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Size selectivity and length-dependent escape behaviour of haddock in a sorting device combining a grid and a square mesh panel

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1   **Size selectivity and length-dependent escape behaviour of haddock in a sorting**

2   **device combining a grid and a square mesh panel**

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10   **Abstract**

11   Size selectivity of a new sorting section combining a sorting grid and a square mesh panel was

12   tested for haddock (*Melanogrammus aeglefinus*) in the Barents Sea demersal trawl fishery.

13   Sampling data for a wide size range enabled investigating the selection process for this species in

14   detail, both for the grid and the square mesh panel. Contrary to earlier studies modelling size

15   selectivity for grids and square mesh panels, which assume that the escape behaviour of all sizes

16   of fish is equal, we applied a model that accounted for that haddock of different sizes can show

17   different escape behaviour. Our results demonstrated that this model could describe the

18   experimental data collected better than existing models. Specifically, our results showed that the

19   likelihood for smaller haddock to seek escape through the grid and the square mesh panel was

20   higher than for bigger haddock that still would manage to escape through the devices if they

21 attempted. The new modelling approach presented in this study may be applicable to other

22 species, selection devices and fisheries.

23 *Keywords:* sorting grid; square mesh panel; combined size selection; haddock; contact

24 probability

Introduction

26 In many demersal trawl fisheries, size and/or species selection in the codend is suboptimal for the

27 intended exploitation pattern, which leads to discards in fisheries (Kelleher, 2005). One strategy

28 to reduce the catch of unwanted sizes and/or species in demersal trawl fisheries is to improve the

29 selectivity in the fishing gear used. While codend selection is the most widespread form for

30 selectivity in trawls (Glass, 2000), in several trawl fisheries it has been supplemented by one or

31 more selection devices installed in the section in front of the codend or in the codend itself.

32 Square mesh panels (Broadhurst, 2000; Catchpole and Revill, 2008; Alzorriz et al., 2016;

33 Graham and Kynoch, 2001; Krag et al., 2016, 2017; Brčić et al., 2016; Santos et al., 2016; Zuur

34 et al., 2001; O'Neill et al. ,2006) and sorting grids (Sistiaga et al., 2010; Herrmann et al., 2013;

35 Lövgren et al., 2016; Jørgensen et al., 2006; Larsen and Isaksen, 1993) are technical devices

36 often used to supplement codend size and/or species selection in demersal trawls. In some trawl

37 fisheries, the use of such additional selection devices has become mandatory. For example, in the

38 Barents Sea bottom trawl fishery targeting cod (*Gadus morhua*) and haddock (*Melanogrammus*

39 *aeglefinus*), the compulsory size selectivity system consists of a section with a 55 mm bar

40 spacing sorting grid followed by a codend with a minimum mesh size of 130 mm (Larsen et al.,

41 2018). In this fishery, several studies have evaluated the efficiency of different grid

42 configurations on cod and haddock (Larsen et al., 2018; Sistiaga et al., 2010).

43　Both fish behaviour and fish morphology affect the sorting efficiency and size selectivity of a

44　specific selection device (Sistiaga et al., 2011), and both aspects have been widely investigated in

45　relation to the selectivity of cod and haddock in trawls. Specially, haddock is one of the most

46　studied species regarding escape behaviour in demersal trawls (Wardle, 1993; Krag et al., 2010;

47　Winger et al., 2010). Several studies on this species include the effect and efficiency of inserting

48　square mesh panels in the trawl. Many of these studies were conducted by Marine Scotland

49　(formerly Fisheries Research Service) and an overview can be found in Fryer et al. (2016).

50　Haddock is widely distributed in the North Atlantic with important commercial fisheries in both

51　European and North American waters (Fryer et al., 2016). Therefore, it is of broad interest and

52　relevance to improve the knowledge and methods applied to quantify escape behaviour and size

53　selectivity of this species.

54　Former studies modelling size selectivity of square mesh panels and grids for haddock and other

55　species have quantified the behavioural aspect of the process by a factor termed "contact".

56　Contact is quantified as the fraction of species that contact the selection device while passing

57　through the trawl that leads to a size-dependent probability of escape. Earlier studies have all

58　assumed/approximated the contact factor to a fixed value and have not allowed it to vary with

59　fish size (Zuur et. al, 2001; O'Neill et al., 2006; Sistiaga et al., 2011, 2017; Larsen et al., 2018).

60　However, several studies in the literature have documented that haddock of different sizes may

61　exhibit different behaviour in a trawl (Grimaldo et al., 2018; Melli et al. 2017, 2018). Therefore,

62　it is relevant to investigate if a modelling approach that avoids the assumption of length

63　independency on the behavioural aspect can improve the modelling of size selectivity processes

64　for haddock in relation to grids and square mesh panels in trawls. Further, such a modelling

65 approach would contribute with new quantitative knowledge about the escape behaviour of

66 haddock in relation to sorting grids and square mesh panels.

67 One of the aims of the present investigation is to discern why former studies have not found the

68 need to account for size-dependent escape behaviour of haddock. Specifically, do all sizes of

69 haddock have a similar escape behaviour in reaction to a grid or a square mesh panel, or was the

70 size range of haddock that could potentially utilize the selection device to escape too narrow,

71 therefore representing the contact factor by a fixed value being a good approximation?

72 Based on the considerations described above, the main purpose of the current study was to

73 investigate, model and quantify escape behaviour and size selectivity of haddock in a new sorting

74 section containing both a grid and a square mesh panel. The study was based on collecting size

75 selectivity data for the new sorting section in the Barents Sea demersal trawl fishery, and

76 quantifying how this new system performed including comparisons with the compulsory grid-

77 based sorting systems in this fishery. Specifically, our main objectives were to:

78 • Determine if there is size-dependent escape behaviour for haddock though the grid

79 and square mesh panel, and if it is the same for both devices.

80 • Determine how any behavioural differences affect size selectivity for the grid and

81 square mesh panel, respectively.

82 • Describe to what extent the grid and square mesh panel each contributes to the

83 combined size selection in the new sorting section.

84 **Materials and methods**

85 **Sorting system**

86   The new sorting design tested in this study combined a sorting grid and a square mesh panel. It

87   was based on the Sort-V single grid system already used in the Northeast Atlantic gadoid fishery

88   (Jørgensen et al., 2006). A detailed description of the Sort-V sorting system is provided in

89   Herrmann et al. 2013 and in Grimaldo et al. 2018. In the new sorting section, the grid was

90   installed upside down compared to the original Sort-V section. In addition, the top panel in the

91   grid section was substituted by a square mesh panel. We hypothesized that placing the steel grid

92   in the lower panel would allow it to sort fish while also acting as a lifting panel to guide fish

93   towards the square mesh panel. The new sorting system was built on a four-panel section made of

94   138 mm nominal mesh size (nms) knotted diamond mesh netting (Euroline Premium

95   Polyethylene (PE), single Ø 8 mm braided twine). It was 29.5 meshes long (approx. 4.6 m) and

96   had 80 meshes of circumference (approx. Ø 1.2 m). All four selvedges were strengthened by 30

97   mm Danline PE ropes. A standard 55 mm bar spacing sorting grid of Sort-V type (1650 mm ×

98   1234 mm) was installed in the section with an inclination angle of $23° ± 2°$ (Fig. 1). According to

99   earlier studies (Kvamme and Isaksen 2004; Isaksen, 1998; Sistiaga et al., 2010) the optimal grid

100   angle is between 23 and 26 degrees. The original top panel in the section was replaced by a

101   square mesh panel made of single Ø 8 mm braided knotless Ultracross netting. The panel was 50

102   meshes long (~3.5 m) and 17 meshes wide (~1.2 m) (Fig. 1).

