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Original Article

Understanding the release efficiency of Atlantic cod (*Gadus morhua*) from trawls with a square mesh panel: effects of panel area, panel position, and stimulation of escape response

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Based on size selectivity data for more than 25 000 cod (*Gadus morhua*) collected during experimental trawl fishing with six different codends, all of which included a square mesh panel, we investigated the effect on cod-release efficiency based on the size of the square mesh panel area, position of the square mesh panel, and stimulation of the escape response. Based on the results, we were able to explain why the BACOMA codend, applied in the Baltic Sea cod directed trawl fishery, releases juvenile cod efficiently, whereas other designs, including a square mesh panel with similar mesh size, are less efficient. Our main findings reveal that the release efficiency of the square mesh panel in the BACOMA codend depends largely on the overlap of the square mesh panel and the catch-accumulation zone in the codend, where cod do not have the option of just drifting further back in the trawl when proximate to the panel. On the contrary, the reduction in panel size by 50% did not significantly affect the release efficiency when the panel overlapped with the catch-accumulation zone. It was possible to stimulate an escape response for cod to achieve a release through a square mesh panel positioned *away* from the catch-accumulation zone. Our findings demonstrated that this release was as efficient as for a panel mounted *in* the catch-accumulation zone of the codend. Devices that stimulate behaviour may improve the release efficiency of cod through square mesh panels in other fisheries where this is a problem.

Keywords: BACOMA, cod (*Gadus morhua*), escape behaviour, escape efficiency, square mesh panels, stimulation of escape.

Introduction

Square mesh panels are often inserted into diamond mesh codends or other sections of trawls to increase the release probability of undersized individuals or non-targeted roundfish species entering the trawl (Catchpole and Revill, 2008). Compared with diamond mesh of the same mesh size, square mesh is more efficient at releasing roundfish, such as cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) (Herrmann *et al.*, 2009; Krag *et al.*, 2011). The relatively small opening angle of diamond mesh tends to correspond poorly to the morphology of roundfish (Herrmann *et al.*, 2009; Krag *et al.*, 2011). In some situations, fishing has led to high retention probabilities of undersized cod. This is often the case in mixed-species trawl fisheries targeting small species, such as the crustacean *Nephrops* (*Nephrops norvegicus*). In these fisheries,

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the efficient retention of *Nephrops* requires codends constructed of relatively small mesh (Frandsen *et al*., 2010). This also results in high retention probabilities of roundfish species, such as cod. Since some Northeast Atlantic cod stocks have been in unsatisfactory condition during the past two decades, the release of cod from fishing gear has become particularly interesting (Madsen, 2007). Therefore, the use of trawls with square mesh panels for *Nephrops* directed trawl fisheries has been the subject of intensive research in recent decades (Catchpole and Revill, 2008). However, not all attempts, where square mesh panels are applied to improve the release efficiency of juvenile cod in the *Nephrops* directed trawl fishery, have been sufficiently successful. Unlike other roundfish species such as haddock, cod is known to enter the trawl close to the seabed and mainly follow a path closer to the bottom panel unless visual stimuli are used to raise their vertical position in the aft end of the trawl (Main and Sangster, 1981, 1985; Ferro *et al*., 2007; Krag *et al*., 2009a; Rosen *et al*., 2012). Furthermore, cod appears to have a low activity level when inside trawls (Briggs, 1992; Rosen *et al*., 2012), making it particularly challenging to achieve sufficient release efficiency for cod through square mesh panels, which often are inserted in the upper panel of the trawl. One example of this challenge is demonstrated in Frandsen *et al*. (2009). They reported a significant increase in the size selection for haddock, but were not able to detect any significant improvement for cod when comparing a trawl using a 120-mm square mesh panel inserted in a section in front of the 90-mm mesh size diamond mesh codend with a similar trawl without this square mesh panel.

One construction that is relatively efficient at releasing juvenile cod through a square mesh panel is the BACOMA codend used in the Baltic Sea trawl fishery targeting cod (Figure 1; Madsen *et al*., 2002). One important feature of the BACOMA codend is that the square mesh panel (6 m long) positioned in the upper panel continues all the way down to the codline, except for a few mesh rows of diamond mesh to ensure a proper geometry when the codend is closed. Therefore, the square mesh of the escapement panel in the BACOMA codend is always available for cod in the aft end of the codend, where most fish have been observed to escape (Beverton, 1963). At this position in the gear, cod will enter the

