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Increasing catch efficiency for *Nephrops* in deep-water shrimp (*Pandalus borealis*) trawl fisheries

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ABSTRACT

In Skagerrak and the North Sea, coastal vessels harvest deep-water shrimp (*Pandalus borealis*) in a mixed fishery, in which catches of *Nephrops* (*Nephrops norvegicus*) are of economic importance for the fleet. Fishermen targeting shrimp in this area must use a sorting grid with a maximum bar spacing of 19 mm, which means that only the smallest *Nephrops* can pass through the grid to be retained in the main codend. Although fish collection bags may be mounted to the grid's fish outlet, most *Nephrops* escape through the large meshes in these bags. Using data from 70 hauls collected during three different commercial cruises, we investigated whether inserting a 15 cm gap in the lower part of the compulsory sorting grid could help retain a higher fraction of the commercial sizes of *Nephrops*. We also evaluated whether this lower gap in the grid would change the catch pattern for the most relevant fish bycatch species in the fishery. The results showed that the gap in the grid significantly increased the catches of *Nephrops* above the minimum legal size and increased the catches of commercial-size shrimp. However, absolute catch rates of *Nephrops* were still low and, from a management point of view, the modest catch increase does not justify the significant increase in the catch of juveniles of a range of fish species as well as undersized *Nephrops*.

1. Introduction

The deep-water shrimp *Pandalus borealis* is an important commercial species in the Northeast Atlantic Ocean (Garcia, 2007). In Norway alone, the annual catches of this species are ~30 000 tonnes, with a market value of approximately NOK 1 billion (Norwegian Directorate of Fisheries, 2020). The largest individuals of deep-water shrimp reach CLs of slightly over 30 mm, so the fisheries are carried out with small-meshed (minimum 35 mm stretched mesh opening) trawls. The use of small-meshed trawls has resulted in an excessive bycatch of fish and other marine organisms. To a considerable extent, this problem was mitigated by the introduction of the Nordmøre sorting grid in the early 1990 s (Isaksen et al., 1992). This grid and similar grid-based devices have been tested in most shrimp fisheries around the world (e.g. Europe: Polet, 2002; Fonseca et al., 2005; Madsen and Hansen, 2001; Larsen et al., 2017; North America: Garcia, 2007; He and Balzano, 2007; He and Balzano, 2013; South America: Pettovello, 1999; Silva et al., 2012; Oceania: Brewer et al., 1998; Asia: Eayrs et al., 2007, Paighambari and Eighani, 2016; Africa: Fennessy and Isaksen, 2007). For a review of tropical fisheries see Eayrs (2007).

The working principle for these grids is that all organisms and debris that cannot pass between the grid bars are guided along the grid to an outlet at the top of the grid section, while everything that penetrates the grid continues towards a second selection process in the main codend (Isaksen et al., 1992; Larsen et al., 2017). While this leads to cleaner shrimp catches, it also results in losses of valuable fish and crustacean species that are too large to pass through the grid. Options for reducing the loss of fish and crustaceans through Nordmøre-grids have been tested in various fisheries, including those with horizontal openings at the base or top (e.g. Madsen and Hansen, 2001; Fonseca et al., 2005).

Coastal vessels in Skagerrak and the North Sea harvest deep-water shrimp in a mixed-species fishery. Apart from the targeted shrimp,

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Nephrops, various species of fish such as cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), hake (*Merluccius merluccius*), monkfish (*Lophius piscatorius*), and ling (*Molva molva*) have traditionally been important for the revenue of the smaller vessels in the fleet. Other species with less or no commercial value, like Norway pout (*Trisopterus esmarkii*), American plaice (*Hippoglossoides platessoides*), and various species of smaller sharks (e.g., spiny dogfish (*Squalus acanthias*) and velvet belly (*Etmopterus spinax*)), are relatively abundant in the catches. The grid was introduced into the legislation governing this fishery in 2013. All fishermen targeting shrimp are now obliged to use a sorting grid with a maximum bar spacing of 19 mm and a codend with a minimum mesh size of 35 mm. However, they are allowed to attach a bycatch codend to the escape outlet in the grid section (Fig. 1a). The foremost 3 m of the upper panel in this codend forms an exit window with square meshes of > 120 mm. Although the bycatch codend retains the largest and normally most valuable fish entering the trawl, a large fraction of the legal-sized *Nephrops* (specimens with CL > 40 mm) are lost through the exit window (Frandsen et al., 2010). Only the smallest individuals can pass through the sorting grid into the main codend, while the remainder enter the bycatch codend, which retains only a few of the largest individuals.

Behavioural studies of *Nephrops* have shown that this species enters the trawl close to the lower panel (Frandsen et al., 2011; Karlsen et al., 2019; Melli et al., 2019). Madsen and Hansen (2001) tested two grid designs with a lower gap in the North Sea shrimp fishery and concluded that such a gap can increase the catches of *Nephrops* in a shrimp trawl fishery but at the cost of higher bycatch levels. Based on these experiments, the Norwegian fishing industry initiated a pilot study in the eastern part of Skagerrak in 2013 to explore the potential of such a grid design for the smaller coastal shrimp vessels, for whom the loss of *Nephrops* with the introduction of the grid was claimed to reduce profitability. Fish bycatch levels in eastern Skagerrak are presumed to be