103

104   Fig. 1.

105

106 The average mesh size of the square mesh panel was estimated from 40 measurements (2×20

107 mesh rows) taken with an ICES gauge applying a force of approximately 4 kg (Westhoff et al.,

108 1962). Mean mesh size was 144.30 ± 2.43 mm (mean $\pm$ SD).

109 **Research vessel, study area, and gear set-up**

110 Experimental fishing was conducted on board the research vessel "Helmer Hanssen" (63.8 m

111 LOA and 4080 HP) between the 6th and 15th of March 2017. The fishing grounds chosen for the

112 tests were off the coast of Finnmark (Northern Norway) between 70˚29'–70˚52'N and 30˚08'–

113 31˚44'E. The towing speed during the trials was 3.5 – 4 knots. The fishing operation was carried

114 out around the clock at depths that ranged between 320-365 m implying complete darkness for all

115 hauls.

116 We used an Alfredo No. 3 two-panel Euronete trawl built entirely of 155 mm nms PE netting

117 (single Ø 4 mm braided knotted twine). The trawl had a headline of 36.5 m, a fishing line of 19.2

118 m, and 454 meshes of circumference at the trawl mouth. It was rigged with a set of bottom trawl

119 doors (Injector Scorpion type, 8 m², 3200 kg each), 60 m sweeps, 28.5 m long bridles (Ø 16 mm),

120 and a 111 m long ground gear. The sides of the ground gear had five 53 cm diameter steel

121 bobbins distributed on a 46 m chain (Ø 19 mm), and the centre of the ground gear had a 19.2 m

122 long rockhopper (with 53 cm rubber discs) that was attached to the fishing line of the trawl.

123 We built a diamond mesh transition section to connect the two-panel trawl belly to the four-panel

124 sorting section. It was made using 138 mm nms Euroline Premium PE knotted netting (single Ø

125 8.0 mm braided twine) and was 35.5 meshes long. A four-panel diamond-mesh codend was

126 attached after the sorting section. It was made from 138 mm nms Euroline Premium PE knotted

127 netting (Polar Gold) (single Ø 8 mm braided twine). The codend was 40 meshes long (approx.

128 6.2 m) and had 64 open meshes in circumference (approx. Ø 1 m). All four selvedges were

129 strengthened by 30 mm Danline PE ropes. The codend had round straps placed every 1.20 m

130 along all its length. The round straps were 6.9 m long, which limited the expansion of the codend

131 to 2.20 m diameter. Because we wanted to evaluate the selectivity properties of the sorting

132 section alone, the codend was blinded by an inner-net constructed of 48 mm Euroline Premium

133 PE knotted netting (Ø 2.2 mm single twine). The inner-net was 300 meshes around, and the

134 difference in meshes around the codend and the inner-net, in addition to the round straps, limited

135 expansion of the codend during the fishing operations. This limitation guaranteed a low opening

136 angle of the diamond meshes in the inner-net, which was estimated to be <28 degrees. Using this

137 maximum opening angle for a diamond mesh of 48 mm and morphological data obtained with

138 the FISHSELECT simulation tool (Herrmann et. al 2009) in Sistiaga et al. (2011), we estimated

139 that no haddock above 13.5 cm in length would be physically able to escape through the inner-net

140 netting.

141 We applied the covered-gear method (Wileman et al., 1996; Grimaldo et al., 2016) and used two

142 covers to collect all fish escaping through the grid (grid cover) and the square mesh panel (panel

143 cover) (Fig. 2). The front part of the covers was made of square meshes of Dyneema netting

144 (knotless 210/54 braided twine). The purpose of the netting material was twofold: i) to ensure

145 that the water flow outside the trawl did not push the cover against the square mesh panel or the

146 grid outlet and ii) to create enough water flow through the meshes to push the fish entering the

147 covers to the cover codend. The back part of the covers was made of diamond meshes of

148 Polyamid PA netting (2.5 mm Ø knotted braided twine). The average mesh size of the covers was

149 estimated from 80 measurements (2 × 20 mesh rows in each of the covers) taken with an ICES

150 gauge (Westhoff et al. 1962). Mean mesh size was 57.41 ± 0.97 mm (mean ± SD). In the last 2 m

151   of the cover, where we expected fish to come in contact with the cover netting, we installed a

152   small mesh size inner-net made of approximately 10 mm meshes to ensure that the smallest fish

153   would not be able to escape from the cover net. The total length of the covers was approximately

154   18 m. At the front of the panel cover we attached six plastic floats (Ø 20 cm and approx. 2.8kg

155   buoyancy each) to ensure that it expanded and stayed clear of the panel. At the grid cover, 16 kg

156   of chains were fixed to the lower panel to secure its opening. Due to that the expanding forces

157   needed in the covers were vertical (both upwards and downwards), we used floats and chains to

158   keep the covers clear from the gear except for kites (see Fig. 2). Floats and chains are easier to

159   install, cheaper and give the possibility to make adjustments easier than with kites. Therefore,

160   they were the preferred option. The floats and chains used were equivalent to the spreading force

161   of the kites used in the tank.

162

163   Fig. 2.

164

165   All haddock > 10 cm in total length present in the codend or the covers were measured to the

166   nearest centimetre.

Modelling the size selectivity for the sorting devices

168   For a fish to escape through a selection device two conditions need to be fulfilled: i) the fish

169   needs to make contact/seek escape through the device; ii) it needs to be morphologically able to

170   pass through the device (Herrmann et al., 2009). When modelling size selectivity/retention

171   probability $r_{device}(l)$ for a selection device like a square mesh panel or a sorting grid, the first

172   condition has traditionally been accounted by a fish size-independent constant contact factor

173   (C_{device}) (Sistiaga et al., 2010). C_{device} holds a constant value that ranges between 0.0 (no fish

174   make contact) and 1.0 (all fish make contact). The second condition often has been modelled by a

175   logistic curve defined by the parameters $L50_{device}$ (length of fish with 50% retention probability

176   conditioned making contact) and SR_{device} (= $L75_{device} - L25_{device}$) (Wileman et al., 1996):

177   $$r_{device}(l, C_{device}, L50_{device}, SR_{device}) = 1.0 - \frac{C_{device}}{1.0 + exp\left(\frac{ln(9)}{SR_{device}} \times (l - L50_{device})\right)} \qquad (1)$$

178   In model (1) l represents the length of the fish. Examples for using (1) to model size selectivity in

179   a trawl section with a square mesh panel include Zuur et al. (2001), O'Neill et. al (2006), Alzorriz

180   et al. (2016), Brčić et al. (2017), Santos et al. (2016) and Krag et al. (2016, 2017), whereas examples

181   for modelling size selectivity in sorting grids include Sistiaga et al. (2010, 2016), Herrmann et al.

182   (2013), Grimaldo et al. (2015), Brčić et al. (2015), Stepputtis et al. (2016), Lövgren et al. (2016)

183   and Larsen et al. (2016, 2017, 2018). A shared limitation for all these selectivity studies is that all

184   sizes within the species investigated were assumed to be equally likely to seek escape/contact with

185   the selection device investigated. For fish so big that they would not be able to morphologically

186   pass through the selection device, the specific value for the C_{device} will not matter as their

187   morphology will anyway prevent escape. Contrary, for fish that can morphologically pass through

188   the selection device, potential size dependency in escape behaviour will affect the contact

189   probability with the selection device and consequently the selection process. Thus, to be able to

190   account for potential differences in escape behaviour for haddock of different sizes, in addition to

191   using model (1) with a constant for C_{device} we also considered the length-dependent model

192   previously proposed by Krag et al. (2014). Krag et al. (2014) used this length-dependent model to

193   model the length-dependent probability for fish to contact a large mesh panel installed in a trawl

194   selection. The latter model contains four parameters ($C1_{device}$, $C2_{device}$, $L50C_{device}$, and SRC_{device}):

195
$$C_{device}(l) = C1_{device} + (C2_{device} - C1_{device}) \times \frac{exp\left(\frac{ln(9)}{SRC_{device}} \times (l - L50C_{device})\right)}{1.0 + exp\left(\frac{ln(9)}{SRC_{device}} \times (l - L50C_{device})\right)} \qquad (2)$$

196 Equation (2) is a flexible formula that enables modelling increasing, decreasing and constant

197 values for C_{device} (l). $C1_{device}$ and $C2_{device}$ are constants constrained to the interval [0.0;1.0] that

198 represent the asymptotic contact values for respectively fish of smallest and largest sizes.

