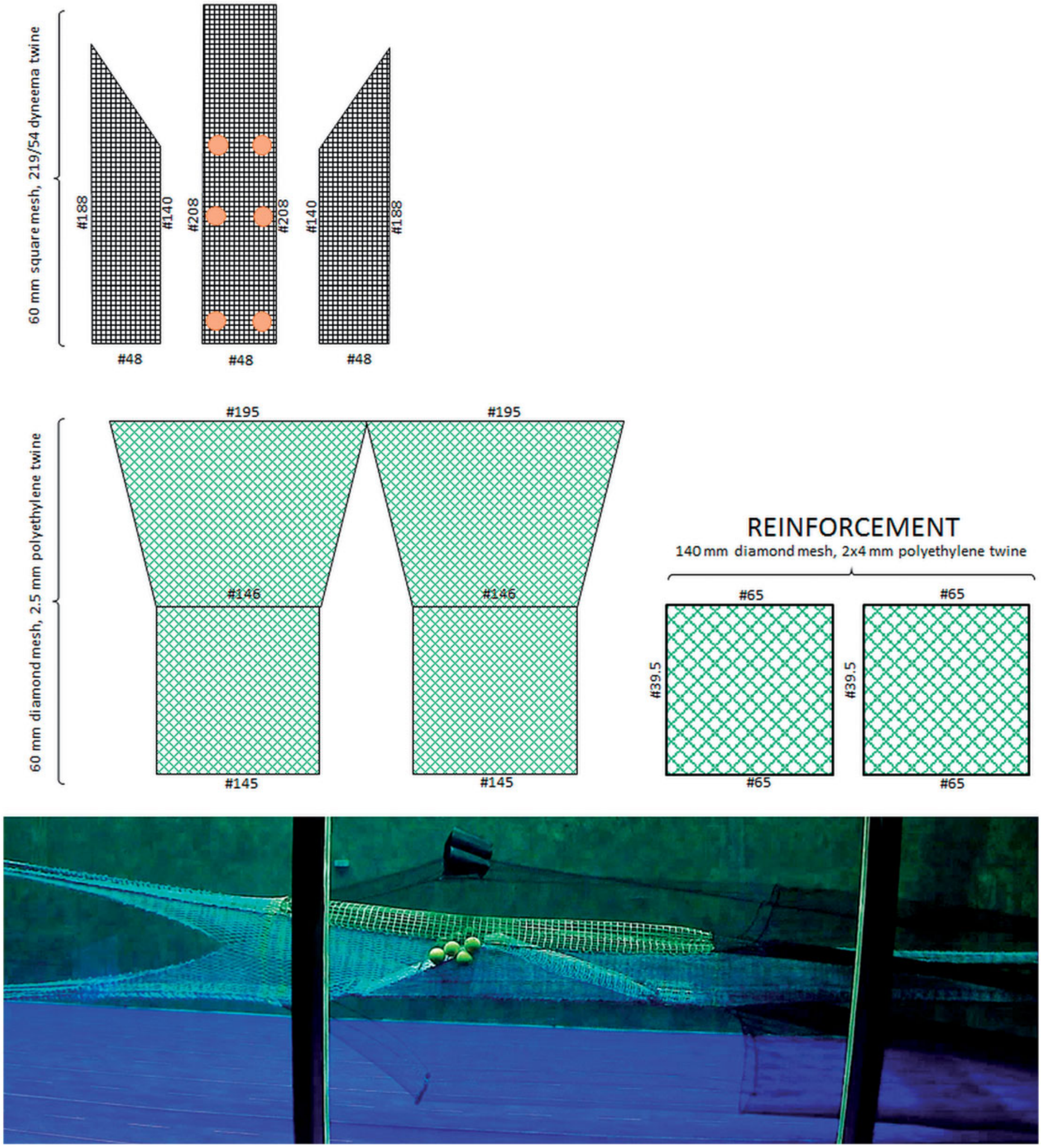

Figure 3. Technical specification of the covers used over the outlet of the grid and the square mesh panel. The picture below shows a snapshot of the tests carried out with the section and the covers in the flume tank before the tests at sea. Note that the kites used in the cover over the square mesh panel in the tests in the flume tank were substituted by six 20-cm floats during the trials at sea. The floats were fixed as specified in the drawing.

80 measurements (2 × 20 mesh rows were measured in each of the covers following guidelines of Wileman *et al.*, 1996) taken with an ICES gauge (Westhoff *et al.* 1962), and resulted in a mean mesh size of 57.41 ± 0.97 mm (mean ± SD). In the last 2 m of the cover, we installed a small mesh inner net made of approximately 10 mm meshes to ensure the smallest fish would not be able to escape from the cover net. The total length of both covers was approximately 18 m. At the front of the panel cover, we attached six plastic floats (Ø 20 cm) to secure its expansion and to ensure that it stayed clear from the panel. At the grid cover, chains weighing 1.6 kg were fixed to its lower panel to secure its opening.

All cod and redfish above 10 cm (total length) caught in the codend or covers were measured to the nearest centimeter. There was no subsampling. Golden redfish and beaked redfish are similar in morphology and shape, and difficult to distinguish especially at smaller sizes (Herrmann *et al.*, 2012). Further, they are often analyzed together as *Sebastes* spp. because the size-selective properties of the sorting devices are practically the same for both species (Herrmann *et al.*, 2012). Thus, all redfish in the study were analyzed as a single species.

To study fish behaviour in the grid section, we used a camera system in three of the hauls. This comprised a GoPro camera and two battery powered red LED lights in a stainless-steel frame. Red light was chosen because it is thought to affect fish behaviour less than more-traditionally used white light (Anthony and Hawkins, 1983). The camera was protected by a stainless-steel housing with a depth limit of 300 m.

