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1 **Development and test of selective sorting grids used in the**

2 **Norway lobster (*Nephrops norvegicus*) fishery**

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15 *Keywords:* Bycatch, *Nephrops norvegicus*, Norway lobster, Selectivity, Sorting grid, Trawl

16 17 **Abstract**

18 Due to generally high discard rates in Norway lobster (*Nephrops norvegicus*) fisheries, a discard
19 ban coming up and to the cod recovery plan in several areas, selective sorting grids have been tested
20 in many areas and are specified by legislation for use in the Kattegat and Skagerrak area bordering
21 Norway, Denmark and Sweden. Grids are very selective, but they can lead to loss of landable
22 Norway lobster and valuable fish species. To improve retention of these species, we developed
23 three new grids using made by polyurethane to make them flexible: One grid had horizontal bars,
24 one had vertical bars, and one had vertical bars and a guiding funnel in front of the grid. Four
25 unselective net bags were used to collect the catch escaping through different parts of the grid or
26 escaping without passing through the grid. Water flow around the grid bars was measured in a

flume tank. The three grids were tested from a commercial trawler in the Kattegat and Skagerrak area. Underwater filming was conducted to assess grid performance and fish behavior. Results showed that a bottom hole in the lower part of the grid allowed species in the lower part of the gear to pass and retained in the bag behind the hole. More flatfish passed the grid with horizontal bars compared to that with vertical bars, but the retention rate was still low. Use of the guiding funnel increased the contact with the grid considerably for both target and unwanted species. In all three grid designs, there were losses of Norway lobster above minimum landing size.

1. Introduction

The Norway lobster (*Nephrops norvegicus*) fishery is among the most economically important demersal species for human consumption in European fisheries (Catchpole and Revill, 2007). To retain Norway lobster, the mesh sizes used are relatively small (normally below 100 mm), which results in high bycatch and discard rates in most Norway lobster fisheries (Catchpole and Revill, 2007) and concern about the effects of this fishery on declining stocks of other species, particularly cod (*Gadus morhua*) (Madsen and Valentinsson, 2010; Eliassen, 2014). Additionally, the high bycatch rates in Norway lobster fisheries will cause problems by the reform of the European Union common fisheries policy that plans for gradual elimination of discards by landing obligations where all individuals of certain species caught are landed (Sardà et al., 2015). This means that unwanted catch (i.e., species or sizes with landing obligations but not of commercial interest) will be attributed to a given vessel's quota.

Results of several experiments from different fisheries indicate that sorting grids can be very selective and help reduce the volume of unwanted bycatch species in the catch of Norway lobster fisheries (Catchpole et al., 2006; Graham and Fryer, 2006; Loaec et al., 2006; Valentinsson and Ulmestrand, 2008; Frandsen et al., 2009; Drewery et al., 2010). Their use has been introduced by legislation in the Skagerrak and Kattegat (Valentinsson and Ulmestrand, 2008; Frandsen et al., 2009; Madsen and Valentinsson, 2010), and the grids are widely used by Swedish fishermen fishing

54 in this area, whereas Danish fishermen use other selective devices (Madsen and Valentinsson,
55 2010).

56 Several studies reported a loss of marketable fish bycatch when grids were used in the Norway
57 lobster fishery (Catchpole et al., 2006; Frandsen et al., 2009; Drewery et al., 2010). The fish
58 bycatch constitutes a part of the economy in most Norway lobster fisheries, particularly flatfish
59 species. A loss of commercial sized Norway lobster also has been identified (Frandsen et al., 2009).
60 Thus, improvements of grids in order to retain commercial fish species and lobster are essential.

61 Some studies have focused on improving the performance of the grid (Valentinsson and
62 Ulmestrand, 2008; Frandsen et al., 2009; Madsen et al., 2010). Results indicate that it is possible to
63 make improvements but also that further development is necessary. In relation to increasing
64 sustainability in the Norway lobster fishery by reducing unwanted bycatches, the upcoming discard
65 ban and an environmental certification (e.g., Marine Stewardship Council; www.msc.org) that may
66 be required of these fisheries. It is thus crucial to improve the grid to make it commercially feasible
67 because of the expected increased use of grids by fishermen in the future.
68 The main objective of this study was to develop and test an improved grid system that is able to
69 increase the retention of marketable fish and Norway lobster but still be highly selective to non-
70 target species. Most previous studies have been conducted based on relative catch comparisons
71 (Catchpole et al., 2006; Valentinsson and Ulmestrand, 2008; Drewery et al., 2010), in which results
72 depend on the size structure of the populations that come in contact with the grid. In this study we
73 used small meshed collecting bags to provide estimates that were population independent. By
74 covering different parts of the grids with the collecting bags we aim at gaining information about
75 where escape takes place. The experiments were conducted in the Kattegat and Skagerrak area,
76 which is characterized by high discard rates (Feekings et al., 2012; Uhlmann et al., 2014) and where
77 management plans have been made to ensure recovery of the cod stock that has been declining over
78 the past 30 years (Madsen and Valentinsson, 2010; Kraak et al., 2013; Eliassen, 2014). During the
79 last decade, development and implementation of selective fishing gears has been a cornerstone of
80 fisheries management in this area (Madsen and Valentinsson, 2010).

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2. Materials and methods

2.1 Grid development

The grid designs are illustrated in Fig. 1. To avoid fishermen safety issues and improve handling properties, the grids were not constructed of metal. Instead, they were made of polyurethane (Carlsen Nets, Denmark) that is very strong and able to sustain temperatures from –30 to 70 °C. This material is flexible, making it possible to wind it directly on the net drum.

To improve the performance of the grid, several changes were made compared to the grid specified by legislation and the grids tested in previous experiments (Valentinsson and Ulmestrand, 2008; Frandsen et al., 2009; Madsen and Valentinsson, 2010; Madsen et al., 2015). First, the grid colour was black to provide a potential contrast effect (Glass and Wardle, 1995; Glass et al., 1995) so that fish might react by trying to avoid the bars and swim out. Second, the bar distance was increased to 45 mm from the 35 mm required by legislation (Madsen and Valentinsson, 2010) and the 40 mm tested in previous experiments (Madsen et al., 2015). This change was aimed particularly at reducing loss of Norway lobster above minimum landing size (MLS). Third, a hole (henceforth bottom hole) was made in the lowest part of the bottom of the grid having only two bars left to guide fish away, particularly cod. The purpose of this hole was to stop benthic debris from blocking the bars in an area which is essential for the passage of Norway lobster, to allow a substantial proportion of Norway lobster to enter the codend (Madsen and Hansen, 2001) without coming into physical contact with the grid, and to let commercial important ground fish (particularly flatfish) enter the codend directly. The height of the bottom hole was increased from 15 cm in a past experiment (Madsen et al., 2015) to 17.5 cm. Two designs of the grid were constructed: one with traditional vertical bars and one with horizontal bars; the aim of the latter was

107 to make it easier for flatfish to pass through the bars since they are of commercial importance in the
108 Danish Norway lobster fishery (particularly plaice).