199 $L50C_{device}$ is the fish length at which C_{device} (l) is the mean of $C1_{device}$ and $C2_{device}$. SRC_{device}

200 defines how quickly C_{device} (l) shifts from a value close to $C1_{device}$ to a value close to $C2_{device}$ with

201 increasing fish length in the vicinity of $L50C_{device}$. Thus, if SRC_{device} is close to *0.0*, the change in

202 C_{device} (l) will appear over a small length range, whereas if SRC_{device} holds a value far from 0.0 the

203 change in C_{device} (l) will cover a wider length span. Fig. 3 shows examples on some of the

204 different length-dependent escape attempt patterns that can be modelled based on (2), and how

205 (2) can lead to different size selection curves when it is applied for C_{device} in model (1).

206

207 FIG. 3

208

209 In this study, we use model (1) with model (2) to model separately the size selection for both the

210 sorting grid and the square mesh panels for standalone deployments. Further, in the preceding

211 section we outlined how this leads to modelling the selection patterns in the complete sorting

212 section consisting of both the sorting grid and the square mesh panel. This includes how the

213 corresponding sets of model parameters ($L50_{grid}$, SR_{grid}, $C1_{grid}$, $C2_{grid}$, $L50C_{grid}$, SRC_{grid}) and

214 ($L50_{panel}$, SR_{panel}, $C1_{panel}$, $C2_{panel}$, $L50C_{panel}$, SRC_{panel}) are estimated for respectively the sorting

215 grid (*device = grid*) and the square mesh panel (*device = panel*).

216   **Describing the selection patterns for the sorting section and parameter estimation**

217   The selection process in the sorting section can be considered dual sequential with an initial

218   escape option through the grid followed by an escape option through the square mesh panel for

219   those fish that did not escape through the grid. The fish that do not escape through the grid nor

220   the square mesh panel, end up being retained in the blinded codend. The experimental data are

221   length class-wise (l) collected in three fractions: i) number escaped through the grid (ng_l); ii)

222   number escaped through the square mesh panel (np_l); and iii) number retained in the blinded

223   codend (nc_l). Therefore, to model the experimentally collected size selection data we needed to

224   quantify the length-dependent probabilities $e_{grid}(l)$, $e_{panel}(l)$ and $r_{codend}(l)$, which express the

225   probability for a fish that enters the sorting section to be collected in respectively the cover over

226   the grid, the cover over the square mesh panel and in the codend. Using model (1) for $r_{device}(l)$

227   and model (2) for $C_{device}(l)$ for both the grid and square mesh panel selection processes, we arrive

228   at:

$$e_{grid}(l) = 1.0 - r_{grid}\left(l, C_{grid}(l), L50_{grid}, SR_{grid}\right)$$

229 $$e_{panel}(l) = r_{grid}\left(l, C_{grid}(l), L50_{grid}, SR_{grid}\right) \times \left(1.0 - r_{panel}\left(l, C_{panel}(l), L50_{panel}, SR_{panel}\right)\right) \quad (3)$$

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

230

231   The special case with constant $C_{grid}(l)=C1_{grid}$ and $C_{panel}(l)=C1_{panel}$ was considered first for

232   modelling the size selectivity in the new sorting section before using the more flexible model (2).

233   The values for the parameters for the overall model (3) were obtained using Maximum Likelihood

234   (ML) estimation based on the experimental data pooled over hauls j (1 to m) by minimizing:

235

236 $-\sum_l \sum_{j=1}^{m} \left\{ ng_{l,j} \times ln(e_{grid}(l)) + np_{l,j} \times ln(e_{panel}(l)) + nc_{l,j} \times ln(r_{codend}(l)) \right\}$ (4)

237

238   where $ng_{l,j}$, $np_{l,j}$, and $nc_{l,j}$ denote the number of haddock caught in haul j with length l that were

239   collected in the cover for the grid, the cover for the square mesh panel, and the blinded codend,

240   respectively (Fig. 2). Determination of goodness of fit of the model selected to describe the

241   experimental data was based on the p-value, model deviance versus degrees of freedom (DOF),

242   and visual inspection of the ability of the model curves to reflect the length-based trends in the data

243   (Larsen et al., 2016). A p-value < 0.05 and deviance >> DOF would indicate poor model fit making

244   it unlikely that the observed deviations between the modelled selectivity curves and the

245   experimental rate are coincidental. Another symptom of poor description of the experimental data

246   is visual disability of the modelled curves to represent the fish size-dependent experimental rates.

247   Akaike information criterion (AIC) values (Akaike, 1974) for the model fits were calculated to

248   help compare the feasibility of using a model with length-independent and length-dependent

249   contact for the grid and square mesh panel size selection. The model with lowest AIC was

250   preferred.

251   The ML estimation using expression (4) with (3) requires aggregation of the experimental data

252   over hauls. This results in stronger data to estimate the average size selectivity, but it does not

253   explicitly consider between-haul variation in selectivity (Fryer, 1991). To account correctly for the

254   effect of between-haul variation in the estimation of the uncertainty in size selection, we estimated

255   Efron percentile confidence intervals (CIs) (Efron, 1982; Chernick, 2007) for both the estimated

256   parameters in equation (3) and the resulting curves for $e_{grid}(l)$, $e_{panel}(l)$, and $r_{codend}(l)$ (as well $r_{grid}(l)$

257   and $r_{panel}(l)$) for the standalone deployment size selection curves) using a double bootstrap method.

258   We used the software tool SELNET (Herrmann et al., 2013) for the analysis and applied 1000

259   bootstrap iterations for the estimation of the CIs.

260 **Investigation of whether a reduced length span in experimental data can hide length-**

261 **dependency in contact probability**

262 Because our data ultimately needed a model with size-dependent contact probability and previous

263 studies have used a model with constant contact probability without reporting problems, we

264 wanted to investigate whether this need could be related to the size range of haddock in the

265 experimental sampling. Therefore, we investigated the ability of model (1) with a size-

266 independent contact to describe the experimental data for the combined size selection in the

267 sorting section, for the grid alone, and for the square mesh panel alone while ignoring the

268 smallest length classes in the collected haddock data. We did this in steps of 5 cm until no

269 haddock < 30 cm were considered in the estimation. For each step, we estimated the p-value,

270 which quantifies the probability of obtaining at least as a big discrepancy between the modelled

271 selectivity curves and experimental data by coincidence. Further, for each case we visually

272 inspected how well the modelled curves reflected the length-dependent patterns in the

273 experimental data.

Results

275 During the sea trials we carried out 20 valid hauls, and we caught and length measured a total of

276 11,189 haddock between 10 and 70 cm (Table 1). Only 23 haddock (0.2%) were below the 13.5

277 cm length class (where we could not rule out release through the codend inner-net with a 100%

278 certainty), making the effect of these on the estimated size selectivity negligible. The two other

279 main species caught were cod (2958 individuals) and redfish (1331 individuals). The data for

280 these species are not presented in this study as the numbers of individuals caught for certain

281 ranges in their length spans were not high enough for the analysis carried out in this study.