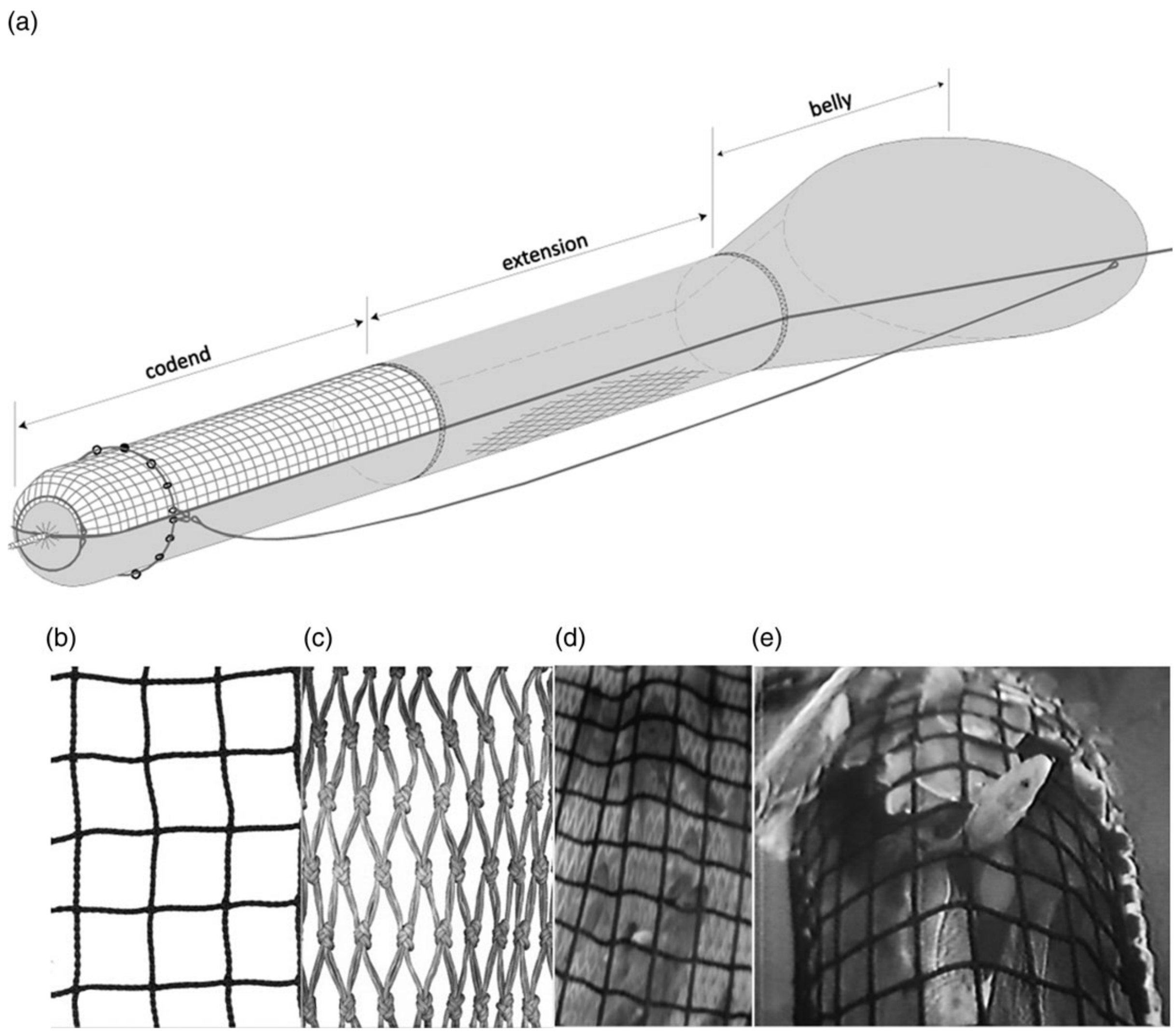

Figure 1. (a) BACOMA codend used in the Baltic trawl fishery targeting cod. (b) Scan of the 120-mm square mesh netting (single-twine Ultra Cross) used in the upper panel of the codend. (c) The 105-mm diamond netting (double-twine polyethylene) used in the lower panel. (d) Image showing cod swimming close to the bottom panel ahead of the catch-accumulation zone. (e) Image of a cod escaping through the square mesh panel just in front of the catch accumulation.

catch accumulation unless they try to escape. One could speculate that this is why the square mesh panel in the BACOMA has acceptable release efficiency for cod. For a square mesh panel positioned away from the catch-accumulation zone, where low release of cod has been found (Bullough *et al.*, 2007), cod has the option to drift deeper into the trawl in the direction of the catch-accumulation zone. Fish appear to have a preference for following the passage that is most open, and so cod might not perceive any other danger in this part of the gear than touching the netting (Wardle, 1993; Glass *et al.*, 1995). This could explain why individuals do not try to escape although they could easily pass through the mesh (Krag *et al.*, 2009b). Especially for panels inserted in the top of the non-tapering sections of the trawl, it could be speculated that it is not attractive for cod to change their direction of movement by 90° to attempt escapement through a square mesh panel unless the most open path is blocked, for example, by large aggregations of fish, or if the geometry in the trawl section is collapsed, making contact unavoidable. Some individuals are exhausted, especially smaller ones as a result of their poorer swimming ability, and are not able to attempt active escapement (Winger *et al.*, 2010). For other individuals, drifting in the direction of the codend may be a more energy-efficient behaviour than attempting to escape (Peake and Farrell, 2006).

In the *Nephrops* directed trawl fisheries, a square mesh panel in the aft end of the codend (as with the BACOMA codend) could result in the high rate of contact between *Nephrops* and the square mesh panel. Thereby, a square mesh panel with a mesh size that allows undersized cod to pass through the mesh could easily release well-sized *Nephrops* (Frandsen *et al.*, 2010). Therefore, the potential contact between *Nephrops* and the panel could result in the loss of valuable catch, as seen in the prawn fishery (Broadhurst *et al.*, 2002). An alternative strategy could be to increase the efficiency of square mesh panels positioned away from the catch-accumulation zone by stimulating cod to attempt escape. Kim and Whang (2010) have described a study where fluttering ropes were employed inside the codend to stimulate fish to escape through the codend mesh. This kind of device may also increase the release efficiency of cod through square mesh panels. If proven successful in a cod directed fishery, this approach could be adapted to the *Nephrops* directed fisheries.

Based on the considerations above, the aim of this study was to investigate the mechanisms that affect the release efficiency of cod through a codend square mesh panel. Because the study was conducted in the cod directed fishery in the Baltic Sea, the baseline codend design was the legal BACOMA codend used there (EU Regulation No. 686/2010). From this starting point, our study aimed to address the following research questions:

(i) Is the efficient release of undersized cod of the BACOMA codend the result of the panel position, which overlaps the codend catch-accumulation zone, where the fish are forced to react to avoid entering the catch, or is it the result of the large panel area?

(ii) If it is the panel position, would it be possible to stimulate an escape response for cod through a less optimally positioned square mesh panel and thereby achieve a release efficiency comparable with that of the BACOMA codend?

Using different variants of BACOMA-like codends during sea trials, we investigated the square mesh panel escapement efficiency for Baltic cod.

Material and methods

Codend designs

We tested six different codends (D1–D6; Figure 2 and Table 1). Codend D1 is the standard BACOMA codend used in the Baltic trawl fishery, defined in EU Regulation No. 686/2010. Codend D2 differed from D1 by a shorter square mesh panel (50% reduced length) positioned at the aft end of the codend. Thus, for codends D1 and D2, the square mesh panel overlapped the catch-accumulation zone. Codend D3 was similar to codend D2 except that the short square mesh panel was positioned closest to the extension piece. The distance from the square mesh panel to the codend's binding strap was ca. 3 m, and so the square mesh panel did not overlap the catch-accumulation zone for codend D3. The last three codends, D4, D5, and D6, were identical with codend D3, except that they had devices mounted to the bottom panel of the codend underneath the square mesh panel. These were meant to guide cod upwards to the square mesh panel and stimulate their escape behaviour instead of allowing them to drift in the direction of the catch-accumulation zone. Codend D4 was mounted with a

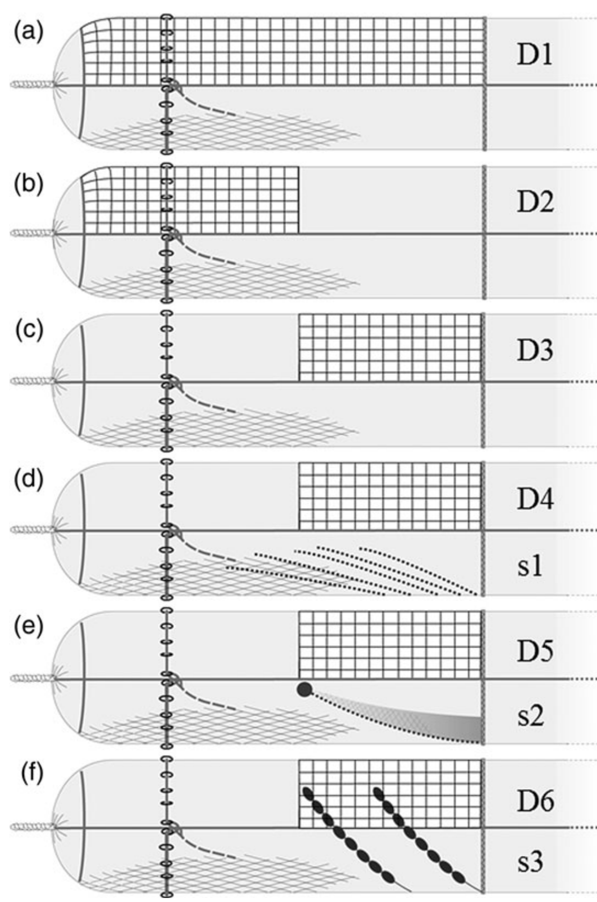

Figure 2. Schematic drawings of the six codend designs. (a) D1: standard BACOMA codend used in the Baltic Sea. (b) D2: same as D1, but with shortened (50%) 120-mm square mesh panel positioned in the aft end of the codend. (c) D3: same as D2, but with the 120-mm square mesh panel located in the front part of the codend. (d) D4: same as D3, but with fluttering ropes mounted as a stimulating device (*s*1). (e) D5: same as D3, but with inclined panel mounted as a stimulating device (*s*2). (f) Same as D3, but with float ropes mounted as a stimulating device (*s*3).

