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1 **Could green artificial light reduce bycatch during Barents Sea** 2 **Deep-water shrimp trawling?**

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11 **Abstract**

12 The Nordmøre grid is widely used in shrimp trawls to reduce the bycatch of fish species.

13 However, small-sized fish species and juveniles still pass through the grid and enter the

14 codend, along with the targeted shrimp. This bycatch of small fish has a negative impact on

15 the ecosystem due to increased fish mortality, and leads to additional sorting work onboard.

16 Some small-sized fish that enter the trawl avoid entering the codend by escaping through the

17 outlet above the grid, without making contact with the grid itself. Design changes that

18 promote this behavior could potentially reduce bycatch in shrimp trawl fisheries. Light-

19 emitting diodes (LEDs) mounted around the escape outlet have previously been found to have

20 either a negative effect, or no effect at all, on fish bycatch species. This study investigates the

21 effect of mounting green LEDs on the lower part of a Nordmøre grid, to determine if their

22 presence would encourage bycatch fish to rise towards the escape outlet prior to contacting

23 the grid. Experimental fishing trials were conducted to assess the size selective properties of a

24 19 mm bar spaced Nordmøre grid with and without LEDs, mounted on a bottom trawl

25 targeting Deep-water shrimp (*Pandalus borealis*). For the four bycatch species investigated,

26 51-100 % of small fish passed through the Nordmøre grid. The addition of green LEDs to the

27 Nordmøre grid did not significantly affect the escape probability or the size selectivity of any

28 of the investigated species. Very few Deep-water shrimp were found to escape through the
29 escape outlet independent of the presence of the LEDs mounted on the grid.

30 *Keywords:* Bottom trawl; Bycatch; LEDs; Nordmøre grid; *Pandalus borealis*; Size selectivity

31 **1. Introduction**

32 The Nordmøre grid is widely used in shrimp trawls to reduce fish bycatch (Broadhurst, 2000;
33 He and Balzano, 2011). However, substantial quantities of small fish species and juveniles
34 can pass through the grid and enter the small-meshed codend along with the targeted shrimp
35 (He and Balzano, 2007). This is a problem also in the Norwegian trawl fishery targeting
36 Deep-water shrimp (*Pandalus borealis*) in the Barents Sea (Larsen et al., 2017). The Deep-
37 water shrimp is a commercially important species, and has been fished since the beginning of
38 the 20th century in all Nordic countries. The international trawl fishery in the Barents Sea is
39 often associated with a juvenile fish bycatch problem (Gullestad et al., 2015), mainly due to
40 the small codend mesh size used in the fishery (minimum 35 mm). Bycatches of juvenile and
41 undersized fish from various species of commercial interest can be significant during periods
42 of the year in the Norwegian Deep-water shrimp fishery. These catches can have a negative
43 effect on the ecosystem and represent an unintended ecosystem impact of the fishery
44 (Gullestad et al., 2017). The Nordmøre grid was initially developed to exclude jellyfish from
45 catches, but is also efficient in excluding bycatch fish species during shrimp trawling (Isaksen
46 et al., 1992). Legislation introduced in Norway in 1991, and internationally in 1993, requiring
47 the use of the Nordmøre grid eliminated the issue of larger sized fish in bycatch. However,
48 smaller fish, often juveniles, are still able to pass through the 19 mm bar spaced grid into the
49 codend, together with the targeted shrimp. The Nordmøre grid system as used in Norway
50 consists of a section with guiding panel, a sorting grid and a fish escape opening in front of
51 the grid (Norwegian Directorate of Fisheries, 2017).