282 However, results for these species are provided in Sistiaga et al. (2017).

283

284   Table 1.

285

286   Size selection of haddock was estimated by fitting the model described by equation (1) to the

287   haul data summarised in Table 1. This was done first by assuming fish size-independent contact

288   probability for both the grid and the square mesh panel. Table 2 lists the fit statistics, and Figure

289   4 shows the fit of the model to the experimental data. The fit statistics and visualization of the

290   model fit show clearly that assuming a fish size-independent contact probability was not adequate

291   because the model could not describe the experimental data sufficiently well. Therefore, equation

292   (1), with the fish size-dependent model (2) for contact with the selection devices, was fitted to the

293   experimental data (Table 2; Fig. 4).

294

295   Table 2.

296

297   Fig. 4.

298

299   The fit statistics in Table 2 demonstrate that for the combined dual selection process in the

300   sorting section and the size selection in the grid and for the square mesh panel standalone, the

301   length-dependent contact model was much better at describing the ongoing selection processes

302   than the model that assumes size-independent contact with the devices. In fact, the p-values for

303   the model with constant contacts were < 0.05 for all three cases, meaning that it is unlikely that

304   the observed discrepancies between the modelled curves and the data were coincidental. This

305   premise is further supported by clear patterns in the deviations between the modelled curves and

306   the experimental rates, especially for the grid escape probability (Fig. 4a) and for the retention

307   probability in the codend (Fig. 4c). This contrasts with the results obtained when model (1) was

308   combined with model (2), in which the grid and panel contact probability varied with haddock

309   size. The p-values for the combined size selection, for the grid, and for the square mesh panel in

310   this case are all > 0.05 (Table 2), which implies that the observed discrepancies between

311   modelled curves and experimental rates could be coincidental. The plots in Figure 4 show that the

312   modelled curves reflect the trends in the experimental data well for codend retention (Fig. 4f),

313   grid escapement (Fig. 4d), and square mesh panel escapement (Fig. 4e). The superiority of the

314   length-dependent model for modelling the size selection of haddock in this sorting system was

315   supported by the AIC results. For all three comparisons, the AIC values were much smaller for

316   the length-dependent contact model than for the length-independent contact model (Table 2).

317   Based on these results, we chose to model the size selection of haddock in the new sorting section

318   based on model (1) with the length-dependent contact model (2). Table 3 shows the parameter

319   values obtained using this model, and Figure 5 shows the size selectivity for the grid (Fig. 5a)

320   and square mesh panel (Fig. 5b) alone. In addition, Figures 5c and 5d show the haddock size-

321   dependent estimated contact probability with the selective devices in the sorting section

322   conditioned that haddock reach the selectivity zone of the device.

323

324   Table 3.

325

326   Fig. 5.

327

328   Figure 5c shows that contact probability with the grid decreased with haddock size between 10

329   and 35 cm, with the value being very high for the smallest haddock. This is reflected in the low

330   retention rate (Fig. 5a) for sizes of haddock that should be able to escape through the grid ($L50_{grid}$

331   at 47 cm and SR_{grid} at 7.5 cm) (Table 3). For haddock > 35 cm, only about 33% were estimated to

332   make selectivity contact with the grid, which is reflected in a relatively high retention rate for

333   sizes of haddock that would have at least a 50% chance of escaping (haddock < 47 cm) if they

334   made contact with the grid. These results demonstrate that smaller haddock were more likely to

335   make selectivity contact with the grid than bigger haddock. For the square mesh panel, the

336   smallest haddock also had higher probability for selectivity contact than bigger haddock (Fig.

337   5d). However, this was only the case for haddock < 20 cm. For haddock > 20 cm the selectivity

338   contact with the square mesh panel was estimated to be approximately 50% for all sizes.

339   **Reduced length span in experimental data can hide length-dependency in contact**

340   **probability**

341   Model (1) with assumed length-independent selectivity contact with the grid and the square mesh

342   panel was fitted to the experimental data with all haddock below a specific length (i.e., 10, 15, 20,

343   25 and 30 cm) excluded from the analysis (Fig. 6, Table 4).

344

345   Table 4.

346

347 Fig. 6.

348

349 The p-values in Table 4 clearly show that when haddock < 20 cm were not included in the

350 analysis, the length-independent selectivity contact model produced an acceptable value. In this

351 scenario, the patterns in the deviations between modelled curves and data points disappeared

352 (Fig. 6). This observation explains why previous studies (Sistiaga et al., 2010, 2016) of sorting

353 grids based on haddock that did not sample fish < 20 or 30 cm reported acceptable results for the

354 length-independent selectivity contact model. If these results are not extrapolated to haddock

355 below their sampling limit (20 or 30 cm), they are still valid and not in conflict with the results

356 obtained in this study.

357 **Comparison of the new sorting section with existing grid-based sections**

358 Figure 7 plots the size selection estimated for the new sorting section against results from the

359 literature for the Flexigrid (Sistiaga et al., 2016) (Fig. 7a) and Sort-V (Fig. 7b) systems. This was

360 done to compare the selectivity performance of the new section with the sorting sections applied

361 in the fishery today. For the Flexigrid and Sort-V systems, the comparison was made with results

362 from Sistiaga et al. (2016) and Sistiaga et al. (2010), respectively.

363 The new sorting section had higher retention rate for a wide span of sizes of haddock, both below

364 and above 40 cm, compared to the Sort-V system (Fig. 7b). The new sorting section and the

365 Flexigrid exhibited very similar size selection for haddock between 20 and 30 cm (Fig. 7a), but

366 for the targeted sizes of haddock (> 40 cm), the new sorting section had significantly lower

367 retention probability for haddock up to 58 cm.

368

369   Fig. 7.

370

Discussion

372   Sorting grids and square mesh panels are common technical devices used to supplement codend

373   size and species selection in demersal trawls (e.g. Catchpole and Revill, 2008; Krag et al., 2016,

374   Lövgren et al., 2016; Jørgensen et al., 2006). Therefore, developing models that enable

375   quantifying size selectivity and escape behaviour through these devices is important. In European

376   demersal trawl fisheries, haddock is one of the most studied species and it is often used for the

377   evaluation of dual size selection systems that include square mesh panels (Graham et al., 2001,

378   2003; Zuur et al. 2001; O'Neill et al., 2006; Fryer et al., 2016) or sorting grids (Kvamme and

379   Isaksen, 2004; Grimaldo et al., 2015; Sistiaga et al., 2009, 2010, 2016). However, only some of

380   these earlier studies modelled and quantified explicitly fish contact probability with the

381   selectivity devices (Zuur et al. 2001; O'Neill et al., 2006; Sistiaga, 2010, 2016; Fryer et al., 2016).

382   Considering contact probability with selection devices is important because it can help identify

383   where potential challenges with the tested device lie. For a sorting grid or a square mesh panel

384   that is not sorting as intended for example, estimating the contact can help identify if the reason

385   for failure is linked to an erroneous choice in the bar spacing or mesh size, or if on the contrary, it

386   is linked to the design or unsuccessful placement of the device in the gear. Moreover, considering

387   length-dependency for the contact parameter contributes to further identify the selective

388   properties of the device tested and behaviour of the species studied. In all previous studies,

389   contact probability has been modelled by a contact parameter that did not account for potential

390   length-dependency for the fish seeking escape through the selective devices.

391 Considering that several authors have successfully described the selective properties of sorting

392 grids and square mesh panels on haddock using a length-independent contact parameter, we first

393 modelled the selectivity of the sorting section tested in the present study using length-

394 independent parameters. However, already the first analyses carried out demonstrated that such a

395 simplified model could not describe the size selectivity of the section tested in the present study

396 properly. Therefore, we used a more complex model that accounted for the potential effect of fish

397 size to describe the probability of haddock contacting the sorting grid or the square mesh panel in

398 the section. This model satisfactorily described the size selection in the grid and in the square

399 mesh panel as well as the combined size selection for the new sorting section.