Table 1. The parameterization of the six codends (D1–D6) used for modelling.

Design	*Edge*	*Short*	*s*1	*s*2	*s*3
D1	1	0	0	0	0
D2	1	1	0	0	0
D3	0	1	0	0	0
D4	0	1	1	0	0
D5	0	1	0	1	0
D6	0	1	0	0	1

The parameter *edge* describes whether or not the square mesh panel overlaps the catch-accumulation zone (0, no overlap; 1, overlap). The parameter *short* describes whether or not the square mesh panel is shorter than the standard BACOMA codend (0, full panel length; 1, panel shortened by 50%). Parameters *s*1, *s*2, and *s*3 describe whether or not the codend design is mounted with a stimulation device (0, no stimulation device; *s*1, fluttering ropes; *s*2, inclined panel; *s*3, float ropes).

stimulation device *s*1, whereas codends D5 and D6 were mounted with stimulation devices *s*2 and *s*3, respectively.

A stimulation device *s*1 consists of several fluttering ropes with positive buoyancy (floating ropes). The ropes were attached to the lower panel beneath the square mesh panel in the codend. The mechanism's purpose was to cause the ropes to flutter at an inclined angle relative to the horizontal when the codend was towed through the water. The stimulation device *s*2 consists of a small-meshed netting panel with a few floats mounted at the aft end of the panel to create an inclination angle. The anterior part of the panel was attached to the lower panel in the codend. The purpose of device *s*3 was the same as device *s*1, but with floats (six floats per rope, with 0.115 kg buoyancy each) on thicker floating ropes that were attached to the bottom panel of the codend in two transversal rows. The combination of ropes and floats was meant to give greater buoyancy than the ropes in device *s*1 and the net panel in device *s*2, and to create fluttering movement more violently than device *s*1. Table 1 summarizes the characteristics of the six codend designs.

Sea trials

Experimental fishing trials with the six codends were conducted in 2012 on-board the German Fishery Research Vessel (FRV) "Solea" (total length 42 m; 950 kW), during two cruises in the Arkona Basin, western Baltic Sea. The first cruise took place 16 March–4 April, and the second cruise took place 17–27 September. The sea state ranged between 0 and 3.5 on the WMO scale (Table 2). During the spring cruise, size selectivity data for cod were collected from 30 valid hauls using codends D1, D2, D3, and D4 (Table 1). During the autumn cruise, size selectivity data for cod were collected from 11 valid hauls using codends D3, D5, and D6. Thus, the use of codend D3 during both cruises allowed the assessment of potential between-cruise effects of the size selectivity of cod. Each of the six codends was fished alternately, while attached to the same trawl and the same extension piece. All hauls were done during daytime at a towing speed of ca. 3 knots. The trawl was a "Codhopper", which had a 160-mm mesh size in the belly and a circumference of 530 meshes. The extension piece was a T90 construction where the diamond mesh netting is turned 90° compared with the traditional use (Wienbeck *et al.*, 2011). The extension piece had 50 open meshes around, were 50 meshes in length, and were made of a nominal 120-mm mesh size and single 5-mm yarn. The codend was the only change in gear between individual hauls.

The covered codend method (Wileman *et al.*, 1996) was applied. Supporting hoops were applied to keep the cover netting clear of the test codend. The cover was connected to the extension piece two mesh rows in front of the codend. It was a two-panel construction of diamond mesh netting with a total of 264 meshes in circumference and 238 meshes long. The cover mesh size was 80 mm. Previous experience during experimental fisheries in the same region has demonstrated that fishing with a smaller cover mesh size is difficult because of the retention of large amounts of herring in the cover (Wienbeck *et al.*, 2011). Following the recommendations of Wileman *et al.* (1996), this cover mesh size was relatively large compared with the codend mesh sizes of 105 and 120 mm. Therefore, special attention was given in the analysis to avoid potential effect of cover size selection on the assessed codend size selection. Specifically, length classes <25 cm were removed from the data before analysis, since there could be expected a considerable probability for that cod <25 cm would be able to escape through a cover with this mesh size (Madsen *et al.*, 2002). The catch was sorted by species, and all cods were length measured to the nearest centimetre below. No subsampling was performed.

Data analysis

To model the length-dependent observed retention probability *r_O* of cod in individual hauls conditioned that they were present in the codend or the codend cover, we used a logistic curve (Wileman *et al.*, 1996):

$$r\_O(l, L50\_O, SR\_O) = \frac{\exp\big([\ln(9)SR\_O] \times [l - L50\_O]\big)}{1 + \exp\big([\ln(9)SR\_O] \times [l - L50\_O)]\big)}. \quad (1)$$

The parameter *L50_O* is the length of cod with 50% chance of being retained given it enters the codend, and the observed selection range was $SR\_O = L75\_O - L25\_O$ (Wileman *et al.*, 1996). The values of *L50_O* and *SR_O* were obtained by fitting (1) to the experimental data using a maximum-likelihood estimation following the procedure described in Wileman *et al.* (1996). The capacity of the logistic curve to model the data from individual hauls was inspected based on the *p*-value. This *p*-value quantifies the probability to obtain at least as big a discrepancy between the fitted model and experimental data as observed by coincidence. Therefore, this *p*-value should not be <0.05 for the applied model to describe the experimental data at an acceptable level (see Wileman *et al.*, 1996 for details).

If no escapement through the 80-mm codend cover, the estimated retention curve based on the estimated *L50_O* and *SR_O* would represent the codend size selection for all length classes. But if cover release in some of the smaller length classes applied in the analysis, the observed retention curve can be biased for the smaller length classes compared with the codend selection curve. Between codend designs (Table 1), we assumed that the mean differences in *L50_O* and *SR_O* were caused by differences in the release efficiency of the square mesh panel. The analysis considered the between-haul variation in the observed codend retention process and the effect of codend design parameters using a model including fixed and random effects (Fryer, 1991). The fitting procedure was conducted in two steps (see Fryer, 1991, for details). First, the hauls were analysed individually to obtain *L50_O* and *SR_O* together with their covariance matrix as described above. Second, maximum likelihood was used to combine these results over hauls using the values of the design parameters (*edge*, *short*, *s*1, *s*2, *s*2, and *s*3) for the codends in individual hauls (Table 1). The additional

Table 2. Results obtained for the observed retention parameters *L50_O* and *SR_O* of cod for individual hauls.