52 The current regulations in the Northeast Atlantic shrimp fishery allow the retention of low
53 numbers of juveniles of commercially important species. A fishing area is closed if the
54 authorities register that a fishing vessel is catching more than eight individuals of cod (*Gadus*
55 *morhua*), 20 haddock (*Melanogrammus aeglefinus*), three redfish (*Sebastes spp.*), or three
56 Greenland halibut (*Reinhardtius hippoglossoides*) per 10 kg of shrimp (Norwegian
57 Directorate of Fisheries, 2011). These strict bycatch rules have led to frequent closures of
58 large shrimp fishing grounds in the Northeast Atlantic in recent years. Closures can last for
59 weeks or months, often resulting in huge operational problems and increased costs for the
60 fishing fleet, i.e. longer distances between potential fishing grounds due to area closures. The
61 bycatch of juvenile fish also causes practical problems, such as increased catch sorting time
62 onboard fishing vessels.

63 Underwater observations have shown that some small fish avoid entering the codend by
64 seeking the escape outlet in the upper panel in front of the Nordmøre grid without making
65 contact with the grid (Larsen, pers. comm.). Therefore, apart from the obvious effect of
66 changing the grid bar spacing (Grimaldo and Larsen, 2005), other changes in the grid section
67 design that affects the ratio of juvenile fish seeking the outlet without contacting the grid
68 could reduce the bycatch of small-sized fish.

69 The use of light-emitting diodes (LEDs) can have an effect on fish behavior (Hannah et al.,
70 2015). In a recent study using various colors of Lindgren-Pitman Electralume® LEDs,
71 Nguyen et al. (2017) found that lights in the lower luminescence spectra, at peak wavelengths
72 464 and 519 nm (blue and green, respectively), and white LEDs, significantly increased the
73 catch of Snow crab (*Chionoecetes opilio*) during field experiments. During trials on cod pots
74 in the Baltic Sea, Bryhn et al. (2014) found that green light resulted in significant increases in
75 both the number and size of fish caught. A number of studies have demonstrated the potential
76 for this type of stimulation to influence the selective properties of trawl gear. For example,

77 Rose and Hammond (2014) found that attaching green Lindgren-Pitman Electralume LEDs to
78 the footrope of a survey trawl resulted in an increased escape rate for Southern Rock sole
79 (*Lepidopsetta bilineata*). Hannah et al. (2015) reported that attaching LEDs to shrimp trawl
80 footgear and illuminating the escape path under the net resulted in a bycatch reduction of 50 –
81 90 % depending on the fish species. The authors also attached similar LEDs close to the
82 Nordmøre grid, resulting in a significant increase in the bycatch of eulachon (*Thaleichthys*
83 *pacificus*). Despite this negative effect, the authors discuss the possibility that illumination of
84 the grid face by artificial light may help other small fish to escape (Hannah et al., 2015).
85 LEDs mounted around the Nordmøre grid escape outlet have been tested to determine if they
86 could promote bycatch escape through the outlet, avoiding grid contact, in Northeast Atlantic
87 shrimp fishery (Larsen et al., 2017). A significant reduction in the probability of seeking the
88 escape outlet was reported for haddock, but not for other species. However, the study had a
89 small sample size, leading to wide confidence intervals in the results for the species
90 investigated. Based on the results obtained by Larsen et al. (2017), it can be speculated that
91 fish are scared by the LEDs in the upper part of the grid section and therefore discouraged
92 from escaping through the outlet. Following on from this, the current study investigated the
93 effect of mounting green LEDs on the lower part of the Nordmøre grid to examine if this
94 would encourage bycatch species to rise towards the outlet and escape without contacting the
95 grid.

96 **2. Materials and Methods**

97 *2.1 Experimental design*

98 Fishing trials were performed on board the research trawler (R/V) "Helmer Hanssen" (63.8 m
99 overall length and 4080 HP) during 19th – 22nd of November 2016. The study area was located
100 in the Northeast of the Barents Sea and the experiments were made within an area of 17 x 5

101 nautical miles (N75°30'-E30°10' to N75°13'-E29°50'). The location for the trials is with sun
102 below horizon in the period 29th October to 7th February and with a depth of 363-381 m we
103 therefore assumed darkness at the fishing depth any time of the day. The fishing trials were
104 carried out using an Egersund Polar 2800# trawl and a pair of Injector Scorpion doors (8 m²,
105 3100 kg). The trawl and doors were linked by 40 m long double sweeps. The ground-gear
106 attached to the fishing line was a 19.2 m long rockhopper constructed of three sections with
107 Ø53 cm rubber discs. In Table 1 it is explained how we executed the hauls with and without
108 artificial lights.