109 The grids were inserted at an angle of 45° in a four-panel section made of 90 mm single thread
110 polyurethane (Fig. 2). A four-panel section was used because it is expected to be more stable than a
111 traditional round two-panel section (Madsen et al., 2010). A wedge section inserted in front of the
112 grid section served as the conversion to the conventional two-panel sections in front of the grid
113 section. The vertical bars grid was tested in two different riggings: one without a guiding funnel and
114 one with a 2 meter long guiding funnel ending 70 cm in front of the grid having a vertical opening
115 on 20 cm (Fig. 2). The advantage of using a guiding funnel is that the catch is concentrated in the
116 lower part of the fishing gear, potentially providing a larger contact area for Norway lobster that
117 might hit the middle or upper part of a grid (Krag et al., 2009). The disadvantage is that the funnel
118 disrupts behavior, particularly by guiding fish downwards, and reduces the use of species-specific
119 behavior as a selectivity tool (e.g., cod are expected to stay higher in the net than Norway lobster
120 and flatfish).

121 Four 8 m long separate small meshed collecting bags made of netting with a 35 mm nominal
122 mesh opening were inserted in the codend and attached to the grid where they were used to collect
123 fish penetrating and escaping from the grid system (Fig. 3). The bags collected individuals escaping
124 through: 1) the hole in the lower part of the grid; 2) the lower half of the grid; 3) the upper half of
125 the grid; and 4) the escape hole above the grid after being rejected by the grid system.

126

127 2.2 *Experimental work*

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129 All grid systems were tested in a flume tank (Hirtshals, Denmark) to assess performance and make
130 adjustments before the sea trials. Approximately 20 fishermen and net markers participated in these
131 tests to comment and discuss the performance of the systems. Measurements of the water flow
132 inside the codend were conducted at the maximum speed for the flume tank of 0.9 m/s (1.8 knots),
133 using an electromagnetic current flow sensor (Valeport, model 802) with a precision of flow

134 measurements $\pm 4\%$. The measurements were taken 10 cm in front of the grid and midway in the
135 vertical direction for the hole, the lower grid and the upper grid sections (Fig. 2). Measurements
136 were also taken 10 cm behind the grid at the same positions for the two vertical bars grids; this
137 measurement was not taken for the horizontal bars grid because it was impossible to penetrate this
138 grid (from above) with the flow meter. A total of 1000 measurements were taken at each position.

139 Experimental sea trials were conducted in March 2010 in the Kattegat and Skagerrak area from a
140 20 m long commercial stern trawler (vessel number: FN 234) with an engine power of 298 kW. The
141 trawler was rigged with a twin trawl system that fishing with its own two identical trawls made for
142 the fishery in this area that mainly targets Norway lobster, having a nominal 100 mm mesh size
143 throughout, 460 meshes in circumference, a horizontal opening around 20 m and a headline height
144 around 2 m. The grid with horizontal bars was fished on one side of the twin trawl system, and the
145 other side was used for other experiments. The grid with vertical bars and the grid with vertical bars
146 and guiding funnel were fished simultaneously in each side of the twin trawl system. For all three
147 grid systems the side position in the twin trawl system was change midway during the sea trials. The
148 towing time varied from around 2 to 4 hours. This duration was on the low end compared to most
149 commercial fisheries, but it was chosen to minimize the risk of potential blocking of the grids by
150 debris that would obscure the selective effect of the grid and blur the results.

151 To obtain the total catch weight, the cover fractions were weighed using a crane scale (Kern HTS
152 1.5T, Germany) on deck, and then the weight of the netting was subtracted. Length measurements
153 were taken for all commercially important species, and all individuals were length measured in
154 most cases. However, subsampling was necessary for haddock (*Melanogrammus aeglefinus*),
155 whiting (*Merlangius merlangus*), and Norway lobster when catches were high. The total length of
156 fish were measured to the nearest cm below and Carapace length of Norway lobster to the nearest
157 mm using an electronic calliper (Sylvac S_cal pro, Switzerland). The midpoints (mean) of the
158 length classes of fish and Norway lobster were used in the subsequent analysis.

159 Underwater video observations (Camera: Inspecam SHF; Control Box WP; www.u-cam.com) of
160 the grid were conducted for two hauls during fishing on the Norway lobster grounds where the

camera was positioned in the extension looking backwards at the grid with horizontal bars. The grid with vertical bars and guiding funnel was filmed in shallow water (around 10 m) with a sandy seabed (i.e., not a Norway lobster habitat), and the camera was fixed midway on the top of the grid looking downwards at the lower part of the grid and the area in front of the grid .

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2.3 Statistical modeling of relative efficiency

167

Each of the three designs sampled data in four compartments. Holst and Revill (2009) proposed a model for the relative efficiencies of a two-compartment model, whereby, under common assumptions, the expected proportion $\phi(\ell)$ of length ℓ fish, caught in the test codend could be suitably fitted by a low-order polynomial:

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$$\text{logit}(\phi(\ell)) \approx \log\left(\frac{q_t}{q_c}\right) + \beta_0 + \beta_1 \cdot \ell + \dots + \beta_k \cdot \ell^k, \quad (1)$$

for some integer k . Here $\log\left(\frac{q_t}{q_c}\right)$ acts as an offset, where q_t and q_c denote the proportions of the

total catch taken out for measurement from the test and the control compartments, respectively.

$\beta_0, \beta_1, \dots, \beta_k$ are the unknown parameters to be estimated.

To handle data from experiments in which fish are collected from more compartments, the model is readily extended to a multinomial model. Assume the gear consists of J compartments indexed by $j = 0, \dots, J-1$, and consider compartment 0 to be the reference (control) compartment. Similar to the binomial model, we may approximate the logit of the efficiency of compartments j , relative to the control, by:

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$$\text{logit}(\phi_j(\ell)) \approx \log\left(\frac{q_j}{q_0}\right) + \beta_{0,j} + \beta_{1,j} \cdot \ell + \dots + \beta_{k,j} \cdot \ell^k, \quad j = 1, \dots, J-1. \quad (2)$$

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185 The increased number of parameters in the multinomial model makes the estimation more data
186 demanding in terms of number of fish caught in each compartment. Furthermore, the model is
187 subject to the same limitations of confounding between the intercepts and the split-parameters.