400 The results of the present study show that the probability for small haddock to seek escape

401 through either the grid or the square mesh panel is higher than for bigger individuals that could

402 have still escaped through the devices if they had made contact with them. Regarding the grid,

403 our results are based on a grid placed with the outlet in the lower panel. Some studies have

404 reported that smaller fish tend to remain closer to the lower panel than bigger fish of the same

405 species when inside a trawl (Krag et al., 2014; Melli et al., 2018). This may be part of the reason

406 for the size-dependent contact pattern observed in our study. However, bigger haddock may also

407 be better at avoiding contact with obstacles or devices they may interpret as a threat than smaller

408 fish due to superior swimming ability. Considering the result obtained in this study and the

409 results reported by Krag et al. (2014), it would be valuable to repeat the present experiment with

410 the grid positioned as it is in the Sort-V grid section, with the escape route upwards, to see if the

411 contact pattern is reversed. Regarding the square mesh panel, it was estimated to have higher

412 selectivity contact than the grid for all sizes of haddock above 25 cm. A potential explanation for

413 the higher estimated panel selectivity contact could be related to the location of the square mesh

414   panel and the fact that haddock has in numerous occasions been reported to seek escape upwards

415   (Engås and Godø, 1989; Wardle, 1993; Beutel et al., 2008; Winger et al., 2010).

416   The findings that the smallest haddock are more likely to utilize an escape opportunity more

417   efficiently than bigger fish that would still manage to escape through the sorting device if they

418   attempted to do so, is in line with the findings of Grimaldo et at. (2018). These authors studied

419   the size selectivity of haddock in a non-tapered four-panel square mesh section. In their

420   experiments, Grimaldo et al. (2018) stablished which sizes of haddock would be able to escape

421   through the panel conditioned that they made selectivity contact with it. The investigation was

422   carried out for haddock >20 cm in length, and for each of the three configurations tested (i: no

423   simulation device; ii: with mechanical simulation device; iii: mechanical and light simulation

424   device) they found out that the escape attempt probability for haddock decreased with increasing

425   fish length.

426   The haddock sampled in this experiment covered a wide range of sizes that, assuming they made

427   selectivity contact with the selectivity devices in the section tested, would have at least some

428   chance of escaping through them (10–58 cm). Compared to some of the former studies that did

429   not sample haddock < 20 or 30 cm (Sistiaga et al., 2010, 2016) or used square mesh panels with

430   smaller mesh sizes (Zuur et al. 2001; O'Neill et al., 2006; Fryer et al., 2016), the size range of

431   haddock that could potentially escape through the sorting devices was much bigger in our study.

432   This likely explains our need for a model that accounts for a length-dependent contact probability

433   to estimate the selectivity of the selection devices in the sorting section. This premise is

434   supported by our explorative analysis in which we ignored haddock below a specific but variable

435   smaller size. The results of the analysis demonstrate that it is not necessary to account for length-

436   dependency of the contact probability if haddock < 20 cm are ignored (Table 4; Fig. 6). However,

437 this finding also illustrates the importance of not extrapolating results outside of the length range

438 sampled. To our knowledge this is the first study that explicitly considers fish size-dependent

439 contact probability in relation to grid and square mesh panel size selectivity. For this we adopted

440 the flexible model for length-dependent contact proposed by Krag et al. (2014), who applied it for

441 modelling escape through a panel with so big mesh size (800 mm) that all fish attempting escape

442 would do so. In our case the situation is more complicated as the selectivity potential of the grid

443 and square mesh panel will limit the sizes of haddock that would be able to escape. To our

444 knowledge the current study is the first one using a length-dependent model for contact

445 probability in relation to a size selection device. As demonstrated by the examples shown in Fig.

446 3, this combination of length-dependent contact probability and size selectivity of the device

447 itself can lead to a variety of different size selection curves. This includes a so-called "cup-

448 shaped" size selection curve with the lowest retention probability for medium sized fish and

449 higher retention for both smaller and bigger fish. Further, the flexibility of our modelling

450 approach and variety of size selection curves it can represent highlights the potential of the

451 approach used, and may therefore be of relevance to model size selection for other species and/or

452 selection devices in trawls and seines.

453 The size selectivity performance of the new sorting system was compared with previous obtained

454 results for the two existing grid systems used today in the investigated fishery (Fig. 7). However,

455 some caution needs to be taken when comparing with results obtained from former fishing

456 cruises as potential differences in average fishing conditions may to some extent affect the size

457 selective performance of the devices tested. Therefore, such comparison is only fully valid under

458 the assumption that average fishing conditions were similar during the cruises in question or

459   under the assumption that differences in fishing condition would not affect the selectivity

460   performances of the devices being tested.

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559   *morhua*) and haddock (*Melanogrammus aeglefinus*) fishery. Fish. Res. 183: 340-351.

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1   FIGURE CAPTIONS

2

3   Fig. 1: Schematic representation of the experimental grid section with the square mesh panel
4   at the top.

5

6   Fig. 2: Technical specification of the covers used over the outlet of the grid and the square

7   mesh panel. The picture below shows a snapshot of the tests carried out with the section and

8   the covers in the flume tank prior to the tests at sea. Note that the kites used in the cover over

9   the square mesh panel in the tests in the flume tank were replaced by six 20 cm floats during

10   the trials at sea. The floats were fixed as specified in the drawing.

11   Fig. 3: Examples on different device contact curves simulated based on model (2) (left

12   column) and the associated size selection curves (retention curves) (right column) based on

13   model (1). A: low and constant contact ($C1_{device} = C2_{device} = 0.2$). B: high and constant contact

14   ($C1_{device} = C2_{device} = 0.8$). C: slow increasing contact ($C1_{device} = 0.2; C2_{device} = 0.8; L50C_{device}$

15   $=30\ cm; SRC_{device} = 30\ cm$). D: fast increasing contact ($C1_{device} = 0.2; C2_{device} = 0.8; L50C_{device}$

16   $=20\ cm; SRC_{device} = 10\ cm$). E: slow decreasing contact ($C1_{device} = 0.9; C2_{device} = 0.3;$

17   $L50C_{device} =30\ cm; SRC_{device} = 40\ cm$). F: fast increasing contact ($C1_{device} = 0.9; C2_{device} = 0.3;$

18   $L50C_{device} =25\ cm; SRC_{device} = 8\ cm$). For all selection curves $L50_{device} =45\ cm$ and $SR_{device} =$

19   $8\ cm$ were used together with the contact model shown in the left column for the specific row.

20

21   Fig. 4: Panels a, b, and c show escape probabilities through the grid, escapement through the

22   square mesh panel, and combined retention in the codend, respectively, using model (1) and

23   assuming length-independent contact probabilities with the grid and square mesh panel.

24   Panels d, e, and f show the same except the contact probabilities with the grid and the square

25   mesh panel were modelled as length-dependent according to equation (2). Circle marks

26   represent the experimental rates, and the thick curve represents the modelled rate based on

27   equation (1). The stippled curves show 95% confidence limits for the modelled rate. The

28   dotted curve represents the population found in each specific compartment (grid cover, square

29   mesh panel cover, and codend).

30

31   Fig. 5: Grid, square mesh panel stand-alone size selection, and estimated selectivity contact.

32   a: grid size selection curve (black curve). b: square mesh panel size selection (black curve). c:

33   Selectivity contact curve for the grid. d: Selectivity contact curve for the square mesh panel.

34   The stippled curves show 95% confidence limits for the selectivity curve or selectivity contact

35   curve. Circle marks represent the experimental rates. Dotted grey and black curve represent

36   the population of haddock entering and being retained in that step of the size selection

37   process, respectively.