Modelling the size selectivity for fish entering the sorting section

We adopted the model used by Larsen *et al.* (2016). This model is a dual sequential model that, when adapted to our sorting system, can be described mathematically by Equation (1). Equation (1) quantifies the fish length (l)-dependent probability of escaping through the grid $e_{\text{grid}}(l)$, of escaping through the square mesh panel grid $e_{\text{panel}}(l)$, and of being retained in the blinded codend $r_{\text{codend}}(l)$.

$$e_{grid}(l) = \frac{C_{grid}}{1.0 + \exp\left(\frac{ln(9)}{SR_{grid}} \times \left(l - L50_{grid}\right)\right)}$$

$$e_{panel}(l) = \left(\frac{C_{panel}}{1.0 + \exp\left(\frac{ln(9)}{SR_{panel}} \times \left(l - L50_{panel}\right)\right)}\right) \times \left(1.0 - \frac{C_{grid}}{1.0 + \exp\left(\frac{ln(9)}{SR_{grid}} \times \left(l - L50_{grid}\right)\right)}\right) \qquad (1)$$

$$r_{codend}(l) = 1.0 - e_{grid}(l) - e_{panel}(l)$$

In Equation (1), C_{grid} quantifies the fraction of fish entering the section that makes contact with the grid to obtain a size-dependent probability of escaping through it [see Larsen *et al.* (2016) for further details]. For those fish, $L50_{\text{grid}}$ and SR_{grid} are the selectivity parameters assuming a *Logit* size selection model (Wileman *et al.*, 1996). For the fish that reach the zone of the panel, meaning that they have not previously escaped through the grid, C_{panel} quantifies the fraction of fish that makes selectivity contact with it and is subject to a size-dependent probability of escape through this square mesh panel. For the fish making selectivity contact, $L50_{\text{panel}}$ and SR_{panel} are the selectivity parameters in the assumed *Logit* size selection model. The size selectivity in the sorting section is therefore fully described by the parameters C_{grid}, $L50_{\text{grid}}$, SR_{grid}, C_{panel}, $L50_{\text{panel}}$, and SR_{panel} [Equation (1)]. The selection properties of the individual devices, *grid*, and square mesh panels are then described by the parameters C_{grid}, $L50_{\text{grid}}$, and SR_{grid}, and C_{panel}, $L50_{\text{panel}}$, and SR_{panel}, respectively, applied in a *CLogit* size selection model. This model and parameters subsequently can be applied to predict the size selectivity for the devices if used individually [see Larsen *et al.* (2016) for further details for applying the model this way].

For the whole grid section (lower and upper grid combined), $L50_{\text{comb}}$ and SR_{comb} represent the overall selectivity parameters being estimated from Equation (1) using the numerical method described by Sistiaga *et al.* (2010).

Estimation of the selection parameters

The estimation was carried out separately for cod and redfish, as described below. The values for the parameters for the overall selection model (1) (i.e. C_{grid}, $L50_{\text{grid}}$, SR_{grid}, C_{panel}, $L50_{\text{panel}}$, and SR_{panel}) were obtained using Maximum Likelihood estimation based on the experimental data summed over hauls j (1 to m) by minimizing Equation (2):

$$-\sum_{l}\sum_{j=1}^{m}\left\{ng_{l,j} \times ln\left(e_{grid}(l)\right) + np_{l,j} \times ln\left(e_{panel}(l)\right) + nc_{l,j} \times ln\left(r_{codend}(l)\right)\right\} \qquad (2)$$

where $ng_{l,j}$, $np_{l,j}$, and $nc_{l,j}$ denote the number of fish caught in haul j with length l that were collected in the cover for the grid and square mesh panel and the codend inner net, respectively (Figure 3). Goodness of fit for the model was tested based on the p-value, model deviance versus degrees of freedom, and inspection of the ability of the model curves to reflect the trends in the length-based data (see Wileman *et al.*, 1996 for further information).

The Maximum Likelihood estimation based on Equation (2) using Equation (1) required summing the experimental data over hauls. However, this does not consider explicit variation in selectivity between hauls, referred to as between-haul variation (Fryer, 1991). Therefore, to account for between-haul variation in the uncertainty for the estimated size selection, the Efron 95% percentile confidence intervals (CIs) (Efron, 1982) were estimated for the model parameters and curves described by $e_{\text{grid}}(l)$, $e_{\text{panel}}(l)$, and $r_{\text{codend}}(l)$. The uncertainty was estimated using a double bootstrap method. The analysis was conducted using the software tool SELNET (Herrmann *et al.*, 2012) and applied 1000 bootstrap iterations for the estimation of the CIs.

With the *CLogit* model and the values for the selection parameters for the *grid* (C_{grid}, $L50_{\text{grid}}$, SR_{grid}) and the panel (C_{panel}, $L50_{\text{panel}}$, SR_{panel}), we obtained the size selection curves for the two grids in stand-alone deployments. The bootstrap procedure described above, was also applied to obtain 95% confidence limits for the stand-alone size selection curves for the grid and the square mesh panel.

Inference on evidence for significant difference in size selectivity between selection curves was based on inspecting the curves for length classes with lack of overlap between the 95% confidence bands.

Results

During the sea trials, we completed 20 valid hauls and length-measured 2 958 cod and 1 331 redfish (Table 1). The length spans varied between 10 and 120 cm for cod, and 10 and 64 cm for redfish.

Selectivity results

Assessment of the size selection of cod and redfish was conducted by fitting the model described in Equation (1) to the haul data summarized in Table 1. The estimated selectivity parameters and

Table 1. Summary of the number of cod and redfish caught and length-measured in each individual haul conducted.