188 The well-known between-haul variation (Fryer, 1991) that occurs when data are collected over
189 multiple hauls was addressed by applying the $\sqrt{\text{REP}}$ correction to the standard errors of the
190 parameters estimates obtained from fitting the above model to the stacked data (Millar et al., 2004).
191 This approach is robust for handling data with scarce observations in individual haul compartment
192 combinations. Confidence bands for the expected proportions were obtained using the delta theorem
193 (Lehmann, 1983). We used the R-package ‘nnet’ for the estimation of our model.

194 The model was applied for cod, haddock, lemon sole (*Microstomus kitt*), Norway lobster, plaice
195 (*Pleuronectes platessa*), and whiting when there was a reasonable number of fish.

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198 **3. Results**

199

200 *3.1 Flow measurements*

201

202 The flume tank tests indicated that the grids and the experimental set-up using collecting bags
203 worked very well after a few adjustments. Flow measurements are provided in Table 1. The flow
204 was highest in front of the lower grid, followed by the hole and then the upper grid. The flow was
205 reduced by < 10% at the lower grid and by ~25% at the upper grid compared to the free stream.
206 There was some reduction in the flow behind the grid compared to the front of the grid.

207

208 *3.2 Catches and distributions*

209

210 Clogging of the grid by seaweed was a problem in several hauls, and we actively searched for
211 areas without any seaweed. Hauls where seaweed was found on the grid were discarded because its
212 presence reduced penetration through the bars and hence influenced selectivity. In the remaining
213 hauls seaweed was not observed on the grid or in collecting bags. One haul was discarded because a
214 large amount (> 5 tonnes) of greater weaver (*Trachinus draco*) was caught. Table 2 lists the number
215 of hauls included in the analysis (10–14) for each grid system and conditions during the sea trials.
216 Total catch weights (all four fractions) varied from 207 to 528 kg for the horizontal bars grid, 375-
217 1034 kg for the vertical bars grid and 307-1289 kg for the vertical bars grid with a guiding funnel.

218 Pooled catches of the different species and their distribution in the four compartments are
219 provided in Table 3. The escape of Norway lobster below MLS was (17.4%) in the vertical bars
220 grid without the guiding funnel, and of about the same magnitude for the horizontal bars grid
221 (5.4%) and vertical bars grid with the guiding funnel (5.8%). The escape of Norway lobster above
222 MLS was 12.8% in the vertical grid with a guiding funnel, 32.5% in the vertical bars grid without
223 the guiding funnel; the value was 24.1% for the horizontal bars grid. The proportion of Norway
224 lobster above MLS passing through the bottom hole in the grid with horizontal bars, vertical bars
225 and vertical bars with guiding funnel was 44.1%, 25.8% and 66.6%.

226 The average escape of cod, haddock, and whiting below MLS was high (67.3–88.0%) in the
227 horizontal and vertical bars grid without the guiding funnel. Escape of cod and whiting above MLS
228 in the vertical bars grid and the horizontal bars grid was high (82.6%–92.6%). A high proportion of
229 plaice (77.3% and 92.4%) above MLS escaped from the horizontal and vertical bars grid without
230 the guiding funnel, respectively.

231 Relatively few cod, haddock, and whiting passed through the bars of the three grids, but those
232 that did so passed through both the lower and upper grid. The proportion of cod, haddock and
233 whiting below MLS passing through the bottom hole in the grid with horizontal bars, vertical bars
234 and vertical bars with guiding funnel was from 5.3–11.0%, 2.2–7.6% and 39.5–46.1%, respectively.

235

For plaice above MLS the proportion passing through bottom hole for the horizontal bars grid, the vertical bars grid and the vertical bars grid with guiding funnel was 14.4%, 5.8% and 45.6%, respectively and for lemon sole the numbers were 5.7%, 2.9% and 24.3%.

3.3 Modeling of proportions

Fig. 3 shows the expected proportions of the catch by length in each of the four compartments for the three different grid designs (with 95% confidence bands). For cod a lower proportion escaped from the vertical bars grid with the guiding funnel compared to the two other grids, and the difference was statistically significant for fish below 30 cm (hereafter, statistical significance is indicated by lack of overlap of the 95% confidence limits). Additionally, the proportion of cod that entered the bottom hole was significantly higher in the range from 20 to 60 cm. The proportion of haddock escaping from the horizontal bars grid was statistically significantly higher for fish below 30 cm compared to the two other grids. No statistically significant difference in escape from the three grids was detected for lemon sole above 30 cm. There is a higher (statistically significantly) escape in the vertical bars grid compared to the horizontal bars grid for lemon sole below 20 cm. A high proportion, but rapidly decreasing with length, of the smallest lemon sole entered the lower grid of the vertical bars grid with the guiding funnel. The proportion of escapees of Norway lobster increased with length for all three grids. At around 50 mm carapace length, the proportion escaping was significantly lower for the vertical bars grid with the guiding funnel compared to the other two grids. The proportion of plaice in the bottom hole section was statistically significantly higher for all lengths for the vertical bars grid with the guiding funnel compared to the two other grids. The escape of whiting below MLS is significantly lower in the vertical bars grid with guiding funnel.

3.4 Underwater observations

262 The observations were limited when fishing on Norway lobster fishing grounds because of
263 clouds of mud. However, it was possible to observe the grid with horizontal bars for limited periods
264 of time. Three flatfish were observed to be sitting on the grid throughout the observation period.
265 Flatfish approached the grid horizontally with the head either facing directly upstream or
266 downstream (not sideways). One plaice facing downstream drifted towards the grid and, upon
267 contact, flipped its tail, which resulted in escape through the escape hole in the upper sheet of
268 netting. Two flatfish, one facing upstream and one facing downstream, passed between the bars of
269 the grid, and another flatfish passed through the bottom hole. Only three round fish appeared on the
270 footage. They were all facing upstream, and no contact with the grid was observed. No Norway
271 lobsters were observed.

272 No fish were observed sitting on the grid with vertical bars for a long period of time. Those fish
273 that stayed on the grid did not slide along the bars passively. Flatfish were able to stay in positioned
274 in front of the grid. In a 5 minutes observation period with good visibility there were 71 flatfish
275 passing through the guiding funnel; 75 observations of flatfish (often the same individual) reacting
276 with a few extra tail beats if they touched the grid; 12 flatfish passing between the bars tail first; 36
277 flatfish drifting along the bottom and passing through the bottom hole. A single plaice facing
278 downstream passed through the grid head first. Small round fish stayed positioned in front of the
279 grid. They seemed to be moved slowly upwards by the flow and ended up escaping through the
280 escape hole. A larger gadoid hit the grid, and it reacted with rapid tail beats and ended up passing
281 between the bars of the grid tail first.