Haul	Codend	*Sea*	*w* (kg)	*c2*	*L50_O*	*SR_O*	R_{25}	R_{33}	No. in codend	No. in cover	*p*-values
1	D3	3.5	190	0	−2.17 (±121.86)	25.40 (± 77.99)	0.91	0.95	99	3	0.86
2	D3	2.5	348	0	21.31 (±14.21)	14.50 (±12.58)	0.64	0.85	197	15	0.97
3	D3	2	486	0	29.13 (±3.42)	13.97 (±5.51)	0.34	0.65	269	75	1.00
4	D3	1	1234	0	31.12 (±1.47)	9.10 (±1.85)	0.19	0.61	725	130	1.00
5	D3	2	1464	0	32.26 (±1.39)	10.30 (±2.00)	0.18	0.54	852	204	0.94
6	D3	1	427	0	30.68 (±2.82)	13.97 (±4.51)	0.29	0.59	339	93	1.00
7	D3	1	898	0	37.51 (±1.25)	7.89 (±2.42)	0.03	0.22	109	95	0.78
8	D3	1	820	0	30.94 (±1.02)	6.44 (±1.12)	0.12	0.67	1000	110	0.98
9	D2	2	291	0	40.30 (±0.83)	7.93 (±1.61)	0.01	0.12	221	250	0.96
10	D2	2	842	0	39.12 (±0.39)	6.82 (±0.69)	0.01	0.12	842	859	0.99
11	D2	2	181	0	37.01 (±1.41)	8.60 (±3.07)	0.04	0.26	127	81	0.81
12	D2	2.5	289	0	36.69 (±0.73)	7.10 (±1.24)	0.03	0.24	259	277	0.42
13	D2	2	1151	0	30.23 (±1.96)	9.58 (±1.96)	0.23	0.65	1226	118	1.00
14	D2	1	312	0	40.20 (±0.54)	6.07 (±1.09)	0.00	0.07	305	338	0.96
15	D1	1	978	0	35.24 (±1.10)	9.14 (±1.89)	0.08	0.37	458	186	0.41
16	D1	1	538	0	38.83 (±0.81)	7.50 (±1.63)	0.02	0.15	258	207	0.67
17	D1	0	704	0	40.59 (±0.76)	5.49 (±1.44)	0.00	0.05	147	154	0.98
18	D1	0	340	0	41.08 (±0.53)	5.87 (±1.04)	0.00	0.05	289	376	0.99
19	D1	0	527	0	41.84 (±0.53)	6.61 (±0.99)	0.00	0.05	372	495	0.97
20	D1	1	422	0	37.74 (±0.88)	7.26 (±1.57)	0.02	0.19	394	160	0.94
21	D1	0	544	0	40.32 (±0.39)	5.73 (±0.74)	0.00	0.06	503	682	0.93
22	D1	0	412	0	39.78 (±0.66)	6.74 (±1.26)	0.01	0.10	279	264	0.27
23	D4	1	868	0	27.85 (±1.99)	7.62 (±2.07)	0.31	0.82	471	49	0.99
24	D4	1	1479	0	31.14 (±1.75)	13.33 (±2.74)	0.27	0.58	924	246	0.74
25	D4	1	587	0	28.17 (±3.29)	7.03 (±2.74)	0.27	0.82	344	17	0.73
26	D4	0	422	0	23.40 (±6.55)	3.27 (±4.36)	0.75	1.00	433	1	1.00
27	D4	1	654	0	26.95 (±3.23)	11.24 (±3.25)	0.41	0.77	790	82	0.55
28	D4	1	578	0	33.19 (±1.03)	8.65 (±1.46)	0.11	0.49	632	177	0.07
29	D4	0	286	0	25.96 (±5.84)	13.19 (±6.42)	0.46	0.76	265	33	0.47
30	D4	1	587	0	31.66 (±1.39)	6.93 (±1.49)	0.11	0.61	628	71	0.85
31	D6	2.5	806	1	41.67 (±1.19)	8.70 (±1.49)	0.01	0.10	136	594	0.84
32	D6	1	882	1	30.62 (±4.01)	20.02 (±12.98)	0.35	0.56	66	48	0.21
33	D6	1	704	1	41.63 (±1.42)	5.51 (±1.46)	0.00	0.03	52	245	0.82
34	D5	1	974	1	36.49 (±1.35)	7.26 (±1.83)	0.03	0.26	95	141	0.80
35	D5	2	752	1	36.77 (±2.05)	8.75 (±3.27)	0.05	0.28	57	52	0.82
36	D5	2	663	1	30.98 (±1.31)	7.24 (±1.53)	0.14	0.65	800	108	0.85
37	D5	1	632	1	29.97 (±1.79)	7.88 (±1.80)	0.20	0.70	1057	104	0.37
38	D5	1	595	1	26.09 (±2.20)	7.10 (±1.87)	0.42	0.89	948	48	1.00
39	D3	1	267	1	32.10 (±0.57)	4.57 (±0.79)	0.03	0.61	526	156	0.92
40	D3	1	257	1	30.44 (±0.83)	6.98 (±1.34)	0.15	0.69	547	170	0.59
41	D3	0	162	1	26.40 (±2.53)	8.45 (±3.03)	0.41	0.85	303	41	0.83

The values in parentheses are 95% confidence intervals. R_{25} and R_{33} quantifies the calculated observed retention probabilities for cod at size 25 and 33 cm, respectively, for the observed retention curve based on formula (1) using the estimated values for *L50_O* and *SR_O*. The parameter *sea* represents the sea state during the specific haul quantified using the World Meteorological Organization sea-state code. The parameter *w* quantifies the total codend catch weight at the end of each haul. The parameter *c2* denotes whether the specific haul was conducted during the spring (0) or autumn (1) cruise. "No. in codend" quantifies the total number of cod >25 cm collected in the codend during the individual hauls. "No. in the cover" quantifies the number of cod >25 cm collected in the cover.

parameters, total codend catch weight (w) and sea state (*sea*), were taken into account because they could influence the parameters *L50_O* and *SR_O* and thus account for some of the variation in parameter values between hauls. To account for the potential between-cruises effect, a fixed effect for the last cruise ($c2$) was added to the modelling. Thus, we arrived at the following global model:

$$L50\_O = a_0 + a_1 \times edge \times short + a_2 \times (1.0 - edge) \times short + a_3 \times (1.0 - edge) \times short \times s1 + a_4 \times (1.0 - edge) \times short \times s2 + a_5 \times (1.0 - edge) \times short \times s3 + a_6 \times (1 - edge) \times w + a_7 \times w + a_8 \times sea + a_9 \times c2, \tag{2}$$

$$SR\_O = b_0 + b_1 \times edge \times short + b_2 \times (1.0 - edge) \times short + b_3 \times (1.0 - edge) \times short \times s1 + b_4 \times (1.0 - edge) \times short \times s2 + b_5 \times (1.0 - edge) \times short \times s3 + b_6 \times (1 - edge) \times w + b_7 \times w + b_8 \times sea + b_9 \times c2,$$