	Cod			Redfish		
Haul	*ng*	*np*	*nc*	*ng*	*np*	*nc*
1	6	1	31	1	25	2
2	10	0	146	2	7	0
3	0	0	331	3	6	0
4	19	0	171	4	17	2
5	12	1	77	5	31	4
6	1	1	15	6	24	5
7	3	2	78	7	47	2
8	37	4	278	8	16	2
9	10	2	70	9	23	1
10	7	0	61	10	12	2
11	4	0	75	11	5	0
12	15	1	67	12	10	0
13	20	2	176	13	21	1
14	7	5	105	14	12	1
15	10	2	97	15	12	1
16	13	3	128	16	21	2
17	14	4	119	17	20	4
18	30	2	380	18	4	1
19	6	4	94	19	17	0
20	7	3	191	1	25	2
Sum	231	37	2690	330	30	971

ng: number in lower cover (grid). *np*: number in upper cover (square mesh panel). *nc*: number in blinded codend.

the fit statistics are provided in Table 2, while Figure 4 shows the fit of the model to the experimental data.

Figure 4 and Table 2 show that model (1) adequately describes the data for both cod and redfish. The curves estimated for grid escape, square mesh panel escape, and codend retention also followed the trend in the corresponding experimental data well (Figure 4). The p-values for the model were >0.05 (Table 2),

Table 2. Parameter values for the model and fit statistics.

	Cod	Redfish
$L50_{\mathrm{comb}}$ (cm)	41.41 (32.95–44.39)	29.33 (26.96–31.94)
SR_{comb} (cm)	25.64 (*–32.78)	13.14 (11.32–15.30)
C_{grid} (%)	51.24 (40.84–71.17)	86.44 (77.33–100.00)
$L50_{\mathrm{grid}}$ (cm)	48.19 (43.35–50.75)	30.40 (26.02–33.78)
SR_{grid} (cm)	7.22 (4.95–10.53)	12.42 (9.65–15.81)
C_{panel} (%)	100.00 (4.22–100.00)	100.00 (70.13–100.00)
$L50_{\mathrm{panel}}$ (cm)	22.98 (18.56–59.94)	16.38 (13.55–20.91)
SR_{panel} (cm)	16.84 (0.10–19.33)	9.73 (5.84–11.54)
p-value	>0.999	0.848
Deviance	104.26	96.7
DOF	200	112

L50 is the length at which a fish has a 50% chance of being retained and *SR* is calculated by subtracting *L25* from *L75*. C_{grid} quantifies the fraction of fish entering the section that makes selectivity contact with the grid whereas C_{panel} quantifies the fraction of fish making selectivity contact with the square mesh panel. DOF denotes degree of freedom. Values in () are 95% confidence limits. *: not defined.

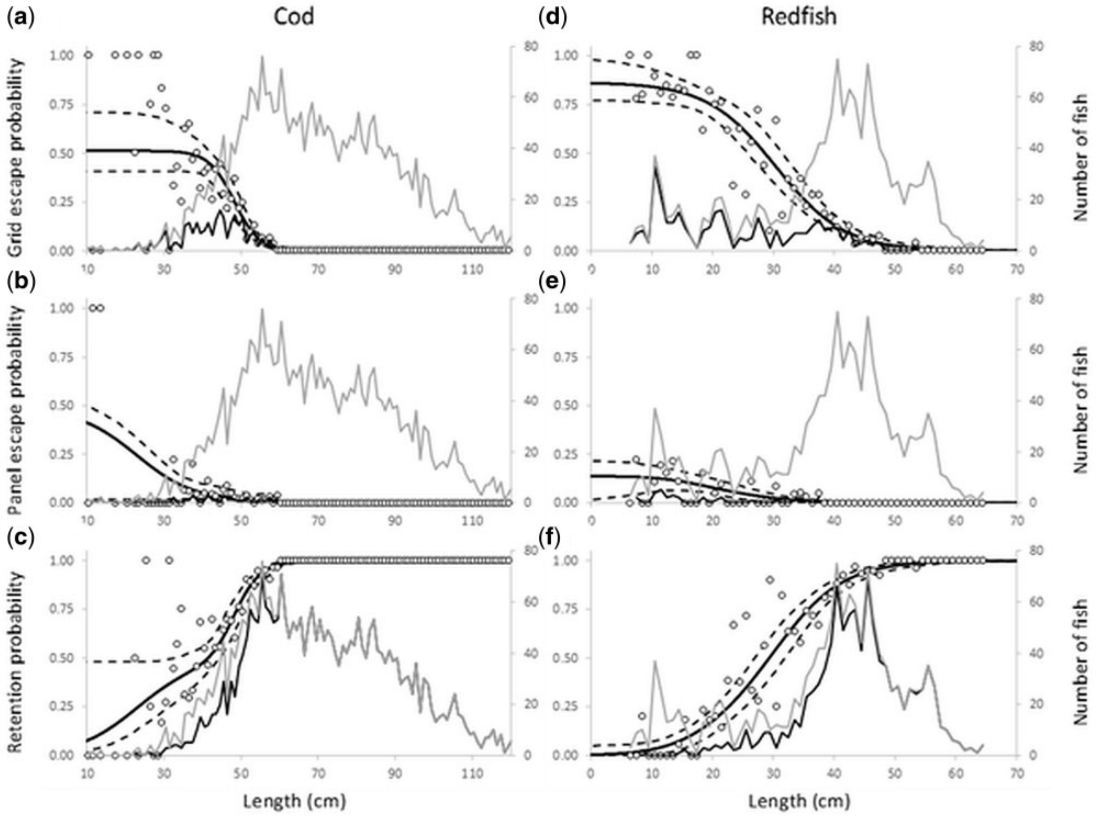

Figure 4. Panels (a), (b), and (c) show the escapement through grid, escapement through square mesh panel and the combined retention in codend for cod, respectively. Panels (d), (e), and (f) show the same for redfish. Circles represent the experimental rates and the thick black curve represents the modelled rate based on Equation (1). The stippled curves show 95% confidence limits for the modelled rate. The grey curve represents the population of cod (left column) or redfish (right column) entering the sorting section, while the thin black curve represents the population found in the specific compartment (grid cover, square mesh panel cover and cod end).