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283

284 **4. Discussion**

285

286 In general, we documented high escape of fish in the two grid concepts in which no guiding
287 funnel was used. We used an experimental codend/collecting bags with small low-selective meshes.
288 In a commercial codend, mesh selection will occur in the codend behind the grid, where additional

289 escape of some of the smallest fish passing through the grid system will occur. The bottom hole
290 seemed to function well in the grids without the guiding funnel, as a relatively high proportion of
291 Norway lobster entered through it, as did a few gadoids. Because the proportion of flatfish was low,
292 it would be relevant to make improvements to retain more flatfish above MLS that are of
293 commercial value. In all grids tested in our experiments, higher proportions of cod, plaice and
294 Norway lobster above MLS entered the bottom hole, compared to a previous experiment (Madsen
295 et al., 2015) having a bottom hole with a lower height (17.5 cm vs 15.0 cm) and with more bars (6
296 versus 2).

297 Use of the guiding funnel increased the proportion of the catch that passed through the hole in
298 the bottom of the grid where they were not subjected to size selectivity caused by grid bars. For cod,
299 more than half of the catch above MLS passed through the hole. For a grid with bars instead of a
300 hole in the lower part, a guiding funnel is an efficient way to increase the contact with the grid in
301 the lower part.

302 The flow in front of the lower part of the grid was not much lower than that of the free steam
303 flow, whereas some reduction was detected in front of the upper grid that might be caused by an
304 upward flow in the direction of the escape hole in the top panel. We observed that relatively large
305 fish demonstrated avoidance behavior near the grid, but this occurred when the visibility in the
306 water was high. Most Norway lobster fisheries are located in deeper water, where the visibility is
307 low due to mud clouds. Smaller individuals with lower swimming performance (Videler and
308 Wardle, 1991) will be less able to react to the grid. Norway lobster is expected to mainly stay in the
309 lower part of the gear (Cole and Simpson, 1965; Main and Sangster, 1985; Krag et al., 2009), and
310 because they have limited swimming ability (Newland et al., 1988; Newland and Chapman 1989), it
311 is likely that their first contact will be with the lower part of a grid device. The water flow, and
312 hence the towing speed, might have an effect on the selection process, but it is not obvious in which
313 direction, and further investigations would be valuable.

314 More plaice above MLS passed through the horizontal bars compared to the vertical bars.
315 However, still more than three-quarters of the plaice above MLS escaped when using horizontal

316 bars. A high rejection rate of flatfish that come in contact with grid bars must be expected, and it
317 will be difficult to increase substantially the retention rate of large flatfish and other selective
318 devices should be considered to increase retention of flatfish. As observed in previous trials with
319 other grid designs and the 35 mm bar distance (Frandsen et al., 2009) and 40 mm bar distance
320 (Madsen et al., 2015) there are still Norway lobster that don't penetrate the grid and escape. For the
321 horizontal bars grid, only around 5% of Norway lobster below MLS escaped whereas 24% above
322 MLS escaped. This indicates that it is actually possible to reduce the loss further by increasing the
323 bar distance. Because a proportion of the Norway lobster catch passes through the upper part of the
324 grid, another potential way to reduce loss is to increase the length of the grid and to increase the
325 contact area, as penetration of Norway lobster through the grid bars will depend on the contact
326 angle (Frandsen et al., 2010) and several escape attempts might be necessary. However, increased
327 length of the grid is expected to increase retention of small fish.

328 We conducted relatively short hauls, but we still had to discard several hauls because the grids
329 were blocked by seaweed. This is a disadvantage of the grid compared to selective escape windows.
330 Under commercial conditions, this problem might add an extra cost for the fishermen, and in some
331 areas it might be impossible to use a grid during certain periods of time. However, it might be
332 possible to find a technical solution to this problem. For example, in shrimp fisheries, sensors on the
333 grid are often used to indicate the water flow through the grid. If the grid becomes blocked, the
334 skipper makes a short stop to lower the grid to a horizontal position to remove trash from the grid.
335 Although this particular solution is not very likely to work for seaweed that has infiltrated the grid,
336 similar approaches should be investigated to find a way it would likely remove. In addition, it likely
337 would work to remove other objects, such as flatfish, that can get stacked on the grid.

338 Grids made of polyurethane tested in this study are currently used by several fishermen in shrimp
339 fisheries in several areas, , and they are satisfied with its performance. The stiffness of the material
340 can be adjusted during the production. The general experience is that the "memory" of the material
341 is limited, which ensures that the grid returns to its original shape after being on the net drum. "The

342 grids made of this material will likely meet the needs of fishermen in terms of improved handling
343 and safety compared with metal grids."

344

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346

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351

352 **References**

353 Catchpole, T.L., Revill, A.S., 2007. Gear technology in Norway lobster trawl fisheries. Reviews in
354 Fish biology and Fisheries 18, 17–31.

355 Catchpole, T.L., Revill, A.S., Dunlin, G., 2006. An assessment of the Swedish grid and square mesh
356 cod-end in the English (Farn Deep) *Nephrops* fishery. Fish. Res. 81, 118–125.

357 Cole, H.A., Simpson, A.C., 1965. Selection by trawl nets in the *Nephrops* fishery. Rapp. P.V. Reun.
358 ICES 156, 203–205.

359 Drewery, J., Bova, D., Kynoch, R.J., Edridge, A., Fryer, R.J., O'Neill, F.G., 2010. The selectivity of
360 the Swedish grid and 120 mm square mesh panels in the Scottish *Nephrops* trawl fishery. Fish.
361 Res. 106, 454–459.

362 Eliassen, S.Q., 2014. Cod avoidance by area regulations in Kattegat – experiences for the
363 implementation of a discard ban in the EU. Mar. Pol. 5, 108–113.

364 Feekings, J., Bartolino, V., Madsen, N., Catchpole, T., 2012. Fishery discards: Factors affecting
365 their variability within a demersal trawl fishery. PLoS One, 7(4): e36409.

366 Frandsen, R.P., Herrmann, B., Madsen, N., 2010. A simulation-based attempt to quantify the
 367 morphological component of size selection of *Nephrops norvegicus* in trawl codends.
 368 Fish. Res. 101, 156–167.

369 Frandsen, R.P., Holst, R., Madsen, N., 2009. Evaluation of three levels of selective devices relevant
 370 to management of the Danish Kattegat-Skagerrak *Nephrops* fishery. Fish. Res. 97, 243–252.