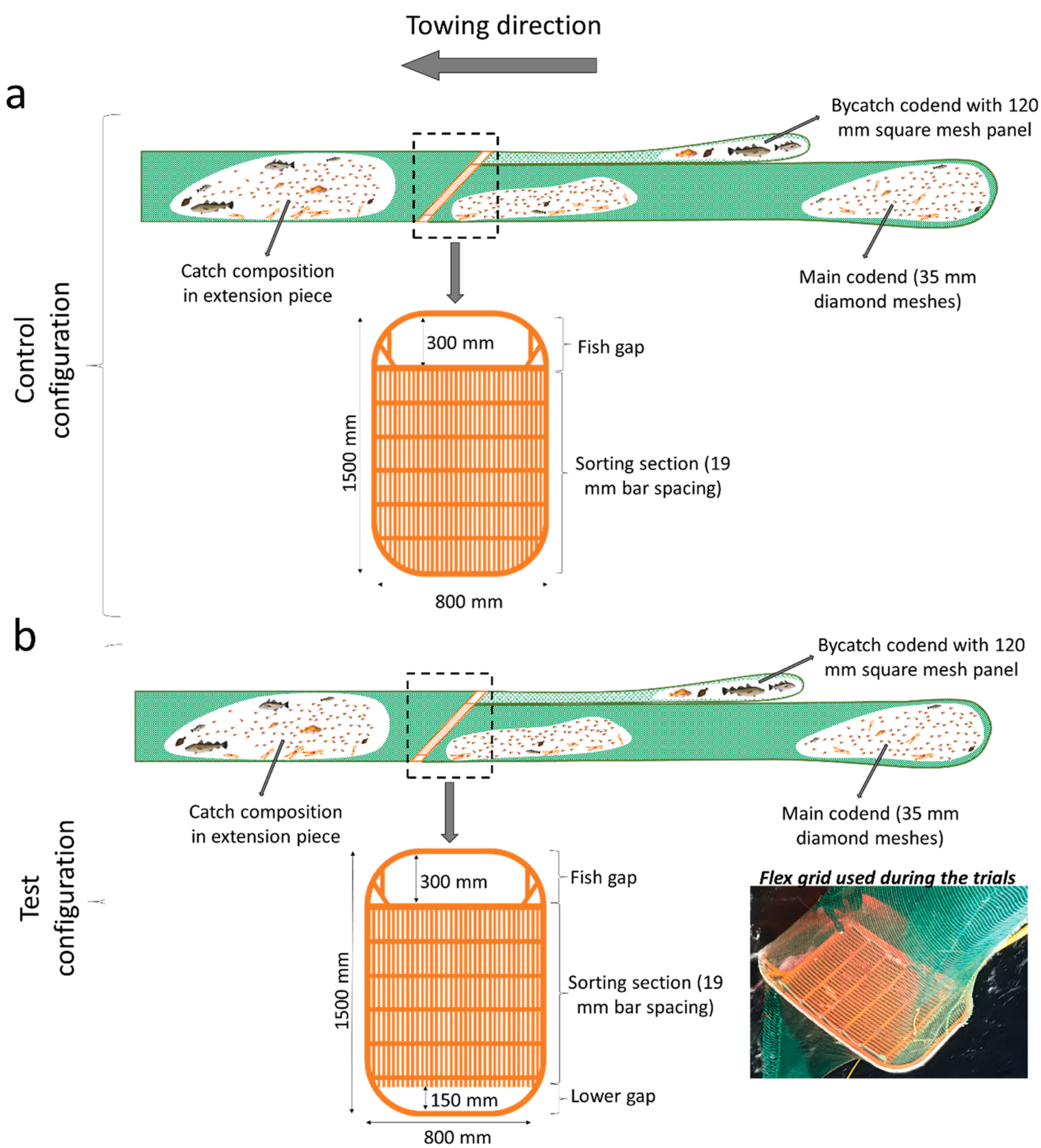

Fig. 1. Experimental design used during the three cruises: (a) the control configuration in the trials, which is the gear configuration used by the shrimp fleet in Skagerrak and south-western Norway and (b) the test configuration.

considerably lower than in the North Sea and the increased bycatch rates may therefore be less than those observed by Madsen and Hansen (2001).

The pilot study showed that when a 10 cm tall rectangular gap was used, catches of legal *Nephrops* doubled while there was no significant increase in the weight of fish bycatch. However, more comprehensive studies were requested by the Norwegian Directorate of Fisheries to allow the use of the grid with a lower gap in the commercial trawl fishery. At the same time, vessels fishing inside 4 n. miles of the baselines were granted an exemption from the mandatory use of a grid until 1 January 2019.

As the deadline approached, it was decided to carry out a more comprehensive field study, looking at the consequences of permitting the use of a lower gap in the grid when fishing inside 4. n. miles from the baselines. The study should cover a wider geographical part of the coastal waters of Southern Norway than the previous study, and at the request of the fishing industry, a 150 mm high gap was used. The aforementioned exemption was extended until the recommendations based on the study were presented.

The overall aim of this study was to determine whether, and to what extent, a lower gap would retain a higher fraction of the commercial *Nephrops*. We also studied potential changes in the exploitation pattern of the most relevant fish bycatch species in the fishery when there was a lower gap in the shrimp grid. Specifically, the study aimed to answer the following research questions:

- To what extent does a lower gap in the shrimp grid increase the fraction of commercial *Nephrops* retained by the gear?
- Does a lower gap in a shrimp grid have any implications for shrimp catches?
- How does a lower gap affect catches of key fish bycatch species?

2. Materials and methods

2.1. Data collection

The data used in this study were collected during three cruises carried out by two coastal vessels along the southern and south-western Norwegian coast. The first cruise was carried out onboard the shrimp trawler *Eli R*, which is 17 m long, has a 335 kW engine, and is rigged for twin-trawl fishing. The trawl doors used were of the Dangren 96" type and weighed 750 kg each. A centre clump of 1100 kg was used, and the sweeps between the doors and the trawls were 25 m long. The two trawls were of the "Killer" type, built as two-panel trawls with a circumference of 1500 meshes and constructed of 60 mm meshes (stretched mesh opening, 90 m fishing circle).

The second cruise was conducted onboard the shrimp trawler *Marie Emilie*. The vessel is 10.99 m long, has a main 300 kW engine, and is also rigged as a double trawler. The trawl doors were of the Thyborøn 96" type and weighed 515 kg each. The centre clump between the trawls was 750 kg, and the sweeps were 36 m long. The two trawls were identical and constructed entirely of 60 mm meshes (stretched mesh opening). The trawls were built of four panels with a circumference of 1750 meshes that resulted in a 105 m long fishing circle.

The third cruise was also carried out onboard the shrimp trawler *Marie Emilie.* The rigging used during this cruise was identical to that used during cruise 2.

The same grid sections, grids and codends were used in all three fishing experiments. The two identical grids were of the "Flex-risten" type: flexible, moulded plastic grids produced by Carlsen Net AS in Esbjerg, Denmark. They were 1500 mm high and 800 mm wide and had a bar spacing of 19.0 mm (sd=0.1). The grids, identical to those used by the shrimp fleet, had a 300 mm tall rectangular gap (fish outlet) at the top that led to the bycatch-retaining codend (Fig. 1a). In addition, the test grid had a 150 mm high rectangular gap at the bottom (Fig. 1b). The foremost 3 m of the top panel of the bycatch-retaining codend was made as an exit window, constructed of square mesh netting with a nominal 125 mm square mesh opening and made of 3.3 mm diameter twine. This exit window was followed by a 12.7 m long codend made of 125 mm (nominal mesh size) diamond meshes. The identical main codends used in the test and control configurations collected the shrimp, *Nephrops*, and fish specimens that passed through the bar spacings of the grid, or specimens that entered through the lower slot in the test grid. They were 11.6 m long, had a circumference of 250 meshes, and were constructed entirely of 35 mm (nominal mesh size) meshes. The actual mesh size was measured using an Omega mesh gauge (Fonteyne et al., 2007). Two rows of 20 meshes each were measured for each codend. Measurements started 4 meshes from the codline. The mesh size of the codend on the experimental side was 36.1 mm (sd= 0.6), while that of the regular trawl was 35.2 mm (sd= 0.9). Before each cruise, the trawls and the grid sections were measured at a net loft to ensure that they were identical. During the trials, the grid sections and codends were exchanged between the trawls about halfway through each experiment.

For each haul, the catches in each codend were kept separate. The bycatch of fish and *Nephrops* in each codend was separated from the shrimp and sorted by species. For the shrimp, a sample of approximately 2 kg was collected from each of the main codends in the test and control gears, and the shrimp carapace lengths (CLs) were measured using a digital calliper with an accuracy of 0.01 mm. For analysis, shrimp with a CL $<$ 15 mm were categorized as undersized shrimp. The CLs of all *Nephrops* were measured using the same digital callipers and rounded down to the nearest mm. Total lengths of all fish were rounded down to the nearest cm below. For practical reasons, some of the fish bycatch species had to be subsampled.

2.2. Data analyses

During the cruises, the test (grid with a lower gap) and control (grid without a lower gap) configurations were fished simultaneously. The data were therefore treated as paired. We used the statistical analysis software SELNET (Herrmann et al., 2012, 2017) to analyse catch data and to conduct length-dependent catch comparisons and catch ratio analyses. The differences in catch efficiency between the gears were assessed, averaged over hauls. For assessing the relative catch efficiency resulting from the lower gap in the shrimp grid, we applied a method for modelling the length-dependent catch comparison ratio (proportion caught in test trawl, CC_l) summed over sets (Herrmann et al., 2017; Olsen et al., 2019):

$$CC_l = \frac{\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}+\frac{nc_{lj}}{qc_j}\right\}} \tag{1}$$

where nt_{lj} and nc_{lj} are the numbers of specimens for each species of length l, caught in the test and the control trawls respectively. h is the number of hauls carried out in each cruise. qt_j and qc_j are subsampling factors that quantify the fraction of the caught individuals whose length is measured for each species in the respective trawl.