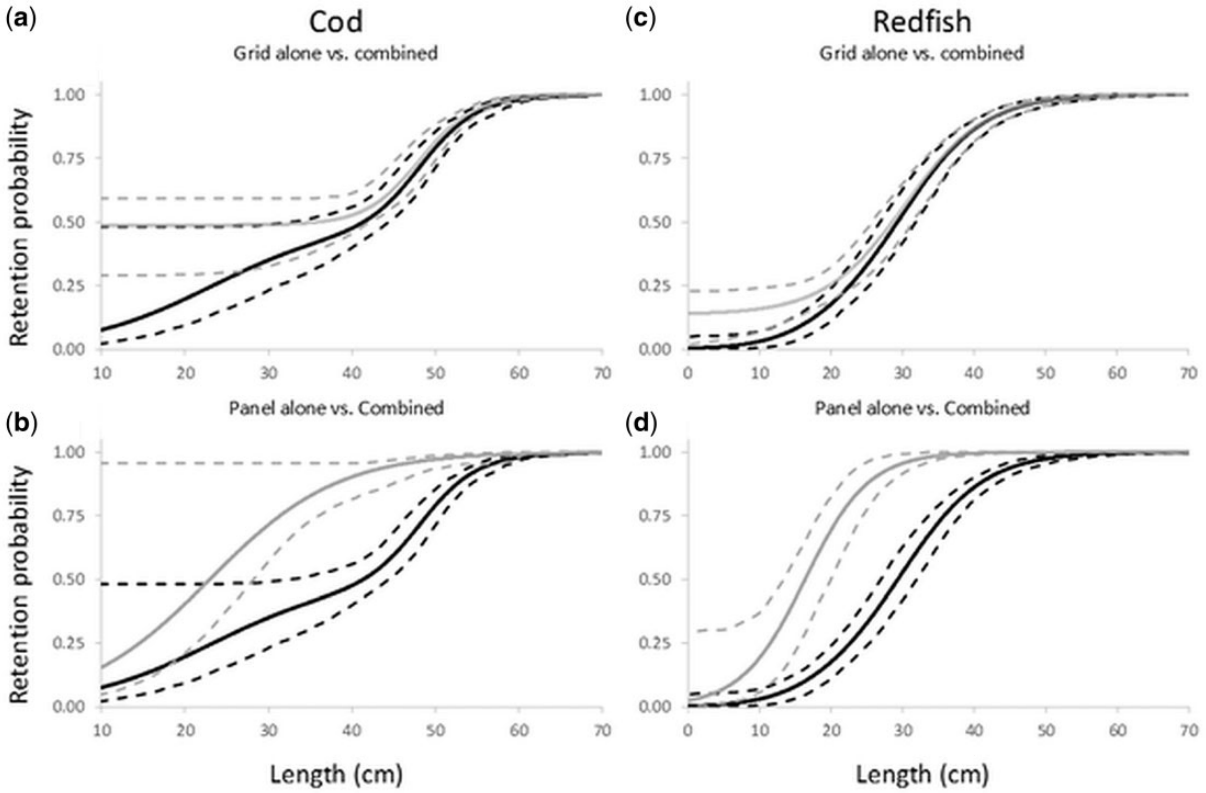

Figure 5. Comparison of the combined size selection in the sorting section (black curve) with that estimated for the grid and square mesh panel alone (grey curve). (a) Overall selection versus grid for cod. (b) Overall selection versus square mesh panel for cod. (c) Overall selection versus grid for redfish. (d) Overall selection versus square mesh panel for redfish. The stippled curves show 95% confidence limits for each selectivity curve.

implying that the observed discrepancy between experimental points and the modelled curves could be a coincidence. Therefore, we are confident that the model results can be applied to describe and investigate the size selection of both cod and redfish in the sorting section.

Approximately 50% (*CI*: 41–71%) of the smaller cod (<40 cm) were estimated to escape through the grid (Figure 4a). This limited percentage is reflected in the C_{grid} value and shows that, on average, 49% of the cod entering the section did not contact the grid (Table 2). The properties of the grid meant that the escape rate of cod longer than 40 cm gradually decreased, leading to no release of cod longer than 60 cm (Figure 4a). In model (1), this was quantified by the parameters $L50_{\text{grid}}$ ∼48 cm and SR_{grid} ∼7 cm (Table 2). For the smallest redfish (<20 cm), the release efficiency of the grid was higher than for small cod, which was reflected in a C_{grid} value of ∼86% (Table 2). However, the release rate decreased gradually for redfish in the size range ∼15–52 cm, with no release above this size (Figure 4d). For the square mesh panel, the release rates were smaller for both cod and redfish compared to the grid, even though, for both species C_{panel} was estimated to be high (Table 2). However, only fish that did not escape through the grid could escape through the square mesh panel. Specifically, it was estimated that the release rate through the square mesh panel for the redfish entering the section would never exceed 14% for any size and that no redfish longer than 35 cm would be released (Figure 4e). The square mesh panel was estimated to release only 5% of cod that were 40 cm long (Figure 4b). For a 30 cm-long cod, the estimated rate was 14%; however, the lower confidence limit was almost 0%. For cod shorter than 30 cm, the results were inconclusive for the release rate through the square mesh panel because of the low numbers of fish below this size and wide CIs. The size selection for the sorting section overall was represented by the retention probability in the blinded codend (Figure 4c and f). For cod that were 40 cm long, the retention probability was estimated to be ∼48%, increasing with size until exceeded 95% at 56 cm (Figure 4c). For redfish, the retention probability increased monotonously with size over a wide size range. The retention was estimated to be 8% at 10 cm and 94% at 45 cm (Figure 4f).