38

39   Fig. 6: First, second, and third columns show grid size selectivity, square mesh panel

40   selectivity, and combined retention in codend, respectively, using model (1) and assuming

41   haddock length-independent contact probabilities with the grid and square mesh panel. Circle

42   marks represent the experimental rates and the thick curve represents the modelled rate based

43   on equation (1). From top to bottom rows, haddock < 10, 15, 20, 25, and 30 cm, respectively,

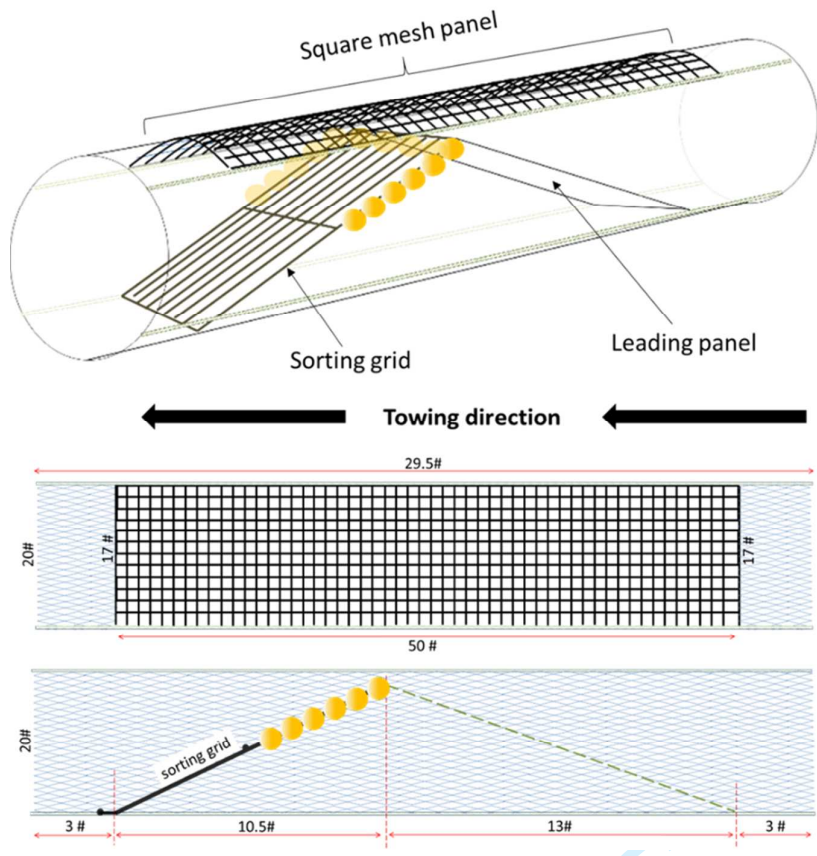44   were excluded from the analysis.

45

46   Fig. 7: Comparison of size selectivity for the new sorting section (black curve) versus existing

47   sorting sections (grey curves). The stippled curves show 95% confidence limits for the

48   selectivity curve. a: Comparison with results for Flexigrid (grey curve) presented in Sistiaga

49   et al. (2016). b: Comparison with results for the Sort-V grid presented in Sistiaga et al. (2010).
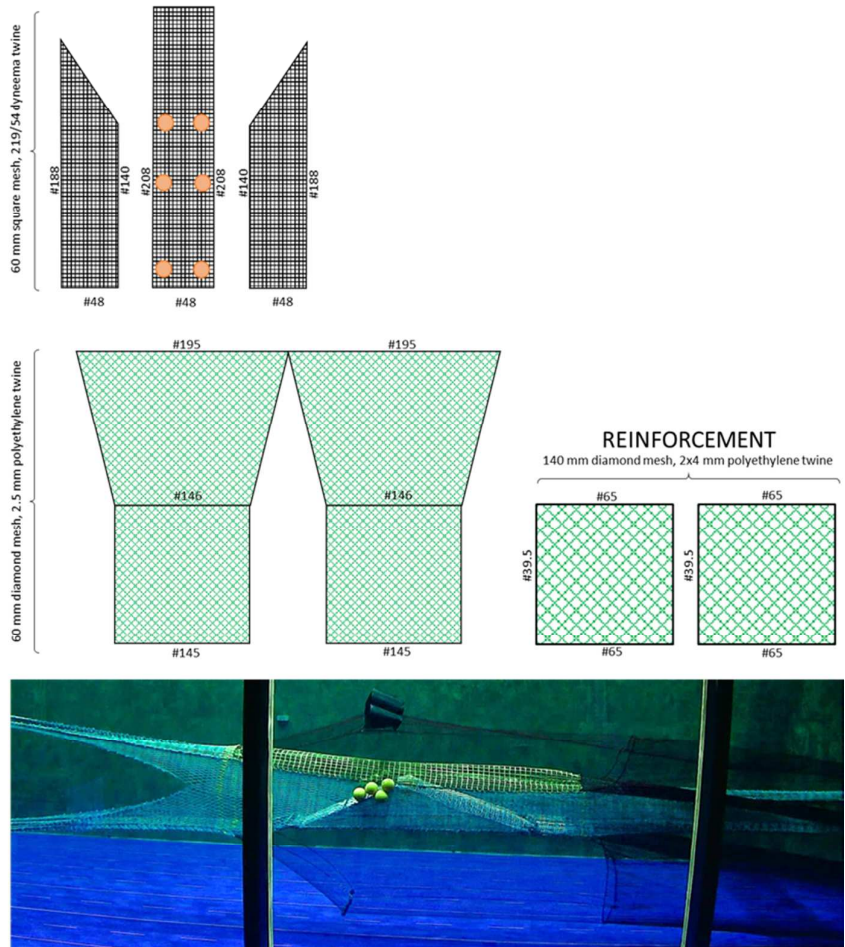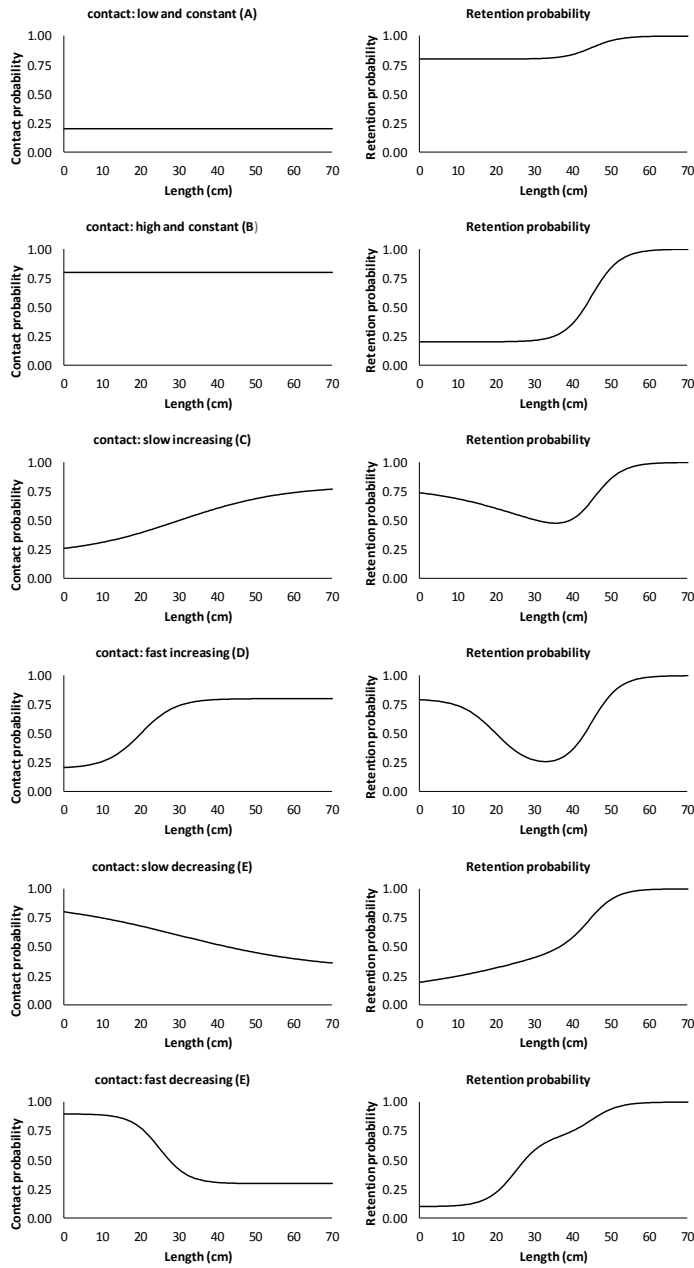
50   FIG. 1