The modelled catch comparison ratio, $CC(l, \boldsymbol{v})$, was estimated by minimizing:

$$-\sum_{l}\left\{\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\times ln(CC(l,\boldsymbol{v}))+\frac{nc_{lj}}{qc_j}\times ln(1.0-CC(l,\boldsymbol{v}))\right\}\right\} \tag{2}$$

where $\boldsymbol{v}$ is a vector of parameters describing the catch comparison curve $CC(l, \boldsymbol{v})$ (Eq. (3)). The outer summation in expression (2) is over the length classes l.

Minimizing expression (2) is equivalent to maximizing the likelihood for the observed data based on a maximum likelihood formulation for binominal data, and is similar in structure to the SELECT model (Millar,

1992) for data pooled over hauls, which is often applied in analysis of fishing gear size selectivity (Wileman et al., 1996).

For equal catch efficiency of the test and standard gears, the expected value for the summed catch comparison ratio is 0.5. Therefore, this baseline is applicable for detecting any difference in catch efficiency between the two gears. The experimental CC_l was modelled by the function $CC(l, \boldsymbol{v})$ as follows:

$$CC(l, \boldsymbol{v}) = \frac{exp(f(l, v_0, \ldots, v_s))}{1 + exp(f(l, v_0, \ldots, v_s))} \tag{3}$$

where f is a polynomial of order t with coefficients v_0 to v_s. The parameters $\boldsymbol{v}$ are estimated by minimizing expression (2). We considered s of up to 4th order with parameters v_0, v_1, v_2, v_3, and v_4. Excluding one or more parameters $v_0 \ldots v_4$ resulted in 31 additional models to be considered as potential candidates for $CC(l,\boldsymbol{v})$. Catch comparison ratios were estimated amongst these models by applying multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017).

The capability of the combined model to describe the data was evaluated based on the p-value, calculated based on the model deviance and the degrees of freedom (DOF). For DOF of the combined model the most conservative estimate was used which equals the DOF for the most complex model used. In general, a combined model with p-values greater than 0.05 is considered to describe the experimental data sufficiently. There are, however, exceptions for overdispersed data (Wileman et al., 1996; Herrmann et al., 2017). Based on the estimated catch comparison function $CC(l, \boldsymbol{v})$, we obtained the relative catch efficiency (catch ratio, $CR(l, \boldsymbol{v})$) between the trawls using the relationship (Herrmann et al., 2017):

$$CR(l, \boldsymbol{v}) = \frac{CC(l, \boldsymbol{v})}{(1 - CC(l, \boldsymbol{v}))} \tag{4}$$

The catch ratio predicts the ratio caught in the test gear compared to the control gear. Therefore, for equal catch efficiency of the test and the control gear for specimens of length l of a given species, $CR(l,\boldsymbol{v})$ should be 1.0. Similarly, $CR(l, \boldsymbol{v}) = 1.5$ means that for specimens of length l there are 50% higher catches in the test trawl than in the control trawl. If $CR(l, \boldsymbol{v}) = 0.7$, the test trawl retains 70% of the number of specimens of length l retained in the control trawl (i.e. a 30% loss).

Double bootstrapping (Herrmann et al., 2017) was used for obtaining the confidence limits for both the catch comparison and catch ratio curves. This method accounts for uncertainty due to between-haul variation by randomly selecting m hauls out of m available with replacement. Within each resampled haul, the size distributions are then resampled in an inner bootstrap procedure. This second resampling accounts for uncertainty in each haul due to a finite number of shrimp, *Nephrops*, and fish being caught and having their length measured in the haul. To account for uncertainty due to subsampling, the data were raised by sampling factors after the inner resampling. The outer bootstrapping loop that accounted for the between-haul variation was performed pairwise for the test and control gears to reflect the experimental design in which both gears were deployed simultaneously. Also, by applying multi-model inference for each of the bootstrap iterations, uncertainty in model selection is accounted for. One thousand bootstrap repetitions were performed and Efron 95% confidence limits were calculated (Efron, 1982). To identify sizes for each of the species where differences in catch efficiency were significant, we checked if the 95% confidence limits for size classes contained the value 1.

For the catch ratio ($CR_{average}$), size-integrated average values were estimated directly from the catch data by:

$$\begin{aligned} CR_{average-} &= \frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nc_{lj}}{qc_j}\right\}} \\ CR_{average+} &= \frac{\sum_{l\geq MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l\geq MLS}\sum_{j=1}^{h}\left\{\frac{nc_{lj}}{qc_j}\right\}} \end{aligned} \tag{5}$$

with the outer summations being over the size classes below (for $CR_{average-}$) and above (for $CR_{average+}$) the minimum legal size (*MLS*), respectively, for each species.

Finally, as the purpose of the lower gap inserted in the grid of the test configuration was to increase the catch efficiency for *Nephrops*, investigating the proportion of undersized individuals in the two setups (grid with and without gap) was of interest. For that purpose, a sustainability indicator (*NRatio*) was estimated directly following Olsen et al. (2019):

$$\begin{aligned} NRatio_{Test} &= \frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l\geq MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}} \\ NRatio_{Control} &= \frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nc_{lj}}{qc_j}\right\}}{\sum_{l\geq MLS}\sum_{j=1}^{h}\left\{\frac{nc_{lj}}{qc_j}\right\}} \end{aligned} \tag{6}$$

where the outer summations include the sizes below (in nominator) and above (in denominator) the minimum length for *Nephrops*, respectively. Therefore, the *NRatio* quantifies the ratio between undersized and target sizes for captured *Nephrops*. This value should ideally be low. The *NRatio* is affected by both the (relative) size selectivity in each gear configuration and the size distribution of the *Nephrops* entering the gears. Therefore, these indicators provide estimates that are specific to the population being fished and cannot be extrapolated to other areas and seasons.

3. Results

3.1. Data collection

The first cruise was carried out in the north-eastern part of Skagerrak (58°54.93 N–59°05.92 N, 10°37.83E–10°46.08E) from 17 to 29 March, 2019. We completed 22 hauls at depths that ranged between 75 and 170 m. Average towing time was 179 min. The shrimp catches varied from 49.2 to 537.6 kg, and 978 *Nephrops* were captured during the cruise. Four bycatch species were captured in a sufficient amount of hauls and in sufficiently high numbers to carry out the catch comparison/catch ratio analysis between the gears: hake (*MLS* = 30 cm), Norway pout (*MLS* not regulated), spiny dogfish (*MLS* = 70 cm), and American plaice (*MLS* not regulated) (Table 1).

The second cruise was conducted from 2 to 13 April 2019 on the fishing grounds outside of Lindesnes (57°58.07 N–58°03.05 N, 06°56.30E–07°17.70E). Twenty-four hauls were performed at depths ranging from 100 to 190 m. Average towing time was 209 min. The shrimp catches varied between 9.0. and 199.9 kg, and 213 *Nephrops* were captured during the cruise. Six species of fish were captured in a sufficient number of hauls and in sufficiently high numbers to carry out the catch comparison/catch ratio analysis between the gears: cod (*MLS* = 40 cm), haddock (*MLS* = 31 cm), velvet belly (*MLS* not regulated), hake, Norway pout and American plaice (Table 1).

Table 1
Number of hauls with catches of each of the species and percentage of individuals measured for each of the species in each of the trawls in each cruise.