To illustrate how well the grid and square mesh panel performed as standalones compared to when used in combination in the new sorting section, we estimated selection curves for this based on model (1) (Figure 5). For both cod (Figure 5a) and redfish (Figure 5c), the estimated selectivity curves for the grid alone were closer to the combined selectivity curves for the sorting section than were the curves for the square mesh panel alone (Figure 5b and d). This was most obvious for redfish, where the confidence bands were narrow for all sizes of fish. For both cod and redfish, the square mesh panel showed significantly higher retention rates for a wide size range compared to the complete sorting section (Figure 5b and d). This was not the case for the grid as a standalone. These results further illustrate that the grid provides the most-efficient contribution to the overall size selection in this sorting section.

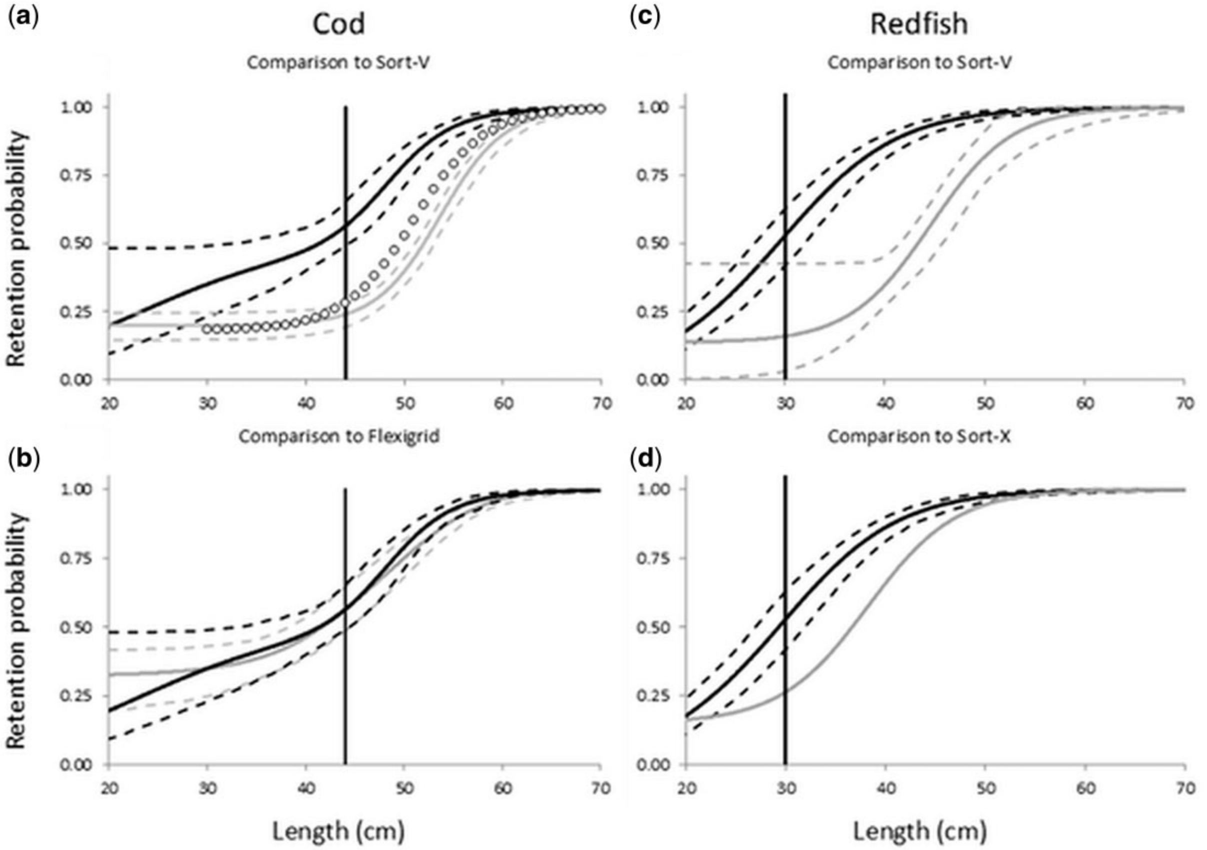

Figure 6. Comparison of the size selectivity for the new sorting section (black curve) with results available in the literature for other sorting grid sections (grey curve and circles). The stippled curves show 95% confidence limits for each selectivity curve. (a) cod results compared to results for the Sort-V grid results of Sistiaga *et al.* (2010) (grey curve) and Grimaldo *et al.* (2015) (circles). (b) cod results compared to results for the Flexigrid system (grey curve) presented by Sistiaga *et al.* (2016). (c) redfish results compared to results for the Sort-V grid (grey curve) obtained by Herrmann *et al.* (2013). (d) redfish results compared to results for the Sort-X grid (grey curve) presented by Herrmann *et al.* (2013).