Square mesh panel
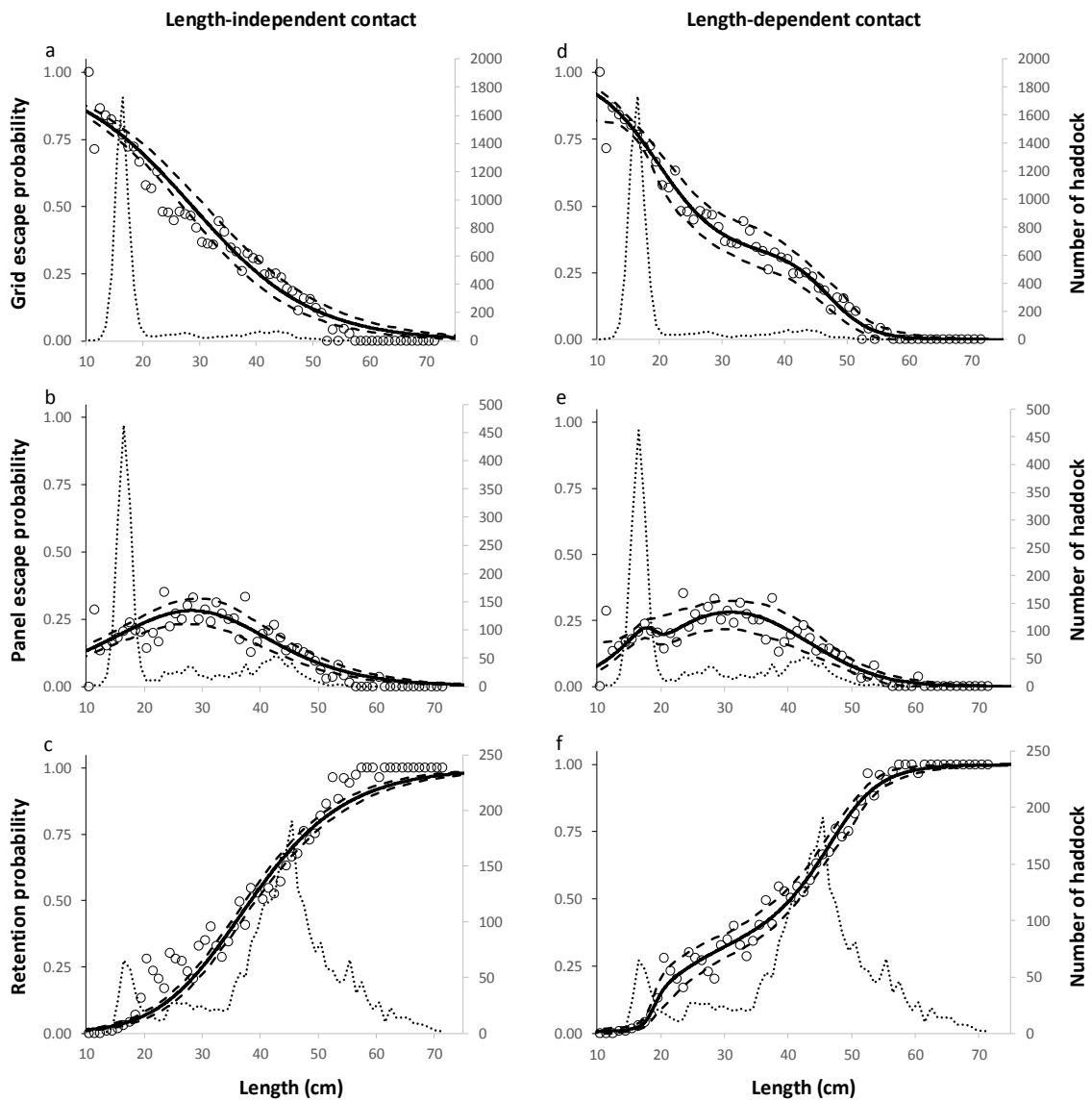
Leading panel

Sorting grid

Towing direction

29.5#

20#   17 #   17 #

50 #

20#

sorting grid

3 #   10.5#   13#   3 #

51

52

53

54   FIG. 2

55

56

57   Fig. 3

58

59   FIG. 4

60

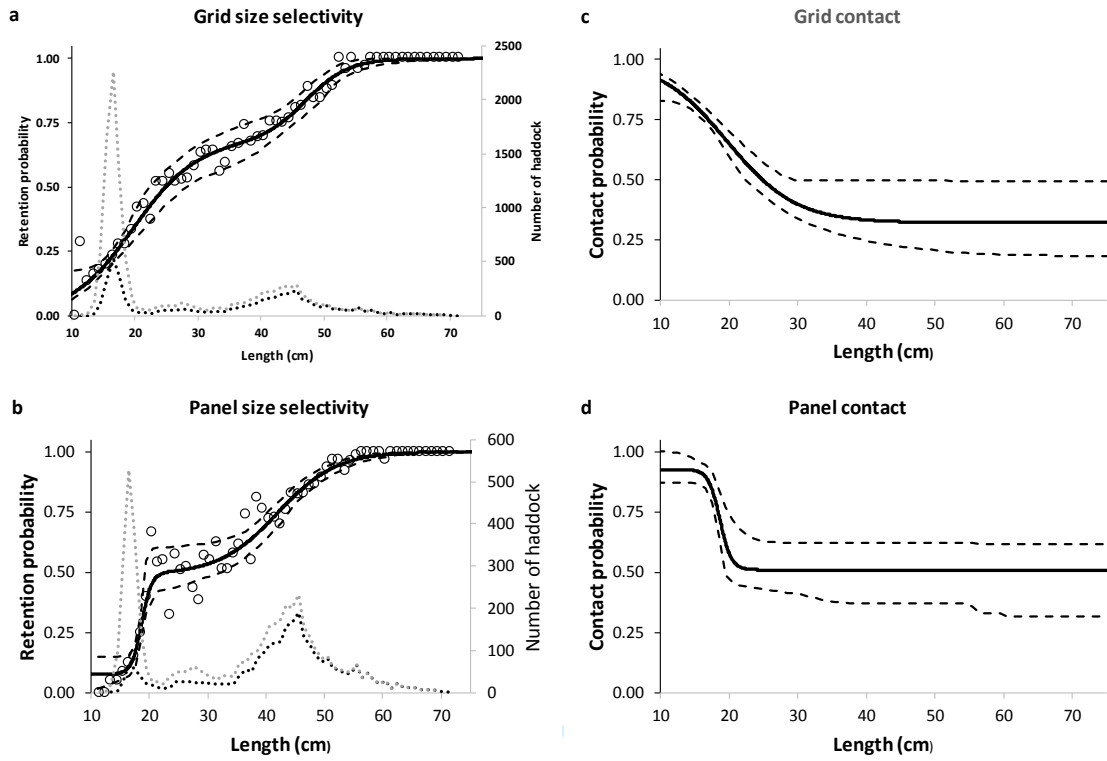**Length-independent contact**   **Length-dependent contact**