		Haddock	*Nephrops*	Hake	N. Pout	Velvet belly	Cod	A. plaice	Spiny dogfish
Cruise 1	N hauls	3	20	20	20	0	7	7	15
	Total individuals in test	2	818	2017	7931	0	7	425	115
	% measured in test	100	100	87	37	0	100	100	100
	Total individuals in control	2	160	1691	7041	0	4	348	28
	% measured in control	100	100	91	39	0	100	100	100
Cruise 2	N hauls	17	23	24	25	19	23	23	0
	Total individuals in test	62	167	549	4609	767	41	310	0
	% measured in test	100	100	100	37	72	100	100	0
	Total individuals in control	54	46	334	3888	425	34	199	0
	% measured in control	100	100	100	42	75	100	100	0
Cruise 3	N hauls	18	22	7	22	22	19	19	18
	Total individuals in test	49	266	2	8415	1527	44	79	312
	% measured in test	100	100	100	37	100	100	100	100
	Total individuals in control	50	74	9	6307	555	45	49	8
	% measured in control	100	100	100	47	100	100	100	100

The last cruise was carried out from 29 October to 8 November 2019 on fishing grounds further north, outside Karmsundet (59°03.71 N–59°28.50 N, 05°03.18E–05°37.66E). We made 24 hauls at depths ranging between 85 and 249 m. Average towing time was 126 min. The shrimp catches varied between 15.5 and 249.1 kg, and 341 *Nephrops* were captured during the cruise. Five fish species were captured in a sufficient amount of hauls and in sufficiently high numbers to carry out the catch comparison/catch ratio analysis between the test and control gears: cod, haddock, Norway pout, American plaice, spiny dogfish, and velvet belly (Table 1).

3.2. Bycatch of Nephrops

The *Nephrops* catches recorded during the three cruises show that the gear configuration with the lower gap in the grid caught more individuals of certain size ranges than the gear configuration with the grid without the lower gap (Fig. 2d–f). The *CR(l, **v**)* and *CR(l, **v**)* curves, which according to the fit statistics presented in Table 2 represent the experimental data well ($p > 0.05$ and/or model deviance ~ DOF), show that the CL ranges of *Nephrops* for which the catch efficiency between the two tested gears differed significantly varied between 31 and 74 mm, 30 and 66 mm, and 34 and 65 mm in cruises 1, 2, and 3, respectively (Fig. 2). Furthermore, the curves have a similar pattern for all three cruises, and they show that the difference in catch efficiency increases with size for the smallest sizes, is largest for *Nephrops* with a CL of approximately 40–60 mm and decreases again for the largest *Nephrops* (Fig. 2).

The size-integrated average values for the catch ratio show that inserting a lower gap of 15 cm in the grid significantly increased the catches of *Nephrops* over the minimum length. This increase was

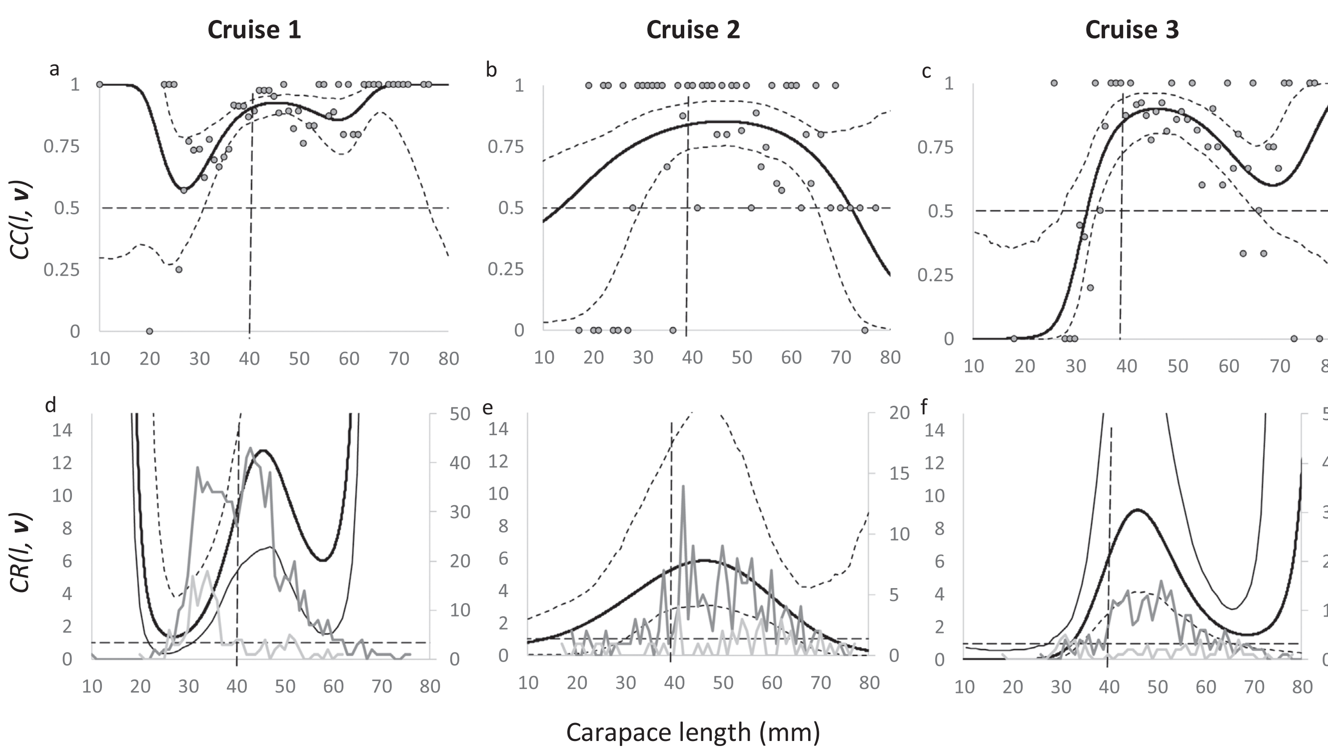

Fig. 2. Catch comparison ratios (plots a–c) and catch ratios (plots d–f) for the trawl configuration with the grid with a lower gap versus the configuration with the grid without the lower gap. In plots a–c the circles show the experimental catch comparison ratios, whereas the solid line and the dotted lines show the modelled catch comparison ratio and the corresponding 95% confidence intervals. Plots d-e show the catch distribution of *Nephrops norvegicus* in the configuration with the lower gap (dark grey) and in the configuration without the lower gap (light grey). The solid black curve is the catch ratio curve, and the dotted curves are the corresponding 95% confidence intervals.

Table 2
Fit statistics (*p*-value, deviance, and DOF) for the catch comparison curve shown in Fig. 2d–f. Size-integrated average values for the catch ratio for *Nephrops* under ($CR_{average-}$) and over ($CR_{average+}$) the minimum length (*ml*) for cruises 1, 2, and 3 and the proportion of undersized individuals with respect to individuals over the *MLS* (40 mm carapace length) caught with the test ($NRatio_{Test}$) and control ($NRatio_{Control}$) configurations during the three cruises. Confidence intervals are provided in brackets.

	Cruise 1	Cruise 2	Cruise 3
p-value	0.104	0.021	0.093
Deviance	60.6	73.6	60.2
DOF	48	51	47
CRaverage − (%)	297 (190–523)	300 (111–567)	113 (62–222)
CRaverage + (%)	1132 (785–2132)	394 (240–747)	478 (289–780)
NratioTest	0.8 (0.5–1.0)	0.2 (0.01–0.4)	0.1 (0.1–0.2)
NRatioControl	2.9 (1.4–6.9)	0.3 (0.1–0.7)	0.5 (0.2–0.8)

significant for all three cruises and on average was estimated to be 1132% for cruise 1394% for cruise 2%, and 478% for cruise 3. However, the gear configuration with the lower gap also captured more *Nephrops* below the *MLS*. This configuration caught on average 297%, 300%, and 112% more individuals below the *MLS* in cruises 1, 2, and 3, respectively, and this increase was estimated to be significant for the first two cruises (Table 2). The ratio of undersized individuals to individuals over the *MLS* caught with the test configuration ($NRatio_{Test}$) was lower than 1 in all three cruises (and significantly lower for cruises 2 and 3), which means that the test configuration caught higher numbers of *Nephrops* over the *MLS* than under the *MLS* during all three cruises. Furthermore, the *Nratio* was higher (significantly so for cruises 1 and 3) for the control configuration than for the test configuration for all three cruises, indicating that the increase in the catches of *Nephrops* in the gear configuration with a lower gap was mainly due to an increase in the catches of *Nephrops* above the *MLS*.