To infer how well the new sorting section performed compared to the grid sorting sections currently in use in the fishery, we plotted the size selection for the sorting section tested in this study against results available in the literature for the Sort-V, Flexigrid, and Sort-X grid systems (Figure 6). These comparisons are valid and relevant under the assumption that both the results obtained for the new sorting design (in this study) and for the existing designs (from literature) reflect how the designs size select cod and redfish on average in the commercial fishing situation.

For the size selection of cod, the results of the present study were compared to those obtained by Sistiaga *et al.* (2010) and Grimaldo *et al.* (2015) with the Sort-V system (Figure 6a), and by Sistiaga *et al.* (2016) with the Flexigrid system (Figure 6b). When compared to the Sort-V system, it was evident that the new sorting section had a higher retention rate for a wide range of sizes of cod both below and above the minimum targeted size of 44 cm. Compared to the Flexigrid (Figure 6b), the new sorting section resulted in a similar size selection for all sizes of cod, with no significant difference for any length class. Regarding redfish, the new sorting section had significant higher retention above the minimum target size of 30 cm compared to results for the Sort-V system obtained by Herrmann *et al.* (2013). For redfish shorter than 30 cm, the confidence bands overlapped (Figure 6c). Compared to previous results obtained with the Sort-X grid system (Herrmann *et al.*, 2013), the comparison indicated that the retention probability for redfish both below and above the minimum target size was higher with the new sorting section. However, because the results provided for the Sort-X by Herrmann *et al.* (2013) had no confidence bands, inferences based on the comparison of these cases are only indicative.

Underwater recordings

The underwater recordings showed that the structure and geometry of the section worked as intended during trawling. There was no observation of a masking effect from the covers or clogging in the grid nor the panel.

We studied the behaviour of cod and redfish in detail in one of the three hauls recorded (65 min of duration). This was the only recording were the position of the camera (looking towards the grid) (Figures 7 and 8) and where underwater conditions allowed species to be clearly distinguished, especially cod and haddock. Most cod entered the section closest to the bottom panel and, then tried to swim downwards seeking passage through the grid (quantified by C_{grid} in the selectivity analysis) (Figure 7a–d and e–h). This downward swimming behaviour of cod is well documented in earlier studies (e.g. Engås and Godø, 1989; Wardle, 1993; Grimaldo *et al.*, 2017) and was observed for 80.3% (95%

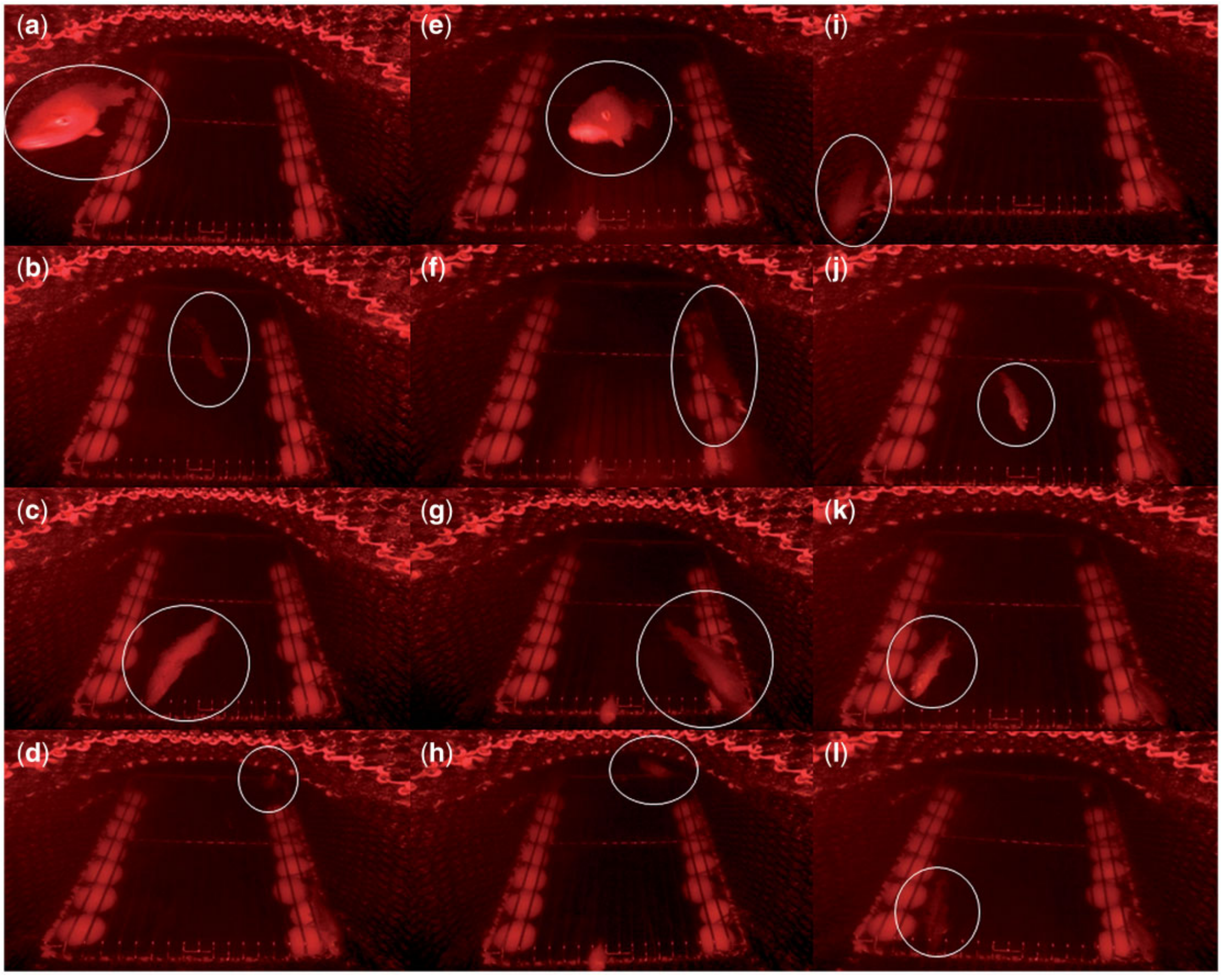

Figure 7. Snapshots from the underwater recordings showing cod trying to swim downwards once they felt the sorting grid (a–d and e–h), and cod first swimming downwards and passing through the grid after making selectivity contact with it (i–l).