371 Fryer, R.J., 1991. A model of the between-haul variation in selectivity. ICES J. of Mar. Sci. 48,
 372 281-290.

373 Glass, C.W., Wardle, C.S., 1995. Studies on the use of visual stimuli to control fish escape from
 374 codends: II. The effect of a black tunnel on the reaction behaviour of fish in otter trawl codends.
 375 Fish. Res. 23, 165–174.

376 Glass C.W., Wardle, C.S., Gosden, S.J., Racey, D.N., 1995. Studies on the visual stimuli to control
 377 fish escape from codends: I. Fish. Res. 23, 157–164.

378 Graham N., Fryer R.J., 2006. Separation of fish from *Nephrops norvegicus* into a two-tier cod-end
 379 using a selection grid. Fish. Res. 82, 111–118.

380 Holst, R., Revill, A., 2009. A simple statistical method for catch comparisons studies. Fish.
 381 Res. 95, 254–259.

382 Kraak, S.B.M., Bailey, N., Cardinale, M., Darby, C., De Oliveira, J.A.A., Eero, M., Graham, N.,
 383 Holmes, S., Jakobsen, T., Kempf, A., Kirkegaard, E., Powell, J., Scott, R.D., Simmonds, J.E.,
 384 Ulrich, C., Vanhee, W., Vinther, M., 2013. Lessons for fisheries management from the EU cod
 385 recovery plan. Mar. Pol. 37, 200–213.

386 Krag, L.A., Madsen, N., Karlsen, J.D., 2009. A study of fish behaviour in the extension of a
 387 demersal trawl using a multi-compartment separator frame and SIT camera system. Fish. Res.
 388 98, 62–66.

389 Lehmann, E.L., 1983. Theory of point estimation. Wiley & Sons Inc., 511 pp.

390 Loaec, H., Morandeau, F., Meillat, M., Davies, P., 2006. Engineering development of flexible
 391 selectivity grids for *Nephrops*. Fish. Res. 79, 210–218.

392 Madsen, N., Frandsen, R.P., Holst, R., Krag, L.A., 2010. Development of new concepts for escape
 393 windows to minimise cod catches in Norway lobster fisheries. *Fish. Res.*, 103: 25-29.

394 Madsen, N., Hansen, K.E., 2001. Danish experiments with a grid system tested in the North Sea
 395 shrimp fishery. *Fish. Res.* 52, 203–216.

396 Madsen, N., Lewy, P., Feekings, J., Krag, L.A., Frandsen, R., Hansen, K., 2016. Improving the
 397 performance of a grid used in Norway lobster fisheries. *J. Appl. Ichthyol.* 31, 525-528.

398 Madsen, N., Valentinsson, D., 2010. Use of selective devices in trawls to support recovery of
 399 the Kattegat cod stock: a review of experiments and experience. *ICES J. Mar. Sci.* 67,
 400 2042–2050.

401 Main, J., Sangster, G.I., 1985. Trawling with a two-level net to minimise the undersized gadoid by-
 402 catch in a *Nephrops* fishery. *Fish. Res.* 3, 131–145.

403 Millar, R.B., Broadhurst, M.K., Macbeth, W.G., 2004. Modelling between-haul variability in the
 404 size selectivity of trawls. *Fish. Res.* 67, 171–181.

405 Newland, P.L., Chapman, C.J., Neil, D.M., 1988. Swimming performance and endurance of the
 406 Norway lobster, *Nephrops norvegicus*. *Mar. Biol.* 98, 345–350.

407 Newland, P.L., Chapman, C.J., 1989. The swimming and orientation behaviour of the Norway
 408 lobster, *Nephrops norvegicus* (L.), in relation to trawling. *Fish. Res.* 8, 63–80.

409 Sardà, F., Coll M., Heymans, J.J., Stergiou, K.I., 2015. Overlooked impacts and challenges of the
 410 new European discard ban. *Fish Fish.*, 16, 175-180.

411 Wang, H., 2008. Exact confidence coefficients of simultaneous confidence intervals for
 412 multinomial proportions. *Journal of Multivariate Analysis* 99, 896–911

413 Uhlmann, S.S., van Helmond, A.T.M, Stefánsdóttir, E.K., Sigurðardóttir, S., Haralabous, J., Bellido
 414 J.M., Carbonell, A., Catchpole, T., Damalas, D., Fauconnet, L., Feekings, J., Garcia, T., Madsen,
 415 N., Mallold, S., Margeirsson, S., Palialexis, A., Readdy, L., Valeiras, J., Vassilopoulou, V.,
 416 Rochet, M-J., 2014. Discarded fish in European waters: general patterns and contrasts. *ICES J.*
 417 *Mar. Sci.* 71, 1235–1245.

418 Valentinsson, D., Ulmestrand, M., 2008. Species-selective Norway lobster trawling: Swedish grid
419 experiments. *Fish. Res.* 90, 109–117.

420 Videler, J.J., Wardle, C.S., 1991. Fish swimming stride by stride: speed limits and endurance. *Rev.*
421 *Fish Biol. Fish.* 1, 23–40.

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1 Table 1. Flow measurements (m/s) in the flume tank at a 0.9 m/s free steam water flow; average with
2 standard deviation (SD).

| Grid | Hole | Lower grid | | Upper grid | |
|------------------------|--------------|--------------|--------------|--------------|--------------|
| | Front | Front | Behind | Front | Behind |
| Horizontal bars | 0.80 (0.092) | 0.83 (0.042) | Na. | 0.69 (0.047) | Na. |
| Vertical bars | 0.81 (0.11) | 0.84 (0.066) | 0.78 (0.077) | 0.67 (0.081) | 0.62 (0.052) |
| Vertical bars, guiding | 0.79 (0.060) | 0.87 (0.048) | 0.71 (0.078) | 0.65 (0.037) | 0.63 (0.043) |

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6 Table 2. Operating conditions during the sea trials; average per haul with standard deviation (SD).

| Grid | No. hauls | Haul duration (hrs) | Depth (m) | Speed (kts) |
|------------------------|-----------|---------------------|-------------|-------------|
| Horizontal bars | 10 | 2.88 (0.84) | 52.2 (16.1) | 2.51 (0.12) |
| Vertical bars | 12 | 2.34 (0.56) | 70.6 (14.0) | 2.48 (0.07) |
| Vertical bars, guiding | 14 | 2.52 (0.68) | 69.6 (13.1) | 2.49 (0.07) |