109 The trawl was equipped with a four-panel Nordmøre grid section, equivalent in dimensions
110 and construction to the two-panel standard Nordmøre grid section (Norwegian Directorate of
111 Fisheries, 2017), which is used by the Norwegian coastal fleet targeting shrimp. The grid was
112 made of stainless steel (1.50 m high and 0.75 m wide) and was mounted to maintain an angle
113 of $45^\circ \pm 2.5^\circ$ while fishing. The bar spacing in the Nordmøre grid was measured using a
114 caliper following the guidelines in Wileman et al. (1996), and recorded as 18.73 ± 0.14 mm
115 (mean \pm standard deviation). A triangular escape outlet was cut out of the top panel of the grid
116 section. It measured 35 meshes long (by 52 mm mesh length) and 70 meshes wide equaling a
117 triangle ca. 1.6 m long and 0.75 m wide, reinforced with a Ø10 mm PE rope (Fig. 1A). To
118 collect fish and shrimp escaping through the escape outlet before reaching the grid, a small
119 meshed cover (mesh size 18.9 ± 1.2 mm) was mounted over the escape outlet (Fig. 1B),
120 following the guidelines in Wileman et al. (1996). Fish and shrimp that passed through the
121 grid were collected in the codend, which contained a small mesh inner net (mesh size $18.5 \pm$
122 0.9 mm) installed with a low hanging ratio to prevent fish and shrimp from escaping. To
123 prevent blocking the grid outlet with the cover, the latter was supported with five Ø200 mm
124 plastic floats (each of 2.7 kg lifting capacity).

125 FIG 1

126 The catch from the cover over the grid outlet and the codend was each separately sorted by
127 species, and all by-catch fish species were measured to the nearest cm. No subsampling was
128 carried out for any of the fish species. The shrimp catch was subsampled, as it was not
129 possible to measure all shrimp caught. A random portion of approximately 1 kg of the shrimp
130 catch in each compartment was taken as a subsample. The carapace length of the shrimp was
131 measured to the nearest mm using callipers.

132 Two different trawl configurations were tested during experimental fishing (Fig. 2):

- 133 • Standard configuration without LEDs.
- 134 • Standard configuration with four green Lindgren-Pitman Electralume® LEDs attached
135 to the lower part of the Nordmøre grid with LEDs pointing in towing direction and
136 downwards (at a 45° angle).

137 FIG. 2

138 2.2 Model for size selection

139 Larsen et al. (2017) used the following model to determine the size dependent probability of a
140 shrimp or fish passing through the Nordmøre grid and entering the codend ($p(l)$):

$$141 \quad p(l, C_{grid}, L50_{grid}, SR_{grid}) = \frac{C_{grid}}{1.0 + \exp\left(\frac{\ln(9)}{SR_{grid}} \times (l - L50_{grid})\right)} \quad (1)$$

142 As the experimental design in the current study is similar to that used by Larsen et al. (2017),
143 the same model is used to describe the size dependent probability of bycatch fish species and
144 shrimp passing through the Nordmøre grid. In model (1) l represents fish length or shrimp
145 carapace length. The probability of making contact with the grid is modeled by the length
146 independent parameter C_{grid} which can have a value ranging from of 0.0 to 1.0. An estimated
147 C_{grid} value of 1.0 for a species means that every individual of that species contacts the grid in
148 a way that gives them a length-dependent chance of passing through the grid. For fish or

149 shrimp making contact with the grid, $L50_{grid}$ denotes the length at which there is a 50 %
 150 probability of being prevented from passing through, and SR_{grid} describes the difference in
 151 length between individuals with respectively 75 % and 25 % probability of being prevented
 152 from passing through the grid. Further details on model (1) can be found in Larsen et al.
 153 (2017).