where a_0 and b_0 denote the intercept values that represent the *L50_O* and *SR_O* values for the BACOMA codend (design D1), respectively; a_1 and b_1 model the change in selectivity by changing codend design from D1 to D2, which consist of shortening the square panel area by 50%, but letting it overlap with the catch-accumulation zone in the codend; a_2 and b_2 model the change in selectivity by simultaneously shortening the square mesh panel area to 50% compared with the standard BACOMA (codend D1), and moving the panel away from the catch-accumulation zone (codends D3, D4, D5, and D6); a_3 and b_3 model the effects on selectivity by using the stimulation device *s*1 (codend D4) in a codend else being of D3 design; a_4 and b_4 model the effects on selectivity by using the stimulation device *s*2 (codend D5) in a codend else being of D3 design; a_5 and b_5 model the effects on selectivity by using the stimulation device *s*3 (codend D6) in a codend else being of D3 design. For codends without overlap of the square mesh panel and catch-accumulation zone, a_6 and b_6 model the potential effects of codend catch weight at the end of the haul, while a_7 and b_7 do it for a potential general effect of codend catch weight; a_8 and b_8 model the effects of the sea state parameter; and a_9 and b_9 model the potential offsets in *L50_O* and *SR_O* for hauls conducted during cruise 2, compared with cruise 1.

Specifically, the second step in the analysis estimated the value of the parameters $(a_0, \ldots, a_9)$ and $(b_0, \ldots, b_9)$ in model (2) and estimated additionally the between haul variation matrix for the selection parameters (*L50_O* and *SR_O*).

In addition to model (2), all possible simpler models which could be derived based on model (2) by eliminating one or more terms at the time were also examined as potential models for describing how *L50_O* and *SR_O* depended on the different parameters. Among the models where all parameters were found to be significant, predictions were made using multimodel inference (Burnham and Anderson, 2002). Models considered were ranked according to their AICc values (Burnham and Anderson, 2002). The AICc is the AIC (Akaike, 1974) with a correction for finite sample sizes. Models with AICc values within +10 in the value of the model with a lowest AICc value were considered further for the prediction of the *L50_O* and *SR_O*, the different codends (D1–D6), and thus also of the retention curves for the codends. The multimodel inference was performed by calculating the Akaike weights for the different models based on AICc values, then by weighting the relative contributions of the different models according to the calculated Akaike weights (Katsanevakis, 2006). The procedure is named hereafter the "predictive model". The predictive model could then be used to assess the consequences of the difference in design on codend selection by plotting the predicted mean retention curves for the different codend designs. The assessment was restricted to certain cod sizes since else the assessment could be biased by cover selection. A conservative size limit for this assessment was 33 cm which is based on a morphological limit above where there is absolutely no chance for a cod to have passed through the 80-mm cover meshes (Wienbeck *et al.*, 2011). For cod >33 cm, it was assumed that the observed retention curve based on formula (1) used with the obtained values for *L50_O* and *SR_O* would also reflect the codend size selection curve.

For cod >33 cm, it was further expected that the escapement probability, through the partly closed diamond mesh made of 105 mm double netting applied in the bottom part of the codends, would be low (<9%; unpublished data). Therefore, it could be assumed that most of the release of cod >33 cm would be through the square mesh panel, and estimated retention probabilities for cod >33 cm could be used as an indicator for the square mesh panel release efficiency. Assessment of the specific retention probability at a specific length of cod for a specific codend can be based on formula (1) and the values of *L50_O* and *SR_O* obtained from the predictive model established based on (2).

The data were analysed using the software tool SELNET (Herrmann *et al.*, 2012). More information on SELNET can be found in Sistiaga *et al.* (2010); Wienbeck *et al.* (2011); and Herrmann *et al.* (2013a, b, c).

Results

Individual hauls

The codend catch weight ranged from 160 to 1480 kg with most hauls below 900 kg (Table 2).

In total, more than 25 000 cods longer than 25 cm were caught during the 41 valid hauls conducted during the two cruises. Results for these fish (retained in codend or codend cover) formed the basis for the analysis in this study.

The logit curve [formula (1)] was sufficient to model the observed retention probability for cod >25 cm in all hauls. The *p*-value for all hauls was >0.05 and therefore, deviation observed between the curve and experimental data could well be a coincidence (Table 2). Therefore, it was valid to use the values for *L50_O* and *SR_O* based on the logit curve to model the observed retention probability for cod >25 cm. The estimated observed retention rate for cod at 25 cm (R_{25}) was <0.5, except for very few hauls meaning that it was possible to cover a sufficient part of the retention curve to obtain estimates for the parameters *L50_O* and *SR_O*. For cod at 33 cm (where negligible effect of potential cover selection occurs, see above), the observed retention probability (R_{33}) varied considerably between hauls and codends (Table 2). The estimated value ranged from 0.03 for haul 33 (codend D6) to 1.0 for haul 26 (codend D4). These results could indicate that the changes in codend design affected the release efficiency of cod through the square mesh panel. Subsequently, a detailed analysis of this is the subject of the following section.

Establishment of the predictive model

Based on the results obtained from the individual hauls (Table 2) and the procedure described in the section Data analysis, we established the predictive model for *L50_O* and *SR_O*. Table 3 outlines the formulas for the eight models which were found to produce AICc values within +10 of the model with the lowest value. Furthermore, Table 3 summarizes the AICc values, the corresponding Akaike weights, and the values for the model factors. The parameter *L50_O* was not affected by reducing the panel area by 50% if it overlapped with the catch-accumulation zone, since the parameter a_1 is absent for all the models. For *SR_O*, the factor b_1 is only present in two of the eight best-ranked models and only with small Akaike weights at, respectively, 0.0583 and 0.0064, meaning that these specific models have very limited weight in the predictive model. On the contrary, a big effect on the predicted *L50_O* value was found for moving the short panel away from the catch-accumulation zone (codend design D3), as all the considered models predict a decrease between 7.53 and 12.93 cm (a_2). For *SR_O*, only one of the eight models in the predictive model includes an effect of moving the short square mesh panel away from the catch-accumulation zone (b_2) and only with small Akaike weight at 0.0428. Stimulation devices *s*1 or *s*2 in a codend with a short panel without overlap the catch accumulation were not predicted to affect the observed selectivity by any of the models. Factors a_3, b_3, a_4, and b_4 were all absent from the models. For stimulation device *s*3, six of the eight models predict an increase in *L50_O*, which ranges between 7.40 and 8.08 cm (factor a_5). The sum of the Akaike weights for these models is 0.9755, and thus this effect is very dominant in the predictive model. For *SR_O*, none of the models includes an effect of stimulation device *s*3 since factor b_5 is absent in all the models. Six of the models predict a positive effect of codend catch weight on *L50_O* for a codend, where the square mesh panel do not overlap with the catch-accumulation zone since factor a_6 is present with a positive

Table 3. Description and ranking of different models tested based on the full predictive model (2).