3.3. Shrimp catches

The shrimp catches in each trawl in cruise 1 (121.7–203.2 kg) were significantly greater than those in cruises 2 (50.0–86.4 kg) and 3 (54.1–96.3 kg) (Table 3). For cruises 1 and 2, the configuration with the lower gap captured on average 5.4 and 7.3 kg more shrimp than the control configuration, whereas the catches were on average equal for both trawl types during cruise 3. The difference in the average catch between the test and control configurations for cruise 2 were due mainly to the significant difference in catch of shrimp above the *MLS*, which was on average 7.7 kg higher for the configuration with the lower gap. Overall, however, the differences in mean catch between the test and control configurations were not statistically significant for any of the three cruises (Table 3).

Table 3
Mean shrimp catches (in kg) above and below the *MLS* caught with the test and control configurations and the differences between them. Confidence intervals are provided in brackets.

		Cruise 1	Cruise 2	Cruise 3
Control	Mean catch < 15 mm (kg)	43.7 (31.6–56.3)	19.9 (14.3–26.3)	17.2 (10.9–24.9)
	Mean catch ≥ 15 mm (kg)	112.6 (89.2–138.1)	43.4 (34.0–52.5)	58.3 (43.2–73.6)
	Mean catch Total (kg)	156.3 (121.7–193.9)	63.3 (50.0–76.3)	75.5 (54.3–96.2)
Test	Mean catch < 15 mm (kg)	46.7 (34.0–61.6)	19.5 (14.0–25.8)	16.6 (10.5–24.1)
	Mean catch ≥ 15 mm (kg)	115.0 (90.8–140.4)	51.2 (39.0–64.3)	58.9 (42.3–74.6)
	Mean catch Total (kg)	161.7 (125.5–203.2)	70.6 (55.7–86.4)	75.5 (54.1–96.3)
Delta	Mean catch < 15 mm (kg)	3.1 (−0.6 to 6.7)	-0.5 (−3.8 to 2.7)	-0.7 (−2.3 to 1.0)
	Mean catch ≥ 15 mm (kg)	2.4 (−7.7 to 11.5)	7.7 (0.1–16.1)	0.7 (−3.6 to 5.0)
	Mean catch Total (kg)	5.4 (−7.5 to 16.7)	7.3 (−1.4 to 16.7)	-0.0 (−5.1 to 5.0)

3.4. Fish bycatch

During the first cruise, we caught 3708 individuals of hake, 14 972 individuals of Norway pout, 773 individuals of American plaice, and 143 individuals of spiny dogfish (Table 1). The results of the size-dependent *CC(l, **v**)* and *CR(l, **v**)* analysis show that for all four species the test configuration caught significantly more individuals in a certain specific range of sizes. In the cases of hake and Norway pout, the lower confidence interval of the *CC(l, **v**)* and *CR(l, **v**)* is just above 0.5 and 1 respectively for a few length classes for the *CC(l, **v**)* and *CR(l, **v**)*, respectively. However, these differences were estimated for the most abundant size classes (10–20 cm for hake and 10–15 cm for Norway pout), which adds confidence to the results obtained (Fig. 3a–b, e–f). For American plaice, the catches differed significantly between the configurations for fish above 15 cm, which shows that some of the largest individuals that were not able to pass between the bars of the grid entered the main codend through the lower gap (Fig. 3c, g). The test configuration also caught significantly more spiny dogfish above 20 cm than the control configuration (Fig. 3d, h). The indicators show that the test configuration caught, on average, significantly more hake below the *MLS* than the control configuration (Table 4). The test configuration also caught on average 13% more Norway pout, 22% more American plaice, and over four times as many spiny dogfish as the control configuration (Table 4). These differences in catch efficiency were significant for hake, Norway pout, and spiny dogfish, but not for American plaice. The fit statistics show that for American plaice and spiny dogfish, the *p*-values were 0.483 and 0.944, respectively, which indicates that the model used represented the experimental data well. For hake and Norway pout, on the other hand, the *p*-values were 0.049 and 0.020, respectively (Table 4). We assume that the low *p*-values in these two cases were due to overdispersion in the experimental data. The *CC(l, **v**)* curves in both cases represent the data well (Fig. 3) and the deviance and DOF were of the same magnitude, indicating a good fit of the model to the experimental data.

During cruise 2, we caught and analysed the data for 883 hake, 8497 Norway pout, 5093 American plaice, 116 haddock, 75 cod, and 1192 velvet belly (Table 1). For cod and haddock, the *CC(l, **v**)* and *CR(l, **v**)* analyses and the size distributions showed that the caches in the two configurations did not differ much (Fig. 4a-b, g–h). Few individuals of these two species were caught, and they were quite large, mainly between 40 and 70 cm in both cases, which greatly limited the potential influence of the lower gap. The indicators show that on average the test configuration caught 12% more cod and 15% more haddock than the control configuration, but the difference was not statistically significant in either case (Table 4). For the other four species, the effect of inserting a lower gap in the grid was clearer, and the *CC(l, **v**)* and *CR(l, **v**)* curves showed similar patterns (Fig. 4c–f, i–l). For the sizes of fish that could pass through the bars in the grid and enter the main codend, the catches were similar for the two configurations. However, as size increased and individuals of the different species began to have difficulties passing through the grid, the difference between the catches became more apparent, with the test configuration catching significantly more individuals than the control configuration in all four cases. The indicators show that the test configuration caught on average 55%, 20%, 56%, and 79% more individuals of hake, Norway pout, American plaice, and velvet belly, respectively, below the *MLS* than the control configuration. In all cases, except for Norway pout, this difference was statistically significant (Table 4). The fit statistics for the data collected during this cruise show that the observed deviation between the experimental *CC(l)* and modelled curves could well be coincidental. This was further corroborated by the finding that the deviance and DOF in all five cases