154 To examine how both of the Nordmøre grid configurations performed on average, analysis
 155 was carried out on data summed over all hauls. The analysis was conducted separately for
 156 each Nordmøre grid configuration based on the data from the hauls with the specific
 157 configuration and separately for each species. Thus, expression (2) was minimized, which is
 158 equivalent to maximizing the likelihood for the observed data in the form of the length-
 159 dependent number of individuals measured as retained in the codend (nC_l), versus the number
 160 collected in the Nordmøre grid cover (nG_l).

$$\begin{aligned}
 161 \quad & - \sum_{j=1}^m \sum_l \left\{ \frac{nC_{jl}}{qC_j} \times \ln \left(p(l, C_{grid}, L50_{grid}, SR_{grid}) \right) + \frac{nG_{jl}}{qG_j} \times \right. \\
 162 \quad & \left. \ln \left(1.0 - p(l, C_{grid}, L50_{grid}, SR_{grid}) \right) \right\} \quad (2)
 \end{aligned}$$

163 In (2), qC_j and qG_j represent the sampling factors for the fraction of individuals that were
 164 length measured in the blinded codend and grid cover for each haul j . The sampling factors
 165 can range in value from 0.0 to 1.0 (1.0 if all individuals are length measured). The outer
 166 summation in (2) is over the hauls conducted with the specific Nordmøre grid configuration
 167 and the inner summation is over length classes in the data (Larsen et al., 2017).

168 The ability of the model (1) to describe the data was based on calculating the corresponding
 169 p-value. A p-value greater than 0.05 implies that the model fits the data sufficiently well. In
 170 case of poor fit statistics (p-value < 0.05), the deviance versus the degrees of freedom and the
 171 residuals were inspected to determine whether the poor result was due to structural problems
 172 when modelling the experimental data, or over-dispersion in the data (Wileman et al., 1996).

173 Efron 95 % percentile confidence bands (Efron, 1982) for the grid passage probability curve
174 (model (1)), and the parameters in it (C_{grid} , $L50_{grid}$, SR_{grid}), were obtained using a double
175 bootstrap method implemented using the software tool SELNET (Herrmann et al., 2012). For
176 each species and grid configuration analyzed, 1000 bootstrap repetitions were conducted to
177 estimate the 95 % confidence limits (Efron percentile) (see Larsen et al., 2017 for further
178 details).

179 To infer the effect of mounting the LEDs to the Nordmøre grid, the difference in the length-
180 dependent grid passage probability $\Delta p(l)$ was estimated:

$$181 \Delta p(l) = p_{LED}(l) - p_{Base}(l) \quad (3)$$

182 where $p_{Base}(l)$ is the grid passage probability obtained for the configuration without LEDs
183 mounted and $p_{LED}(l)$ is the grid passage probability obtained for the configuration with
184 mounted LEDs. The 95 % confidence intervals for $\Delta p(l)$ were obtained based on the two
185 bootstrap population results (1000 bootstrap repetitions in each) for $p_{Base}(l)$ and $p_{LED}(l)$,
186 respectively. As they are obtained independently from each other, a new bootstrap population
187 of results for $\Delta p(l)$ was created using:

$$188 \Delta p(l)_i = p_{LED}(l)_i - p_{Base}(l)_i \quad i \in [1 \dots 1000] \quad (4)$$

189 where i denotes the bootstrap repetition index. As resampling was random and independent
190 for both groups of results, it is valid to generate the bootstrap population of results for the
191 difference based on (4) using two independently generated bootstrap files (Moore et al.,
192 2003). Based on the bootstrap population, Efron 95% percentile confidence limits were
193 obtained for $\Delta p(l)$ as described above. In general, the confidence limits for $\Delta p(l)$ cannot
194 exceed what is spanned by $p_{Base}(l)$ and $p_{LED}(l)$ together and will often be smaller (Moore et
195 al., 2003). Therefore, using this approach will increase the power of inference of the effect of
196 mounting LEDs to the Nordmøre grid compared to the simple strategy based on the search for

197 non-overlapping confidence limits between the two curves for the grid passage probability.