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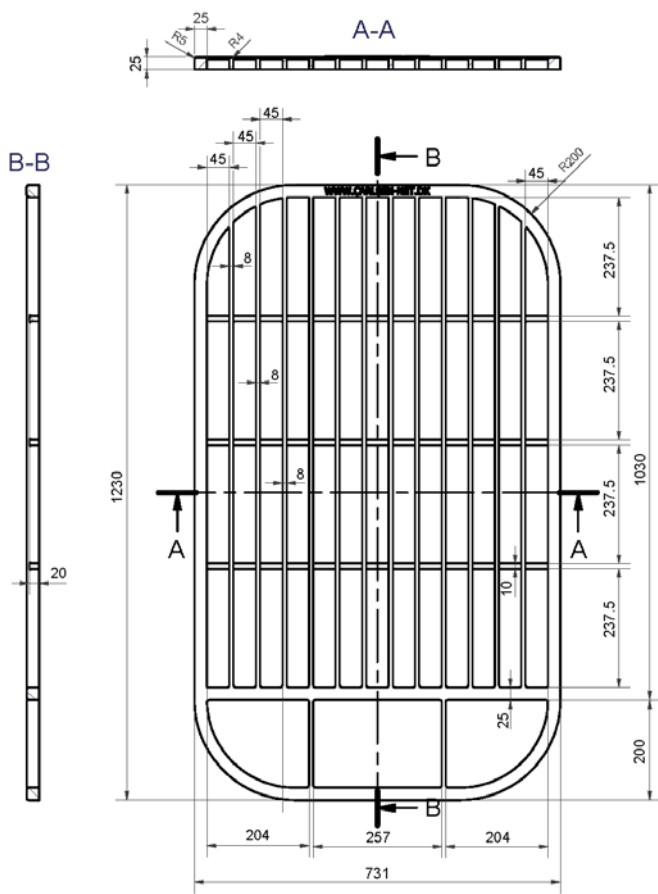
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Table 3. Catches of the main species for all hauls pooled divided by MLS. Proportions with 95% confidence limits based on a weighted average of multinomial standard errors over individual hauls (Wang, 2008). No estimates are made (NA) for observations with very low numbers.

| | Horizontal bars | | Vertical bars | | Vertical bars, guiding | |
|-----------------------|--------------------|--------------------|--------------------|--------------------|------------------------|--------------------|
| | < MLS | ≥ MLS | < MLS | ≥ MLS | < MLS | ≥ MLS |
| <i>Cod</i> | | | | | | |
| Total (no.) | 225 | 92 | 627 | 139 | 611 | 244 |
| Escape | 88.0% (78.2-97.8%) | 82.6% (67.2-98.1%) | 85.0% (77.4-92.6%) | 89.2% (80.2-98.2%) | 49.9% (38.9-60.9%) | 45.9% (30.7-61.1%) |
| Upper grid | 4.0% (0.3-7.7%) | 2.2% (0-6.3%) | 5.3% (0.8-9.8%) | 2.2% (0-5.0%) | 6.5% (0.9-12.2%) | 0.4% (0-1.2%) |
| Lower grid | 2.7% (0-6.6%) | 1.1% (0-3.1%) | 3.0% (0-6.1%) | 1.4% (0-4.1%) | 5.4% (0-11.0%) | 0.8% (0-2.4%) |
| Bottom hole | 5.3% (0-12.1%) | 14.1% (0-28.4%) | 6.7% (2.3-11.1%) | 7.2% (0-16.9%) | 38.1% (28.7-47.6%) | 52.9% (38.3-67.4%) |
| <i>Haddock</i> | | | | | | |
| Total (no.) | 2004 | 3 | 1499 | 15 | 4480 | 144 |
| Escape | 84.7% (82.1-87.3%) | 100.0% (NA) | 67.3% (61.3-73.3%) | 53.3% (36.0-70.7%) | 47.8% (43.8-51.8%) | 35.4% (24.9-45.8%) |
| Upper grid | 1.1% (0.4-1.9%) | 0.0% (NA) | 14.9% (10.3-19.5%) | 6.7% (NA) | 2.2% (0.9-3.4%) | 0.0% (NA) |
| Lower grid | 3.2% (2.0-4.3%) | 0.0% (NA) | 10.2% (6.4-14.0%) | 6.7% (NA) | 3.9% (2.1-5.7%) | 3.5% (0-7.0%) |
| Bottom hole | 11.0% (9.0-12.9%) | 0.0% (NA) | 7.6% (4.3-10.9%) | 33.3% (4.2-62.5%) | 46.1% (42.1-50.1%) | 61.1% (49.3-72.9%) |
| <i>Lemon sole</i> | | | | | | |
| Total (no.) | 337 | 35 | 362 | 69 | 549 | 74 |
| Escape | 85.8% (81.1-90.4%) | 85.7% (72.1-99.4%) | 75.1% (63.9-86.4%) | 85.5% (73.0-98.0%) | 55.4% (41.7-69.0%) | 73.0% (46.9-99.1%) |
| Upper grid | 3.0% (0.3-5.7%) | 8.6% (1.1-16.0%) | 6.9% (0-13.9%) | 4.3% (0-9.6%) | 5.8% (0.1-11.6%) | 2.7% (0-7.6%) |
| Lower grid | 5.3% (1.5-9.2%) | 0.0% (NA) | 13.3% (6.2-20.3%) | 7.2% (0-14.2%) | 8.4% (0.9-15.9%) | 0.0% (NA) |
| Bottom hole | 5.9% (2.3-9.6%) | 5.7% (0-16.0%) | 4.7% (0-10.1%) | 2.9% (0-7.6%) | 30.4% (18.4-42.5%) | 24.3% (0-49.6%) |
| <i>Norway lobster</i> | | | | | | |
| Total (no.) | 573 | 540 | 780 | 1072 | 846 | 1175 |
| Escape | 5.4% (1.8-9.0%) | 24.1% (16.1-32.1%) | 17.4% (11.2-23.7%) | 32.5% (25.6-39.3%) | 5.8% (1.7-9.9%) | 12.8% (7.9-17.6%) |
| Upper grid | 9.8% (5.8-13.8%) | 12.6% (7.1-18.1%) | 25.8% (18.5-33.1%) | 22.3% (16.2-28.4%) | 9.3% (4.6-14.1%) | 8.7% (4.7-12.6%) |
| Lower grid | 37.7% (30.0-45.4%) | 19.3% (11.9-26.6%) | 26.8% (19.3-34.3%) | 19.4% (13.6-25.2%) | 20.5% (13.4-27.5%) | 11.9% (7.2-16.7%) |
| Bottom hole | 47.1% (39.4-54.9%) | 44.1% (34.6-53.5%) | 30.0% (22.9-37.1%) | 25.8% (19.8-31.9%) | 64.4% (56.1-72.7%) | 66.6% (59.6-73.6%) |
| <i>Plaice</i> | | | | | | |
| Total (no.) | 753 | 278 | 3463 | 1197 | 2860 | 954 |
| Escape | 59.4% (49.6-69.2%) | 77.3% (64.5-90.2%) | 78.8% (75.8-81.9%) | 92.4% (88.9-95.9%) | 34.5% (29.3-39.8%) | 50.2% (40.4-60.1%) |
| Upper grid | 9.3% (3.8-14.8%) | 4.0% (0-8.8%) | 2.9% (1.5-4.4%) | 1.3% (0-2.8%) | 1.7% (0.2-3.2%) | 1.7% (0-3.9%) |
| Lower grid | 11.3% (4.7-17.9%) | 4.3% (0-9.8%) | 1.4% (0.4-2.5%) | 0.5% (0.1-0.9%) | 5.7% (3.1-8.3%) | 2.5% (0-5.5%) |
| Bottom hole | 20.1% (12.1-28.0%) | 14.4% (4.0-24.8%) | 16.8% (14.4-19.3%) | 5.8% (2.8-8.9%) | 58.1% (52.8-63.3%) | 45.6% (36.0-55.1%) |
| <i>Whiting</i> | | | | | | |
| Total (no.) | 1703 | 740 | 4917 | 1039 | 6766 | 1975 |
| Escape | 85.8% (81.3-90.3%) | 92.6% (88.1-97.1%) | 86.8% (84.4-89.2%) | 88.0% (82.7-93.2%) | 54.7% (51.1-58.3%) | 48.2% (42.1-54.3%) |
| Upper grid | 4.4% (1.8-7.0%) | 1.8% (0-3.8%) | 7.7% (5.7-9.6%) | 5.2% (2.1-8.3%) | 1.6% (0.6-2.5%) | 0.9% (0-2.0%) |
| Lower grid | 2.7% (1.0-4.4%) | 1.6% (0-3.3%) | 3.4% (2.1-4.6%) | 3.8% (1.2-6.5%) | 4.3% (2.6-5.95) | 3.0% (0.7-5.3%) |
| Bottom hole | 7.1% (4.3-9.9%) | 4.1% (1.5-6.6%) | 2.2% (1.0-3.3%) | 3.0% (0.4-5.6%) | 39.5% (36.0-42.9%) | 47.9% (41.9-53.9%) |