CI: 70.4–88.7%) of the 71 cod observed entering the section (Supplementary material, cod video). Compared to cod, redfish entered the section relatively evenly distributed, a behaviour also documented in the literature (e.g. Larsen *et al.*, 2016). Furthermore, the behaviour conclusions of redfish drawn from our quantitative data were corroborated by the underwater recordings, because they showed that redfish were effective at escaping through the grid (Figure 4d). The recordings also showed that redfish that did not manage to escape through the grid sought upwards escape through the panel meshes (Figure 8a–d and e–h). This active behaviour inside the section, which is similar to the well-documented behaviour of haddock (e.g. Winger *et al.*, 2010; Sistiaga *et al.*, 2016), is not as well documented for redfish and was observed for 84.21% (95% *CI*: 68.4–100%) of the redfish 19 identified in the recordings (Supplementary material, redfish video).

Discussion

In this investigation, we tested a new fish-sorting design comprising a sorting grid and a square mesh panel in the Barents Sea gadoid fishery. The aim was to investigate whether such a section could provide any advantage in terms of the size selectivity of cod and redfish compared to the compulsory grid-only systems currently in use the fishery. When compared to the compulsory grid systems the new system has the advantages of being shorter, lighter and therefore more manoeuvrable and safe. The section is also less complex in construction than the existing grid sections, which makes it easier to maintain and repair. An additional advantage is that the size selection properties of the section can be partially modified with interchangeable square mesh panels of different size/shape.

For cod, the overall selectivity of the new tested section resulted in a $L50_{\text{comb}}$ value that was lower than desired and, on average, lower (41.41 cm) than the minimum target size for cod in the Barents Sea (44 cm). Furthermore, the upper confidence limit for the value was just above 44 cm (44.39 cm), indicating that, for the system to be in line with current legislation, $L50_{\text{comb}}$ would have to be increased (Table 2). When compared specifically with the Sort-V section, the tested section retained significantly more undersized cod than the Sort-V section (Figure 6a). This can be a major disadvantage for the tested section, especially in areas where the juvenile cod population is abundant, although juveniles not released from the section may still escape through the codend meshes. An advantage with the tested system was that it retained significantly more commercial-sized cod than the Sort-V grid, which, in areas with low juvenile densities, would