Model rank	AICc	Delta AICc	Akaike weight		Factor									
					a_0, b_0	a_1, b_1	a_2, b_2	a_3, b_3	a_4, b_4	a_5, b_5	a_6, b_6 (×1 000)	a_7, b_7 (×1 000)	a_8, b_8	a_9, b_9
1	378.61	0.00	0.7506	*L50_O*	41.87 (1.86)	–	−12.92 (2.34)	–	–	7.40 (2.05)	9.34 (3.58)	−6.26 (3.07)	–	–
				SR_O	5.19 (0.57)	–	–	–	–	–	–	2.45 (0.76)	0.64 (0.31)	–
2	382.83	4.22	0.0911	*L50_O*	41.88 (1.86)	–	−12.91 (2.33)	–	–	7.43 (2.04)	9.38 (3.57)	−6.34 (3.07)	–	–
				SR_O	5.72 (0.56)	–	–	–	–	–	–	2.76 (0.79)	–	–
3	383.72	5.11	0.0583	*L50_O*	38.50 (0.88)	–	−10.56 (1.72)	–	–	7.57 (2.12)	4.21 (1.94)	–	–	–
				SR_O	6.59 (0.42)	−2.09 (0.78)	–	–	–	–	–	–	1.49 (0.38)	−1.39 (0.58)
4	384.34	5.73	0.0428	*L50_O*	38.59 (0.89)	–	−10.75 (1.77)	–	–	7.77 (2.15)	4.14 (1.98)	–	–	–
				SR_O	6.15 (0.50)	–	1.47 (0.59)	–	–	–	–	–	0.86 (0.33)	−1.62 (0.65)
5	385.31	6.70	0.0263	*L50_O*	38.63 (0.90)	–	−7.85 (1.15)	–	–	8.08 (2.15)	–	–	–	–
				SR_O	6.19 (0.42)	–	–	–	–	–	1.95 (0.55)	–	0.73 (0.31)	−1.25 (0.52)
6	386.07	7.45	0.0181	*L50_O*	38.59 (0.98)	–	−12.16 (2.13)	–	–	–	5.27 (2.21)	–	–	3.70 (1.53)
				SR_O	6.26 (0.42)	–	–	–	–	–	1.85 (0.55)	–	0.74 (0.30)	−1.33 (0.52)
7	388.14	9.53	0.0064	*L50_O*	38.45 (0.98)	–	−12.80 (2.11)	–	–	–	6.33 (2.16)	–	–	3.84 (1.53)
				SR_O	6.61 (0.42)	−2.25 (0.77)	–	–	–	–	–	–	1.57 (0.38)	−1.63 (0.59)
8	388.15	9.54	0.0064	*L50_O*	38.55 (0.89)	–	−7.53 (1.14)	–	–	7.88 (2.13)	–	–	–	–
				SR_O	5.09 (0.56)	–	–	–	–	–	–	2.54 (0.74)	0.65 (0.31)	–

Ranking is based on AICc values for the models. Delta AICc is the difference between the AICc value for the specific model and the AICc value for the model with the lowest AICc value. The Akaike weights for the individual models are based on the Delta AICc values following the procedure described in Katsanevakis (2006). "−" denotes that the specific factor is not present in the specific model. Values in parenthesis are standard errors of the factors.

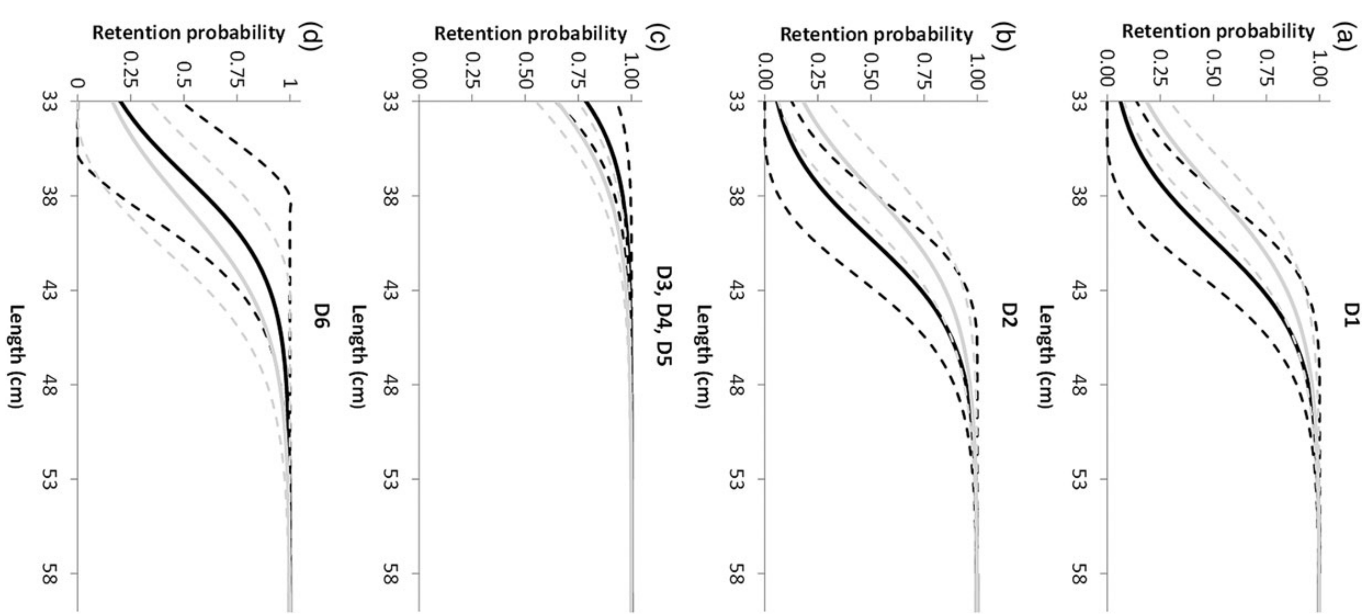

Figure 3. Changes in the retention probability for codend catch weight at 200 kg (black curves) and 700 kg (grey curves). (a) Standard BACOMA codend (D1); (b) codend with a shortened square mesh panel which overlapped with the catch-accumulation zone (D2); (c) codend with a shortened square mesh panel positioned away from the catch-accumulation zone (D3) and for codend with respectively stimulation devices s1 (D4) and s2 (D5) since these three codends all had identical predictions of retention probability; (d) codend with float ropes mounted in the lower panel below the shortened square mesh panel, which was positioned away from the catch-accumulation zone (D6). Stipple curves represent 95% confidence intervals for the mean curve.

Table 4. Predicted values for the selection parameters *L50_O* and *SR_O* for the six different codends.