MLS: cod (*Gadus morhua*) = 30 cm; haddock (*Melanogrammus aeglefinus*) = 27 cm; lemon sole (*Microstomus kitt*) = 26 cm; Norway lobster (*Nephrops norvegicus*) = 40 mm carapace length; plaice (*Pleuronectes platessa*) = 27 cm; whiting (*Merlangius merlangus*) = 23 cm.

Vertical bars grid



Horizontal bars grid

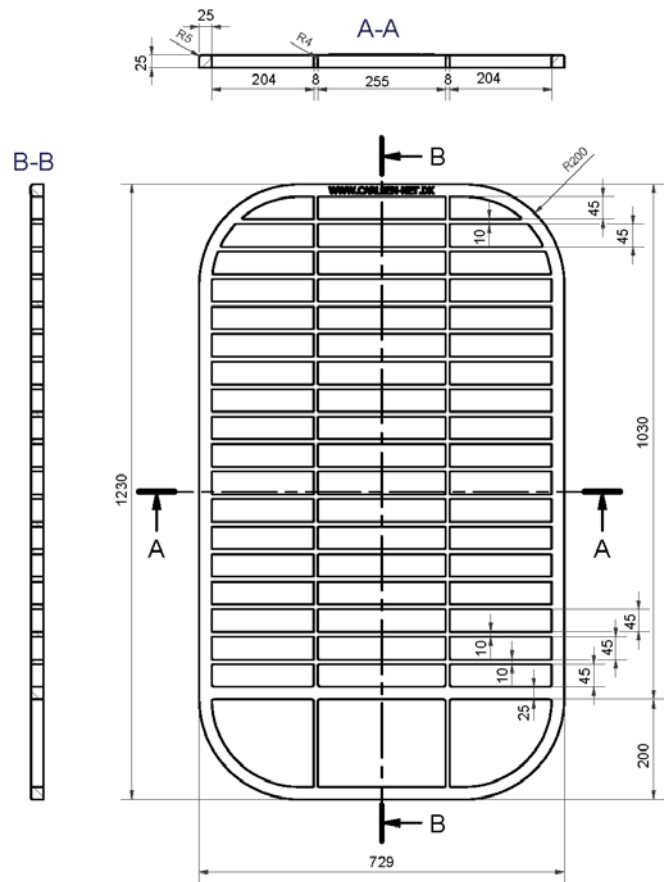


Fig. 1. Technical drawings of the grids. Distances in millimeter. R indicates the center of afcorner with the corner radius in millimeters.