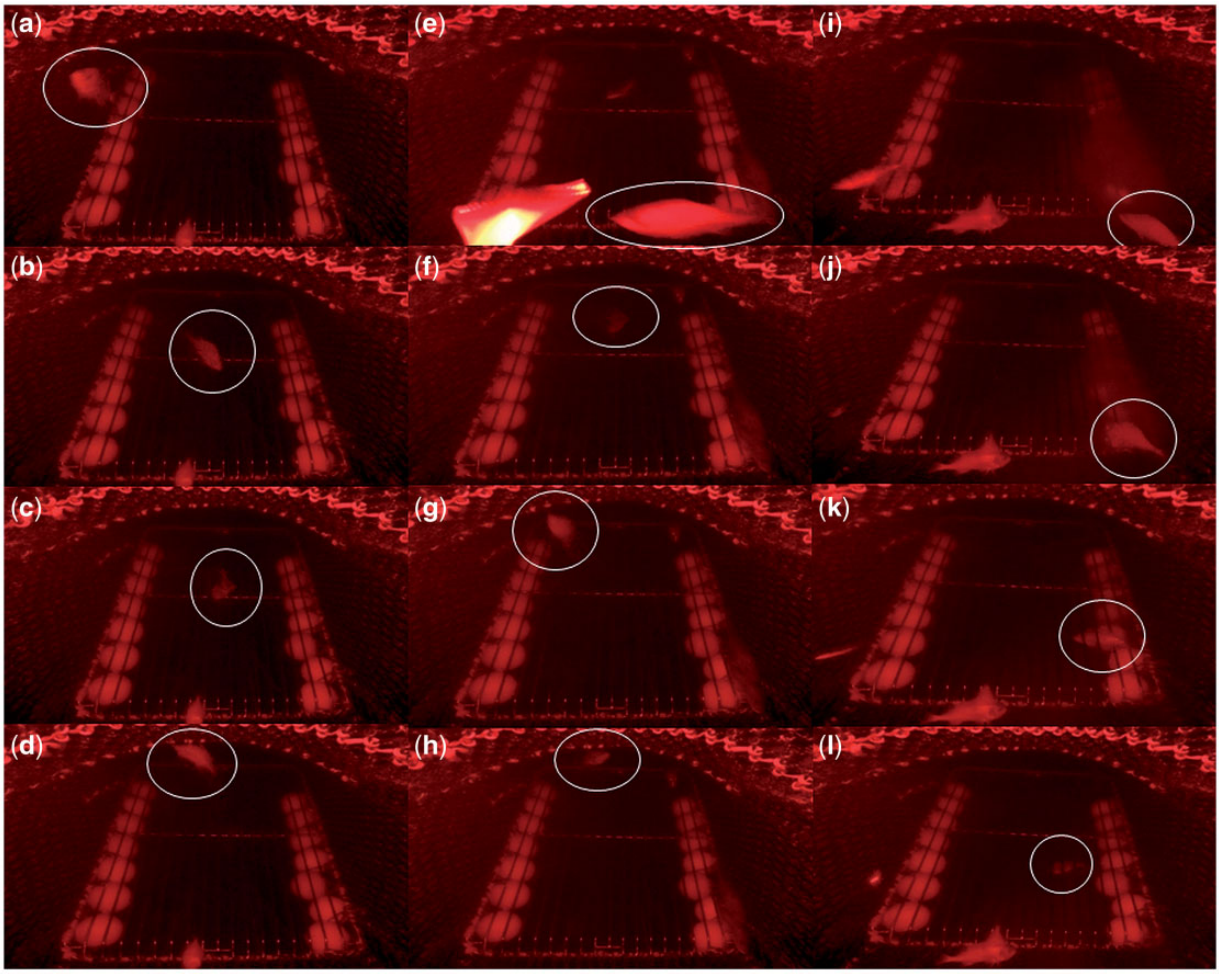

Figure 8. Snapshots (a–d) and (e–h) show two sequences where redfish first attempt to escape through the grid and after not being able to pass through the grid they contact the square mesh panel. The snapshots in sequence (i–l) show a redfish successfully escaping through the grid.

make the gear commercially more efficient according to current legislation. Previous studies showed that the Flexigrid system is less efficient at releasing juvenile fish than the Sort-V system (Sistiaga *et al.*, 2016). In the current study, we observed that, although differences between the Sort-V system and the new sorting section were clear, there were no significant differences between the Flexigrid and the new sorting system, neither for the fish shorter than 44 cm nor for the fish longer than 44 cm (Figure 6b). Assuming that the selective properties of the legal and compulsory Flexigrid system are satisfactory for cod from a management point of view, which, according to the results obtained by Sistiaga *et al.* (2016), is questionable, then the system presented in this study could also be a valid option for this fishery.

In terms of redfish, the average $L50_{\text{comb}}$ was also lower (29.33 cm) than the minimum target size for redfish in the fishing area (30 cm). Furthermore, the upper confidence interval was just under 2 cm bigger than the minimum size, demonstrating that, for the gear to be in line with current regulations for redfish, $L50_{\text{comb}}$ would have to be increased (Table 2). The differences indicated in Figure 6c show that, while the new sorting section did not retain significantly more undersized redfish than the Sort-V system (Herrmann *et al.* 2013), it retained substantially more commercially valuable sizes of this species. This demonstrates that, from a commercial point of view, it could be more profitable to use the new sorting system than the Sort-V grid system without adding any challenges from a management point of view, especially in areas where beaked redfish is most abundant.

The results show clearly that the fish-sorting design should be improved to enhance the selectivity of the smallest sizes of cod and redfish. Whereas the grid installed with the opening in the lower panel was not found to perform as well as the grid with the opening in the upper panel combined with a lifting panel (which is the compulsory Sort-V design), the contribution of the panel to the release of these two species was found to be a major issue. Especially for redfish, the release efficiency for the square mesh panel was low (Figure 4e). The C_{panel} values estimated were high, implying that redfish did make contact with panel when they were not able to escape through the grid (Table 2). This high contact value is in line with results for the double steel grid system presented by Larsen *et al.* (2016), which showed that redfish were effective at contacting the upper grid of the section tested. This indicates, that compared to cod, which have been reported multiple times to seek outlets in a mainly downwards direction (Engås and Godø, 1989; Wardle, 1993; Grimaldo *et al.*, 2017), redfish seek outlets more actively and also upwards, similar to other species, such as haddock (Winger *et al.* 2010). Even if the C_{panel}

values for redfish were high, the $L50_{\text{panel}}$ values estimated for the panel were low, indicating that the mesh size used in the panel was too small for redfish. Based on the design guide for redfish provided by Herrmann *et al.* (2013) we would expect a higher $L50_{\text{panel}}$ than the one estimated here. However, this result from Herrmann *et al.* (2013) was obtained for another mesh type than square meshes, therefore this result should only be used as indicative here. For optimal escape through the square mesh panel the fish would need to attack the mesh perpendicularly (angle of attack = 90°). If the actual attack angle is lower than 90°, the projected mesh becomes rectangular and the opening becomes smaller [see Krag *et al.* (2014) for the concept of mesh projection]. We could speculate that this is the reason for the low values obtained for $L50_{\text{panel}}$ for both cod and redfish. Specifically, if we assume that the attack angle is as low as the grid angle (23°), the mesh would look like a rectangular mesh with a shape of 28 × 72 mm. This mesh could thereby potentially explain low values obtained for $L50_{\text{panel}}$ (Table 2), although we could expect that to some extent fish would adjust their angle of attack on their way to the square mesh panel. As we assume that the obtained low $L50_{\text{panel}}$ values are the main cause to the unanticipatedly low $L50_{\text{panel}}$ values, changes in the projected mesh (shape and size) would potentially improve the selectivity performance of the panel and the sorting efficiency of the section. Based on the above speculation, there are two obvious ways to increase $L50_{\text{panel}}$. First, to improve the attack angle for the fish towards the square mesh panel increasing the grid angle, and second, to use rectangular meshes instead of square meshes so that the projected mesh would become a square mesh that corresponds with the desired mesh size. The high C_{panel} values estimated for both species showed that the concept of guiding fish towards a second device with the grid was successful (Table 2). Combining this with the above described potential ways of improving $L50_{\text{panel}}$, we believe that the new sorting concept presented in this study can have a potential if those modifications are applied.

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Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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