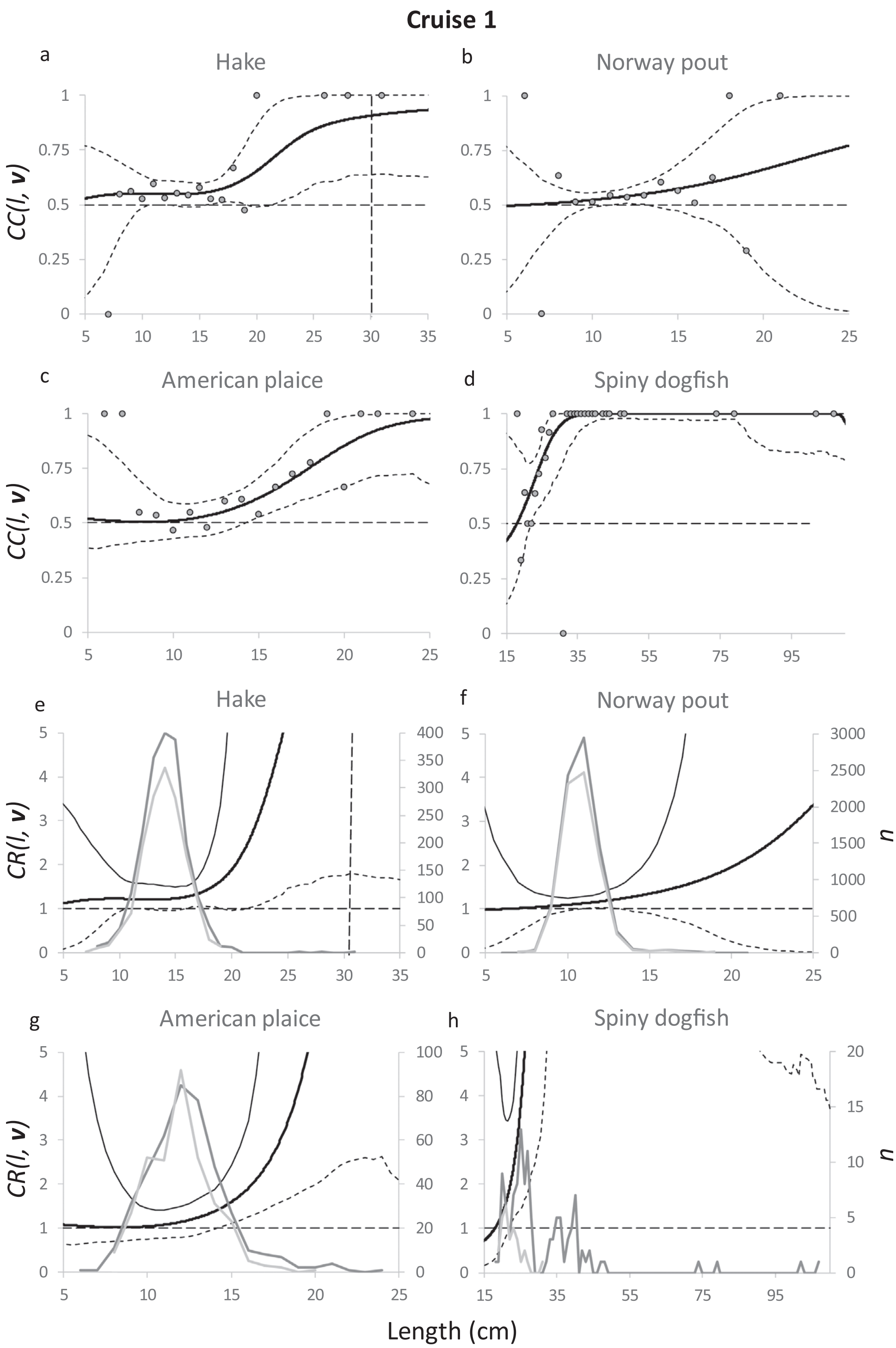

Fig. 3. Results of *CC(l,* ***v****)* (above) and *CR(l,* ***v****)* (below) analyses for hake (*Merluccius merluccius*, a, e), Norway pout (*Trisopterus esmarkii*, b, f), American plaice (*Hippoglossoides platessoides,* c, g), and spiny dogfish (*Squalus acanthias,* d, h) caught during cruise 1. The plots are built as in Fig. 2.

were of the same magnitude (Table 4). We assume that the low *p*-value observed for Norway pout (Table 4) was due to considerable subsampling (Table 1) and consequent overdispersion in the experimental data.

During the third cruise, we caught 14 722 Norway pout, 128 American plaice, 99 haddock, 89 cod, 2082 velvet belly, and 320 spiny dogfish (Table 1). As in cruise 2, the catches for cod and haddock were low, and the *CC(l,* ***v****)* and *CR(l,* ***v****)* plots did not show significant differences between the catches in the test and control gear configurations (Fig. 5a–b, g–h). The patterns observed for the *CC(l,* ***v****)* and *CR(l,* ***v****)* for velvet belly, Norway pout, and American plaice were similar to those observed in cruise 2 (Fig. 5c–e, i–k). The numbers of individuals caught with both configurations were similar at sizes that could pass through the grid, but the differences increased with increasing fish size. In the control configuration, the larger individuals were sorted out by the grid, but in the test configuration some of the larger individuals were able to pass towards the main codend through the lower gap. For a certain range of sizes, the difference between the two configurations increased with size, as the probability of passing between the bars of the grid decreased with size while the probability of passing through the lower gap

Table 4
Fit statistics (*p*-value, deviance, and DOF) for *CC(l,* $\boldsymbol{v}$*)* and size-integrated average values for the catch ratio under ($CR_{average-}$) and over ($CR_{average+}$) the *MLS* for all species included in the analysis from each cruise; 95% confidence intervals are provided in brackets. "#" is used in the cases where the species was not caught during the cruise in question. "* " is used when the indicator could not be calculated due to lack of fish above or below the *MLS* in either the test or control gear.

		Cruise 1	Cruise 2	Cruise 3
Cod	p-value	#	0.315	0.006
	Deviance	#	30.0	60.6
	DOF	#	27	36
	CRaverage+ (%)	#	112 (59–217)	257 (100–700)
	CRaverage- (%)	#	*	68 (39–115)
Haddock	p-value	#	0.137	0.049
	Deviance	#	31.6	40.2
	DOF	#	24	27
	CRaverage+ (%)	#	115 (72–259)	67 (17–189)
	CRaverage- (%)	#	*	105 (68–162)
Hake	p-value	0.049	0.841	#
	Deviance	21.1	22.4	#
	DOF	12	30	#
	CRaverage+ (%)	*	*	#
	CRaverage- (%)	119 (101–138)	155 (117–203)	#
N. pout	p-value	0.020	$>$ 0.001	0.249
	Deviance	21.2	38.0	16
	DOF	10	13	13
	CRaverage (no *mls*) (%)	113 (101–125)	121 (98–142)	133 (112–157)
A. plaice	p-value	0.483	0.290	0.447
	Deviance	12.6	19.7	23.2
	DOF	13	17	23
	CRaverage (no *mls*) (%)	122 (93–159)	156 (115–207)	161 (107–242)
Spiny dogfish	p-value	0.944	#	1.000
	Deviance	14.9	#	10.3
	DOF	25	#	43
	CRaverage (no *mls*) (%)	411 (210–1040)	#	400 (395–405)
Velvet belly	p-value	#	0.330	0.998
	Deviance	#	26.5	14.7
	DOF	#	24	33
	CRaverage (no *mls*) (%)	#	179 (116–423)	275 (202–385)

remained similar (Fig. 5c–e, i–k). In the case of spiny dogfish, the configuration with the lower gap caught significantly more individuals of the smallest sizes until approximately 73 cm, at which point the difference became non-significant (Fig. 5f, l). The indicators for cod and haddock show that the test configuration captured more cod and less haddock above the *MLS* than the control configuration, but these results were not statistically significant. For the other four species, the indicators show that the test configuration caught on average 33% more Norway pout, 61% more American plaice, 175% more velvet belly, and 300% more spiny dogfish than the control configuration, and these differences were statistically significant. The *CC(l,* $\boldsymbol{v}$*)* fit statistics for these four species show that the model represented the data well, as the *p*-value was > 0.05 in every case. For haddock and cod, the *p*-value was < 0.05, but this low value was assumed to be a consequence of overdispersion in the experimental data, as visual observation of the model fit to the data did not reveal a systematic pattern in the difference between the model and the experimental observations.

4. Discussion

Installation of a lower gap in the shrimp grid significantly increased catches of *Nephrops* without loss of the target species. At the same time, catches of hake, Norway pout, American plaice, velvet belly, spiny dogfish, cod, and haddock increased, although the level of significance for some of the species differed between cruises, mainly due to varying prevalence of some of the species.