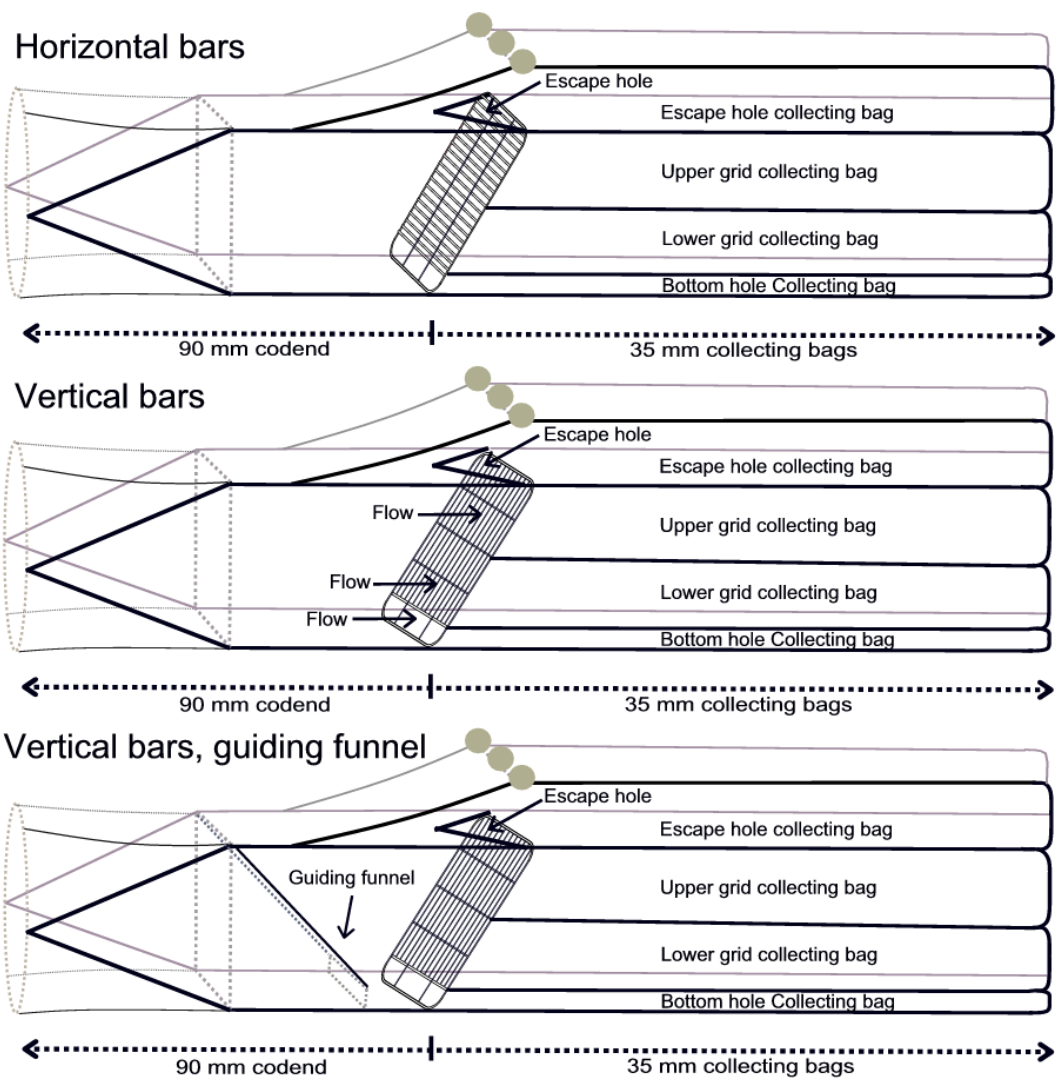


Fig. 2. Illustration of the grids and the principles of the experimental design. The 90 mm mesh size netting was used in front of the grid and the 35 mm small mesh netting was used for collecting bags that collect fish penetrating the grid system or escaping through the escape hole. Three floats were attached on the top collecting bag above the grid. Positions of flow measurements taken 10 cm in front and behind the grid (for the grid with vertical bars) are indicated by arrows. Drawing not to scale.

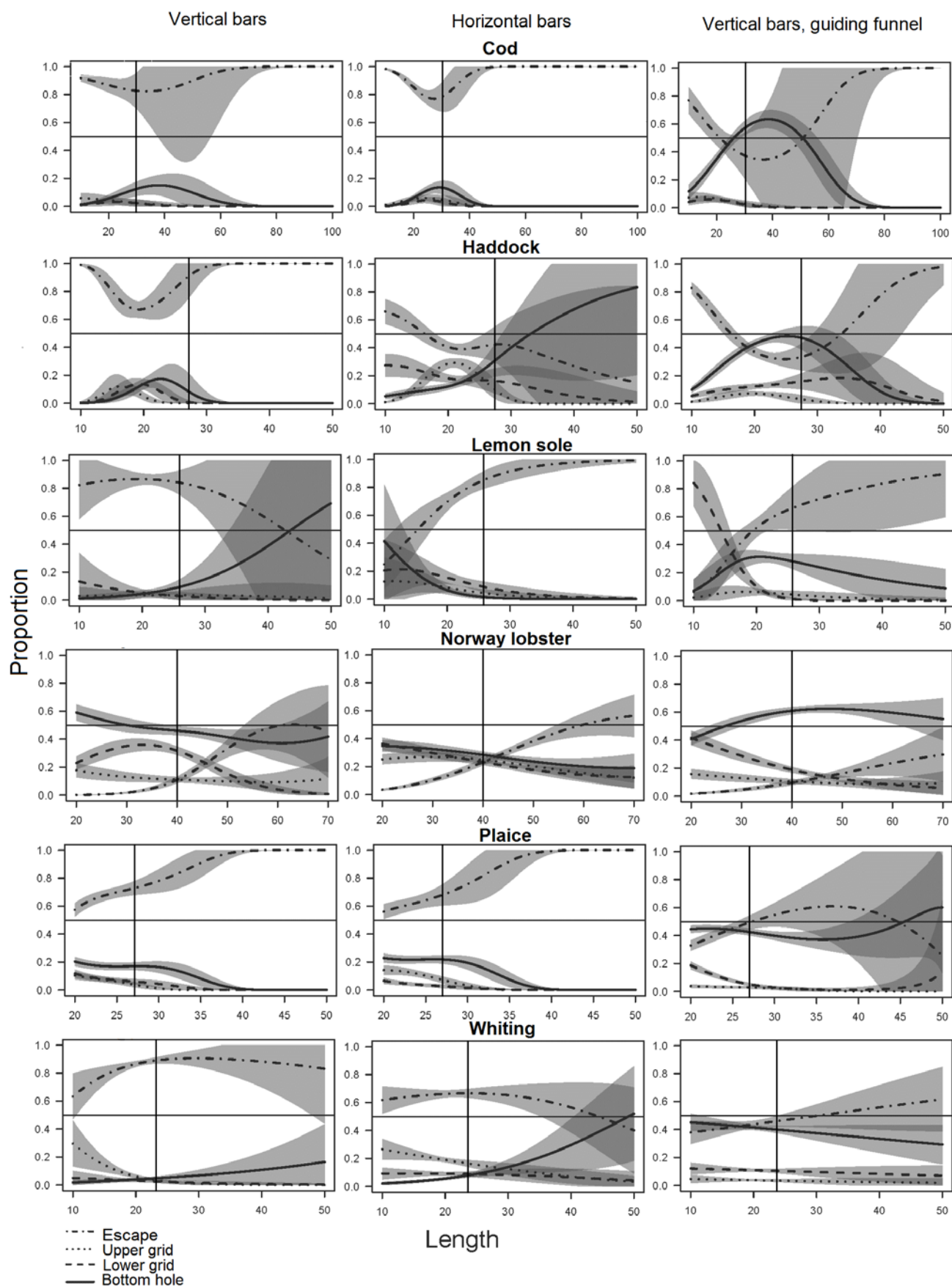


Fig. 3. The proportion by length in each of the four collecting bags for the horizontal grid (left), vertical grid (middle), and vertical grid with guiding funnel (right). The shaded areas indicate the 95% confidence bands. Length is in cm for fish and mm carapace length for Norway lobster. Minimum landing size (length provided in Table 3) is indicated by a vertical line.