	200 kg		700 kg	
Codend	***L50_O* (cm)**	***SR_O* (cm)**	***L50_O* (cm)**	***SR_O* (cm)**
D1	40.29 (37.41 – 43.17)	5.84 (4.77 – 6.90)	37.65 (35.62 – 39.69)	6.89 (5.92 – 7.86)
D2	40.29 (37.41 – 43.17)	5.70 (4.56 – 6.84)	37.65 (35.62 – 39.69)	6.75 (5.49 – 8.01)
D3 – D5	29.47 (27.08 – 31.85)	5.92 (4.70 – 7.13)	31.04 (29.65 – 32.43)	7.01 (6.04 – 7.98)
D6	36.74 (31.93 – 41.54)	5.92 (4.70 – 7.13)	38.31 (34.18 – 42.44)	7.01 (6.04 – 7.98)

Predictions are made considering the models in Table 3, weighted according to the Akaike weights for the different models. Predictions are shown for 200 and 700 kg codend catch. Sea-state parameter *sea* = 0 and conditions during the spring cruise ($c2 = 0$) were used.

value. Only two models include an effect on *SR_O*. For a general effect of codend catch weight (factors a_7 and b_5), the two highest ranked models include a negative effect on *L50_O* while the remaining models do not have any effect. Three models, including the two best ranked, predict an increase in *SR_O* with an increased codend catch weight. None of the models includes an effect of the sea state on *L50_O*, since a_8 is absent from all the models. Contrary, seven of the eight models include an effect on *SR_O* by predicting a higher value with an increasing value of the sea state parameter. Some of the lower ranked models include a between-cruise effect on the observed selection parameters. For *L50_O*, this effect is absent in six of the eight models and the sum of the Akaike weight for the two models which include this effect is only 0.0245. For *SR_O*, five of the models predict a lower value for the second cruise. The sum of the Akaike weights for these five models adds up to 0.1519.

Comparing predictions for different codend designs

The predictive model (Table 3) was applied in predictions of the codend size selection for cod >33 cm, for codend catch weights at 200 and 700 kg, respectively (Figure 3 and Table 4). The catch-weight values were selected because they are both within the range for most hauls conducted during the sea trials. It was seen that the codend size selectivity was to some extent affected by codend catch size, but that the confidence limits for the predicted selection curves for each of the codends at these two catch weights overlapped (Figure 3). This was also the case for the predicted parameter values of *L50_O* and *SR_O* since their 95% confidence intervals for 200 and 700 kg catch weight overlap for each of the six codends investigated in the study (Table 4).

The effects of the different design changes are illustrated in Figure 4. Shortening the square mesh panel by 50%, while maintaining overlap with the catch-accumulation zone, do not have any effect on the retention probability of cod since the predicted selection curves for codend D1 and D2 were nearly identical (Figure 4a and b). Moving the square mesh panel away from the catch-accumulation zone increased the retention probabilities of the smaller cod considerably with a clear significant difference between the selection curves for codends D2 and D3 (Figure 4c and d). The application of float ropes (*s*3) to a square mesh panel positioned away from the catch-accumulation zone decreased the predicted retention probabilities of cod considerably, i.e. the release efficiency was considerably improved (Figure 4e and f).

When stimulation device *s*3 was used to stimulate cod escapement behaviour, no significant difference was found between the release efficiency of a square mesh panel positioned *away* from the catch-accumulation zone, compared with the release efficiency from a panel of double size positioned *in* the catch-accumulation zone, since the confidence limits for the selection curves overlapped (D6 compared with D1; Figure 4g and h).

Discussion

Based on selectivity data for more than 25 000 cod collected during experimental trawl fishing with six different codends, each with a square mesh panel, the effect of (i) size of the square mesh panel area, (ii) position of the square mesh panel, and (iii) stimulation of the escape response on cod-release efficiency was investigated. This study helped to establish and quantify which parts of the BACOMA codend design used in the Baltic Sea cod directed trawl fishery were vital to the efficiency of the square mesh panel. It increased our understanding of the escapement behaviour of cod through square mesh panels and why other square mesh panel designs are potentially less effective. This knowledge may be used to improve the BACOMA codend further, or develop codend designs for other fisheries to reduce the discards of cod and potentially other roundfish species.

One of the two main findings in our study was that the release efficiency of the square mesh panel in the BACOMA codend largely depends on the position of the square mesh panel along the codend itself (0–6 m from the codline), while the size of the square mesh panel area was not found to affect the observed retention curve significantly. An overlap of the square mesh panel and the catch-accumulation zone increased the release efficiency of cod. This is in line with the results in Beverton (1963), showing that most of the fish escape close to the codline. In this aft end of the codend, cod do not have the option to drift further back, but have to attempt escape to avoid entering the catch accumulation.

When the panel was moved away from the catch-accumulation zone, the release probability was reduced drastically compared with the BACOMA codend and the codend with a similar short panel positioned in the catch-accumulation zone. Although not directly comparable, these results were in line with those of Graham *et al.* (2003), Graham *et al.* (2004), and Bullough *et al.* (2007). They found no significant effect on the selectivity of haddock (*M. aeglefinus*), whiting (*Merlangius merlangus*), and other species when a 3-m square mesh panel was positioned >6 m away from the codline, compared with a gear without the square mesh panel.

A reasonable explanation for the low selectivity is that not all fish come in contact with a square mesh panel positioned away from the codline, although they swim through the panel area inside the gear (Glass and Wardle, 1995; Zuur, 2001). This illustrates that it may not be sufficient to insert a square mesh panel in a trawl to increase size selectivity. The fish must also use it. The second main finding of the current study demonstrates that it is possible to stimulate the escape response for cod to achieve an release probability through a square mesh panel positioned away from the catch-accumulation zone, as efficient as for a panel mounted in the catch-accumulation zone or