The increase in the catches of *Nephrops* generated by the presence of the lower gap was limited to CLs between approximately 30 and 70 mm. As anticipated, specimens smaller than 30 mm passed between the bars in the grids, while specimens with carapace lengths above 70 mm have a low probability of passing through the gap due to their complexly sculptured morphology. Therefore, the probability of *Nephrops* being caught in the test trawl, of those caught in one of the trawls, is described by a bell-shaped curve. Thus, in addition to increased retention of legal-sized *Nephrops*, the gap also led to increased retention of undersized *Nephrops* (below 40 mm CL).

As expected, no loss of shrimp catch was associated with the presence of the lower gap in the grid. In principle, the lower gap should only increase the probability that shrimp will pass through the grid. The lower gap also decreases the risk of flatfish, skates, debris, and seaweed clogging the grids, as they will to some extent pass through the gap. Thus, any catch difference for shrimp was likely to be in favour of the trawl containing the grid with the lower gap. This was the case for all three cruises. The catches in the trawl with the grid with the lower gap were on average greater than those in the control trawl, although the difference was not statistically significant in any case.

Regarding the bycatch of fish, the insertion of a gap in the lower 15 cm of the grid was expected to affect mainly those sizes of fish that are too large to pass between the bars in the grid and at the same time too small to be retained by the fish collecting bag. The effect of a gap would be most noticeable for fish species that, like *Nephrops*, position themselves close to the lower panel of the gear (Graham and Fryer, 2006; Melli et al., 2019). Relative to the moving trawl, hake reportedly drift backwards close to the lower panel (Alzorriz et al., 2016; Cuende et al., 2020), and the results from cruises 1 and 2 showed that the catch increase in the trawls with the lower gap in the grid became significant for hake of approximately 15 cm, which is probably the size at which they begin to have difficulty passing through the 19 mm bar spacing of the grid (Tokaç et al., 2018). A similar pattern was observed in the catch comparison results for both velvet belly and spiny dogfish. This indicates that, relative to the moving trawl, these two shark species also drift backwards close to the lower panel. Shark eyes seem to have low spatial resolution and they exhibit poor or no optomotor response (Ryan et al., 2016; Scarfe, 1979), which can in turn explain this outcome.

Previous studies reported that the vertical distribution of different flatfish species in the extension piece of the trawl can vary, but that in relation to the moving trawl, these fish drift backwards close to the lower panel (Melli et al., 2019; Larsen et al., 2021). We found that the retention of American plaice for length classes < 30 cm was greater when the lower gap was present in the grid, which suggests that substantial numbers of this species remained close to the lower panel in the extension piece. The results from cruise 3, which was the only cruise in which American plaice > 30 cm were present, showed that the effect of the gap decreased for fish over this size, most likely because fewer individuals could pass through the gap with increasing fish size, and it is likely that most American plaice over this size entered the bycatch codend.

For Norway pout, which was the most abundant bycatch species during all three cruises, the catches *in the test and control trawl* differed significantly for at least some length classes in every cruise. However, the curves for the most abundant length classes of this species were flatter than those for hake, velvet belly, or spiny dogfish. Although Norway pout is small and most of the length classes caught would be expected to be able to pass between the bars in the grid, the pattern in the curves could indicate that individuals of this species are more uniformly distributed across the cross section of the grid than other bycatch species. This would reduce the impact of the presence of a lower gap in the grid. A more homogeneous entry pattern corresponds with the behaviour of fish species that try to stay clear of the trawl netting (Glass

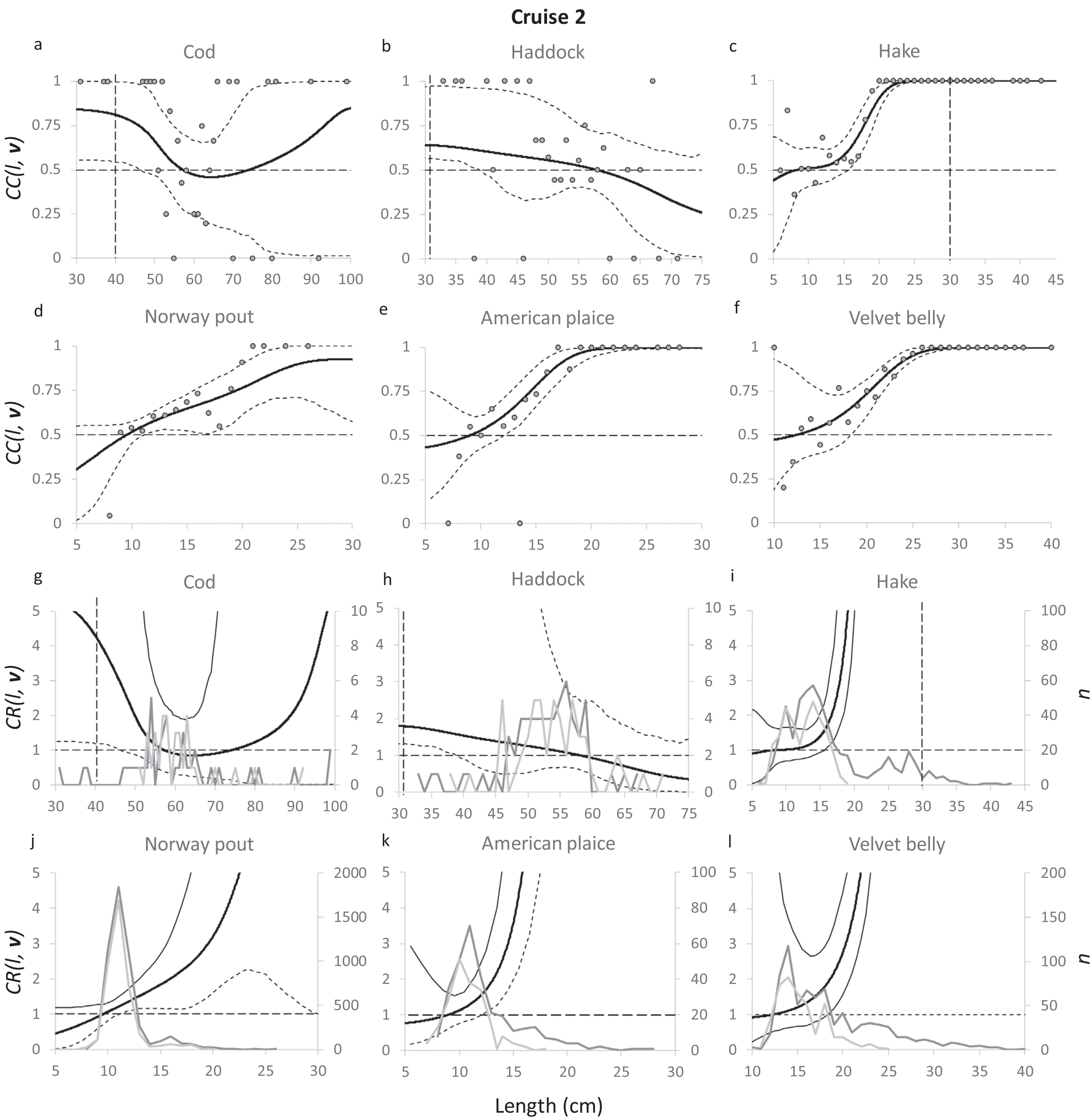

Fig. 4. Results of *CC(l, v)* (two upper rows) and *CR(l, v)* (two lower rows) analyses for cod (*Gadus morhua*, a, g), haddock (*Melanogrammus aeglefinus*, b, h), hake (*Merluccius merluccius,* c, i), Norway pout (*Trisopterus esmarkii,* d, j), American plaice (*Hippoglossoides platessoides,* e, k), and velvet belly (*Etmopterus spinax,* f, l) captured during cruise 2. The plots are built as in Fig. 2.

et al., 1993), e.g. pelagic species.