61

62
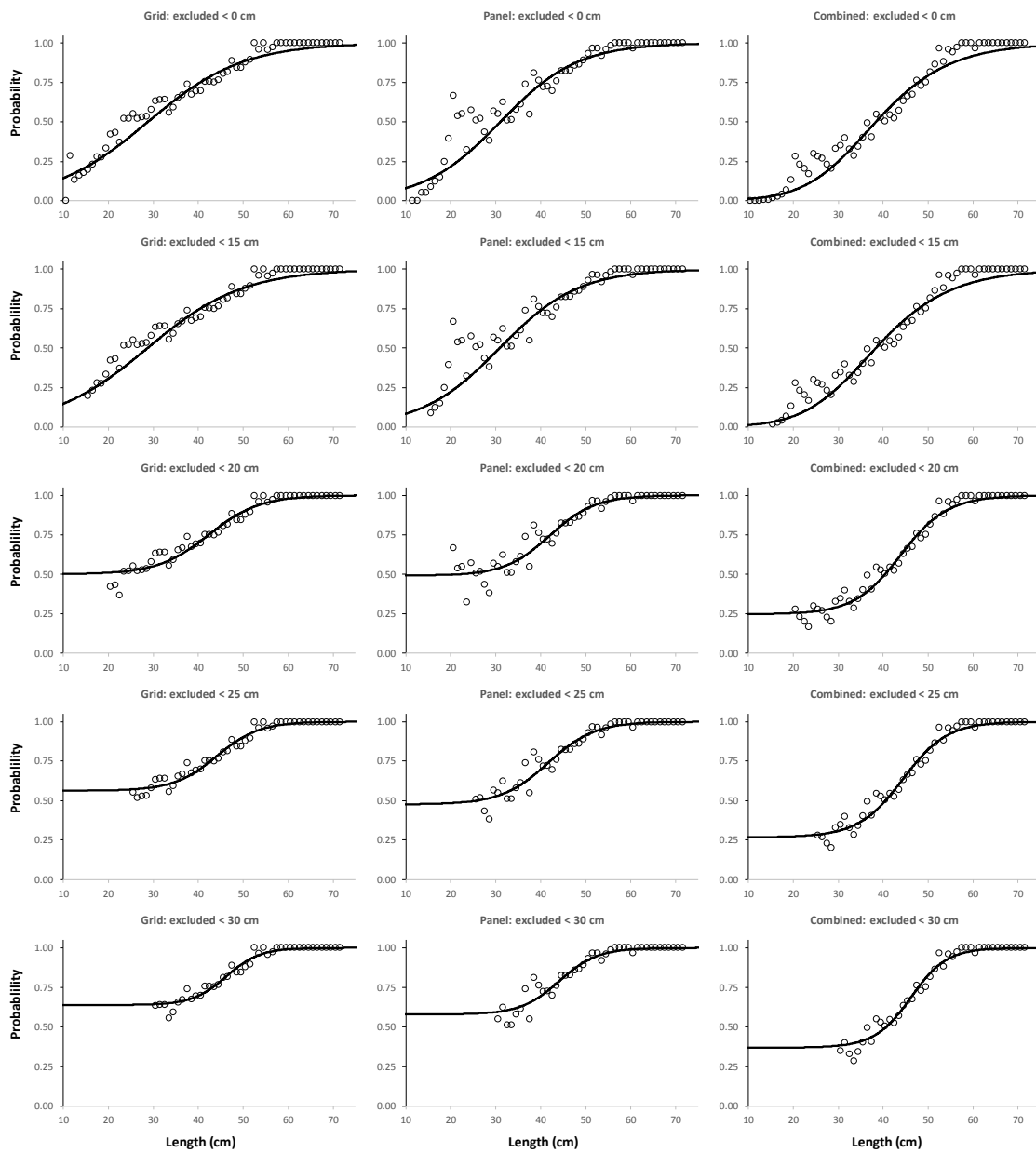
63   FIG. 5

64

65
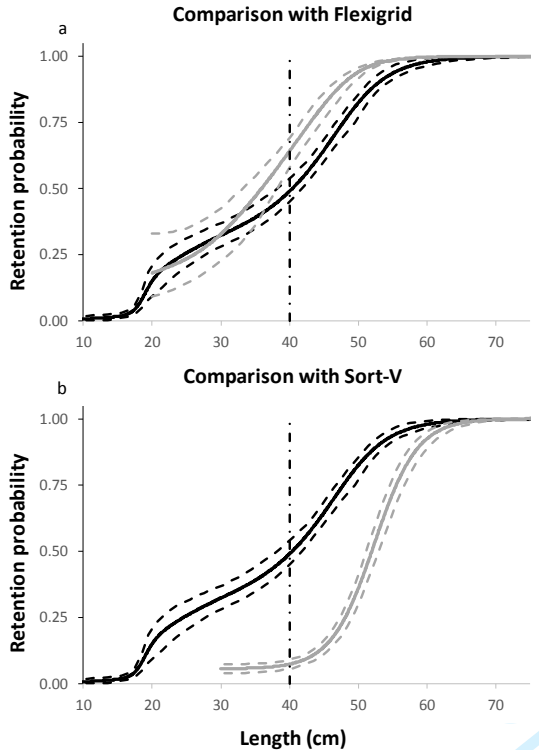
66   FIG. 6

67

68

69   FIG. 7

70

71

1   Table 1: Number of haddock caught and length measured in individual hauls conducted

2   during this study. *ng*: number in cover over the grid; *np*: number in cover over the square

3   mesh panel; *nc*: number in the blinded codend.

Haul	*ng*	*np*	*nc*
1	65	63	84
2	37	43	44
3	8	1	3
4	163	37	212
5	574	166	210
6	459	176	124
7	481	150	144
8	1064	406	301
9	245	96	243
10	218	50	59
11	178	52	55
12	662	99	258
13	561	217	139
14	255	85	188
15	189	89	131
16	190	61	135
17	271	77	156
18	478	193	136
19	114	26	63
20	105	40	60
sum	6317	2127	2745

4

5

6   Table 2: Statistics for the fit of model (1) considering constant contact probabilities (length-

7   independent contact) and size-dependent contact probability, respectively, as described by

8   model (2) (length-dependent contact). Statistics were calculated for the combined size

9   selection in the sorting section (combined), for the grid size selection alone (grid), and for the

10   square mesh panel alone (square mesh panel). DOF denotes degree of freedom.

Model		Grid	Square mesh panel	Combined
Length-independent contact	AIC-value	11971.23	4487.70	16458.93
	p-value	< 0.0001	< 0.0001	< 0.0001
	Deviance	118.60	163.27	281.86
	DOF	59	58	118
Length-dependent contact	AIC-value	11897.67	4395.07	16292.74
	p-value	0.9587	0.1754	0.6763
	Deviance	39.04	64.64	103.68
	DOF	56	55	111

11

12

13   Table 3: Parameter values for the model with length-dependent device contact. Values in

14   parentheses are 95% confidence limits.

Device	Grid	Square mesh panel
$C1_{device}$	1.00 (0.82–1.00)	0.93 (0.87–1.00)
$C2_{device}$	0.32 (0.19–0.49)	0.51 (0.28–0.62)
$L50C_{device}$ (cm)	19.71 (17.74–23.46)	18.68 (17.83–23.04)
SRC_{device} (cm)	11.00 (4.36–16.73)	1.83 (0.00–9.62)
$L50_{device}$ (cm)	47.14 (41.95–51.37)	41.98 (37.87–47.67)
SR_{device} (cm)	7.48 (3.28–12.26)	11.12 (5.93–14.77)

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17   Table 4: Fit statistics for length-independent contact model when data for haddock below

18   specific lengths were excluded.

Data excluded below length (cm)	Grid			Panel			Combined		
	p-value	Deviance	DOF	p-value	Deviance	DOF	p-value	Deviance	DOF
0	< 0.0001	118.60	59	< 0.0001	163.27	58	< 0.0001	281.86	118
15	< 0.0001	113.00	54	< 0.0001	153.99	54	< 0.0001	266.98	108
20	0.3731	51.58	49	0.1611	58.72	49	0.1863	110.30	98
25	0.6779	39.18	44	0.2786	49.03	44	0.4737	88.21	88
30	0.8268	30.68	39	0.4121	40.31	39	0.7002	70.99	78

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