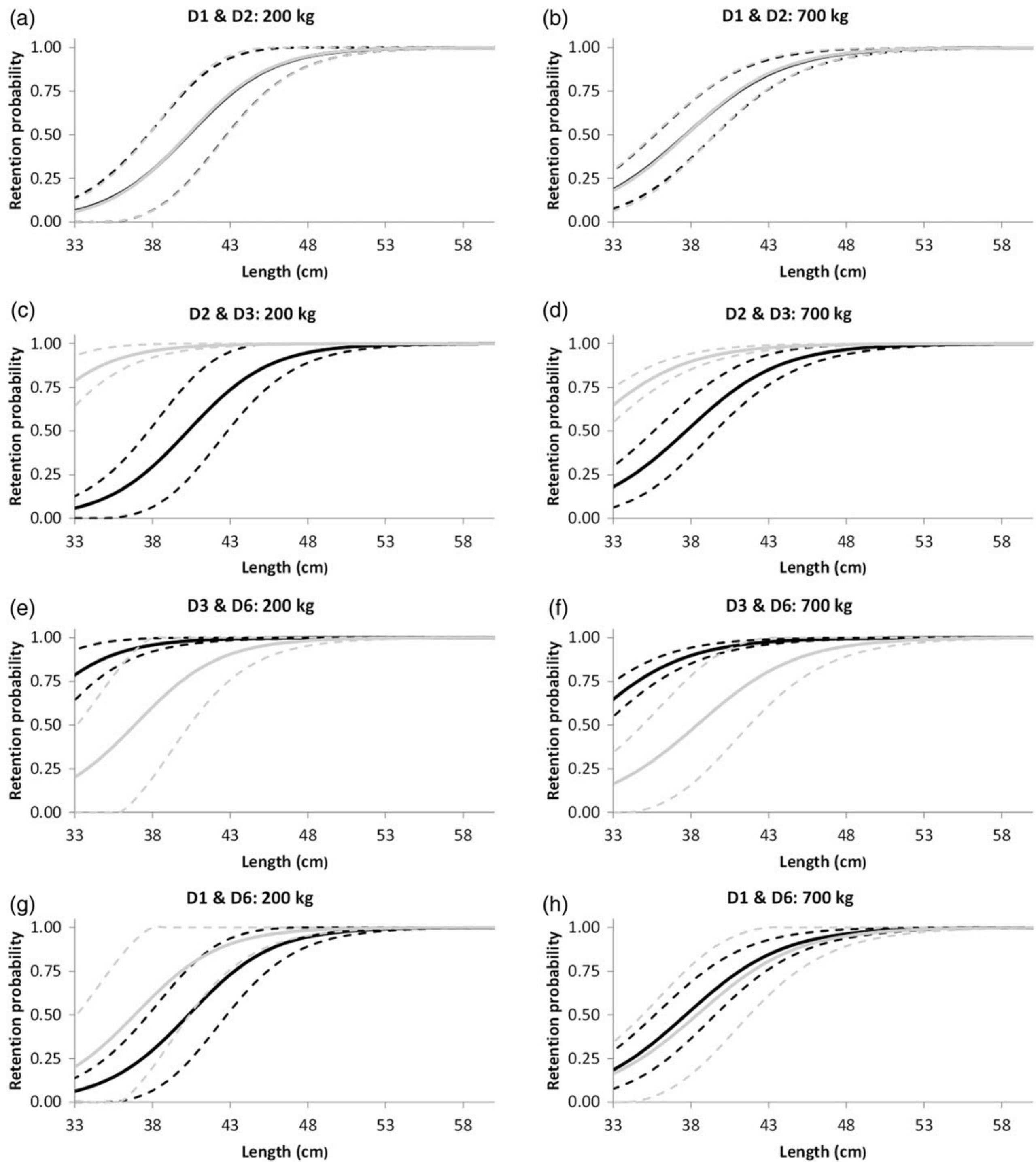

Figure 4. Changes in the retention probability predicted at the codend catch weight of 200 kg (left panels) and 700 kg (right panels) by: (a and b) shortening a square mesh panel (50%), but which still overlapped the catch-accumulation zone (D2; grey curves) vs. the standard BACOMA codend (D1; black curves); (c and d) moving a shortened square mesh panel away from the catch-accumulation zone (D3; grey curves) compared with a short panel overlapping the catch-accumulation zone (D2; black curves) ; (e and f) applying float ropes mounted in the lower panel below the shortened square mesh panel which was positioned away from the catch-accumulation zone (D6; grey curves) compared with no use of a stimulation device (D3; black curves); (g and h) applying float ropes below the shortened square mesh panel positioned away from the catch-accumulation zone (D6; grey curves) compared with the standard BACOMA codend (D1; black curves). Stipple curves represent 95% confidence intervals of the mean curve. The sea-state parameter *sea* and the cruise parameter *c*2 were both set to zero for all the predictions shown.

even as the standard BACOMA codend design. Only one of the three stimulation devices tested was found to stimulate the escapement of cod through the square mesh panel. Underwater recordings conducted in a later sea trial revealed that the buoyancy of the fluttering ropes (*s*1; Figure 2d) was simply not high enough to balance the drag forces on the ropes at the towing speed applied. Therefore,

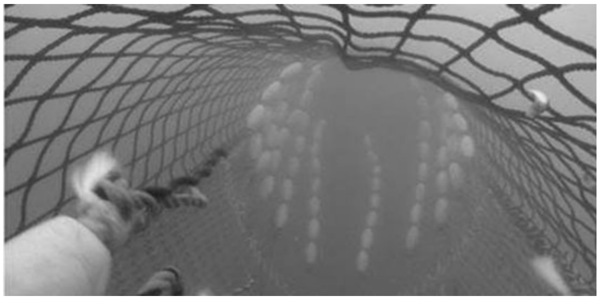

Figure 5. Image of the float ropes (*s*3) during towing speed at three knots. An image is taken at the front part of the codend looking towards the aft end.

the ropes were lying almost flat along the lower panel in the codend underneath the square mesh panel. It could therefore not be expected that this device would effectively stimulate the escape response through the square panel inserted in the upper panel. In contrast, underwater recordings of the float ropes (*s*3; Figure 2f) revealed much better buoyancy, resulting in a proper guiding angle towards the upper panel and simultaneously irregular/fluctuating movements (Figure 5). This observation explains why the float ropes increased the release efficiency through the square mesh panel. It is likely that the design of this device could be improved further by testing the physical behaviour of different design variants in the flume tank, or with underwater recordings during fishing operations.

An underwater recording of the guiding panel (device *s*2; Figure 2e) revealed that too few floats were mounted at the aft end of the guiding panel to overcome the drag forces during towing. Therefore, the panel did not guide the cod sufficiently towards the square mesh panel. It is therefore unknown if a modified stimulation device based on this design could function for cod. For future tests of this type of design, it might be necessary to use larger and/or more floats at the aft end of the panel.

In a tank experiment, Kim and Whang (2010) have used physical contact stimuli to encourage juvenile fish to contact the netting in a codend. Both tested designs, a free-end flag-like net panel and an array of free-ended ropes, reduced the retention rate of juvenile red sea bream (*Pagrus major*) compared with a conventional codend without the stimulating devices. Glass and Wardle (1995) were able to increase the proportion of haddock and whiting escaping through a square mesh panel positioned ∼5–7 m away the codline with the use of a black tunnel. The black tunnel was made from a section of black netting positioned immediately behind the square mesh panel. Video recordings revealed that the fish were reluctant to swim into the tunnel, and thus increased the number of escapes through the netting in front of the tunnel.

Whereas gadoids like haddock and whiting have a vertical preference of swimming in the upper part of the trawl, cod tends to stay closer to the bottom panel (Ferro *et al.*, 2007; Krag *et al.*, 2009a). The findings of the current study may lead to better solutions for improving the release efficiency of cod through square mesh panels in other fisheries, where this is a problem. For example, this could be helpful in mixed fisheries targeting *Nephrops*, which require small-meshed codends to retain the target species, and which might lose a valuable catch if a square mesh panel of large mesh size is applied in the aft end of the codend. In this fishery, Frandsen *et al.* (2009) tested a codend with a short square mesh panel in the section in front of the codend and without any stimulation device, with little effect on selectivity. Based on our results, the position of the square mesh panel in the trawl is a likely explanation for the high retention rate of cod reported by Frandsen *et al.* (2009). Consequently, it would be relevant to test the performance of a short square mesh panel positioned away from the catch-accumulation zone and with stimulation device *s*3 (a modified D6) in a *Nephrops* directed fishery to determine the possibility of increasing the square mesh panel escapement efficiency for cod without simultaneously losing many *Nephrops*. However, it can be questioned if fishers will be willing to accept technical devices based on float ropes like device *s*3. Additionally, their efficiency might be easy to manipulate. Therefore, the success of implementing such devices in commercial fishery will be strongly dependent on the acceptance by fishers. The ongoing implementation of discard bands in several European fisheries which will put more responsibility on fishers to avoid unintended catches might help the implementation of such devices, especially since no technical problems handling the different stimulating devices in the current study occurred.

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