Cod and haddock are two of the most important commercial species in Skagerrak and the North Sea, and the former is severely overfished (Ulrich et al., 2017). Therefore, any gear change that would increase the bycatch of juveniles of these two species would be unacceptable from a management perspective. Small individuals of these two species were caught only on cruise 2. Although the trawl with the grid gap captured more fish up to a length of 40–50 cm than the configuration without the gap, the numbers of fish caught were very low. Thus, it is difficult to draw conclusions about the effect on these two species of inserting a lower gap in the grid.

Previous studies that tested the effects of lower gaps in shrimp grids reported results that agree well with those of the present study. Madsen and Hansen (2001) tested a grid design in the North Sea shrimp trawl fishery that was similar to the one tested in the present study. As in our experiment, they provided an opening for the largest fish on top of the grid, and they tested the effect of lower gap heights of 10 and 15 cm on the catch efficiency for *Nephrops*. The authors showed that a lower gap effectively increased the catches of *Nephrops*, but it also substantially increased the catches of Norway pout. Fonseca et al. (2005) tested a modified Nordmøre grid with a 20 cm tall lower gap and concluded that while the lower gap was very efficient at avoiding the loss of *Nephrops* caused by the insertion of the grid (> 85% of the *Nephrops* were retained), a substantial bycatch of species such as blue whiting

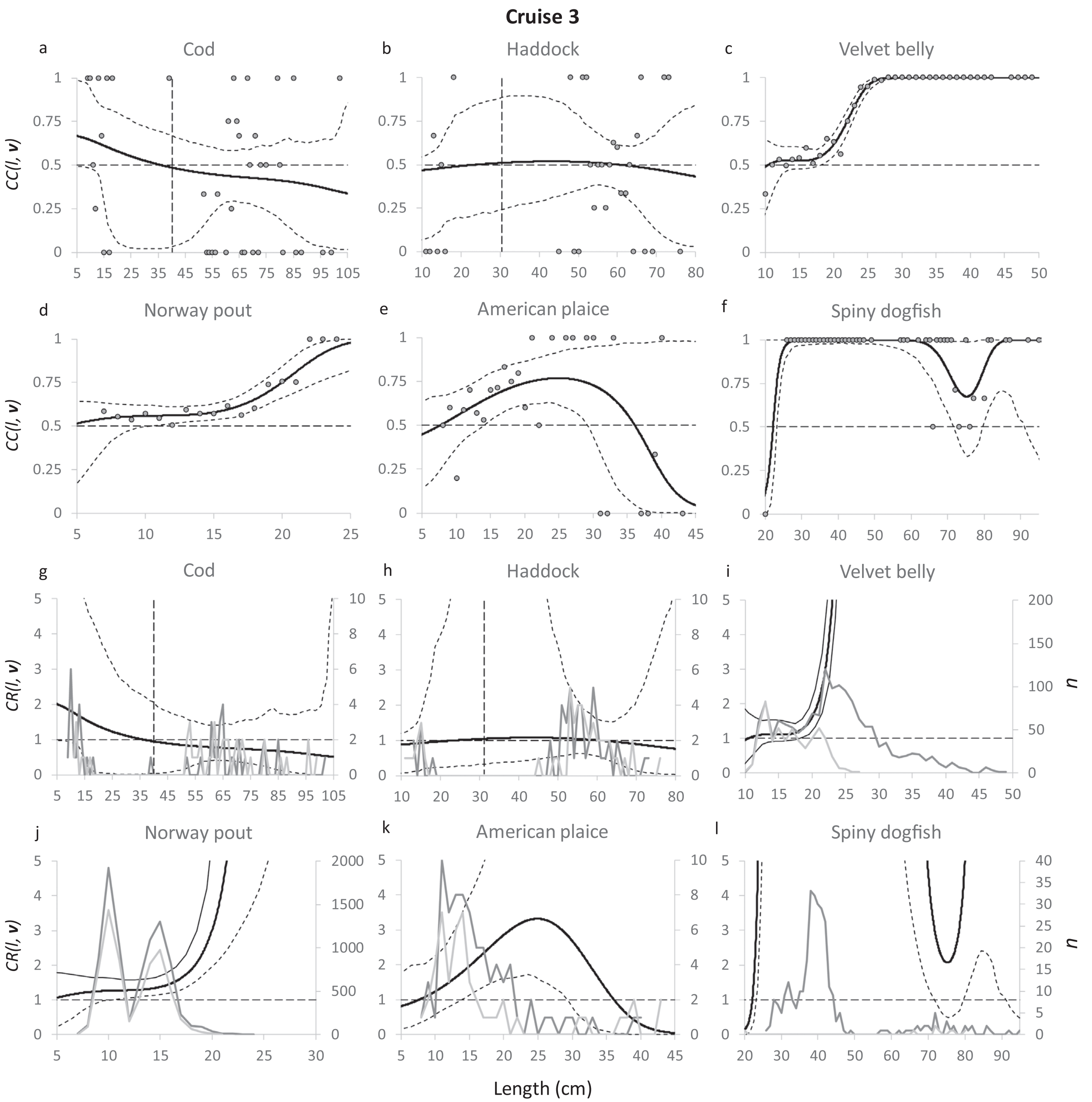

Fig. 5. Results of *CC(l, v)* (two upper rows) and *CR(l, v)* (two lower rows) analyses for cod (*Gadush morhua*, a, g), haddock (*Melanogrammus aeglefinus*, b, h), velvet belly (*Etmopterus spinax,* c, i), Norway pout (*Trisopterus esmarkii,* d, j), American plaice (*Hippoglossoides platessoides,* e, k) and spiny dogfish (*Squalus acanthias,* f, l) captured during cruise 3. The plots are built as in Fig. 2.

(*Micromesistius poutassou*) entered the main codend through the lower gap.

The results from these two earlier studies and the present study show that lower gaps in grids increase the retention of *Nephrops* efficiently, but that the bycatch of other species is also substantially increased. One way to retain the benefit of the lower gap with respect to *Nephrops* and also mitigate the increase in juvenile bycatch may be to use stimulators (obstructions like e.g. floats, ropes and chains) in the lower panel of the extension piece. Stimulators have shown potential to lead fish away from the lower gap (Melli et al., 2018, 2019) without affecting the catch of *Nephrops*.

Although a lower gap significantly increased the catch rates of *Nephrops*, overall catch rates of *Nephrops* were low across all three fishing experiments. At the same time the gap increased catches of several bycatch species, including protected species like spiny dogfish. It was therefore concluded that the benefits of a gap were not sufficient to allow its use in the coastal shrimp fishery in southern Norway. Because the catches of *Nephrops* in the three cruises in our study were generally low, less effort to reduce the losses of *Nephrops* in the northern shrimp fishery may be made in the future. However, the results obtained here may be relevant for other situations with higher incidences of *Nephrops*.

CRediT authorship contribution statement

Ólafur A. Ingólfsson: Conceptualization, Methodology, Data curation, Writing – review & editing, Investigation, Methodology. **Terje Jørgensen**: Conceptualization, Project administration, Funding acquisition, Data curation, Writing – original draft preparation, Methodology, Writing – review & editing, Investigation, Methodology. **Manu Sistiaga**: Formal analysis, Visualization, Writing – original draft preparation, Writing – review & editing, Methodology. **Bent Herrmann**: Formal analysis, Writing – review & editing. **Methodology Liz Kvalvik**: Data curation, Writing – review & editing, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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