198 All analyses described above were conducted using the analysis tool SELNET (Herrmann et
199 al., 2012).

200 3. Results

201 3.1 Collected data

202 During the trials, a total of 16 hauls were carried out, eight with the standard configuration
203 and eight with the LED configuration (Table 1). Trawling time was kept as constant as
204 possible, and was approximately 2 hours for all 16 hauls. Four important bycatch fish species
205 were caught in sufficient numbers during the trials to be included in the investigation and the
206 length of each individual was measured. A total of 4908 redfish, 3834 American plaice
207 (*Hippoglossoides platessoides*), 1655 cod and 674 haddock were measured (Table 1). The
208 Deep-water shrimp had to be subsampled (subsampling ratios varied from 2.32 % to 100.00
209 %) and a total of 4613 individuals were measured.

210 TABLE 1

211 Overall, the results for the four bycatch species showed that 51-100 % of small fish passed
212 through the Nordmøre grid. See C_{grid} values in Table 2 and sections 3.2.-3.6 for further
213 details.

214 TABLE 2

215 FIG. 3

216 3.2 Size selectivity and grid passage probability for American plaice

217 For American plaice, the fit statistics showed that model (1) described the experimental data
218 well, as p-values were over 0.05 (Table 2), and the fitted curves followed the trends in the
219 experimental data well for both configurations tested (Fig. 3). The values for C_{grid} were very

220 high at 99-100 %, meaning that only 0-1 % of the American plaice that entered the gear
221 would escape through the outlet without first contacting the grid. C_{grid} did not differ
222 significantly between the two configurations tested (Table 2), as the confidence intervals
223 completely overlapped. Almost all of the American plaice in the size range 4-32 cm passed
224 through the Nordmøre grid with a continuously decreasing passage probability reaching zero
225 at around 32 cm (Fig. 3). Therefore, American plaice up to 32 cm in length have a high risk of
226 being caught in a trawl using a Nordmøre grid with 19 mm bar spacing. The estimated $L50_{grid}$
227 values combined with the estimated C_{grid} values imply that approximately 50 % of the
228 American plaice that enter the trawl pass through the Nordmøre grid into the codend. The
229 estimated SR_{grid} values were relatively large, around 40-45 % of the $L50_{grid}$ value (Table 2).
230 This is likely due to the variety of different ways in which flatfish contact the grid and could
231 explain the low slope of the grid passage curve (Fig. 3). This type of process has previously
232 been successfully applied to explain size selection of Greenland halibut in fish sorting grids
233 (Herrmann et al., 2013), and similar process can be expected for American Plaice. The
234 difference in retention probability between the two designs (Delta plot, Fig. 3) exhibit almost
235 identical curves, demonstrating that the addition of LEDs to the grid did not affect the grid
236 passage probability for American plaice.

237 *3.3 Size selectivity and grid passage probability for cod*

238 The fit statistics showed that for cod, model (1) described the experimental data well for the
239 standard and LED configurations, with p-values greater than 0.05 (Table 2). C_{grid} values were
240 high, at over 70 %, with no significant difference between designs, resulting in the majority of
241 the smallest sizes of cod (<15 cm) passing through the Nordmøre grid and into the codend.
242 For cod between 15 and 25 cm, the grid passage probability decreased gradually with
243 increasing size (Fig. 3), and no cod above 25 cm entered the codend. The two grid passage
244 probability curves are nearly identical (Delta plot, Fig. 3) and not significantly different from

245 0.0 for any sizes of cod. This implies that adding LEDs to the Nordmøre grid does not
246 significantly affect the grid passage probability for this species.

247 *3.4 Size selectivity and grid passage probability for haddock*

248 For haddock, the power in the experimental data was weaker compared to the other species
249 investigated, as fewer individuals were caught (Table 1). This resulted in wider confidence
250 bands, which prevented inferences on haddock. Since confidence intervals for the curve in the
251 delta plot contained 0.0 (Fig. 3), no effect was detected for haddock by mounting LEDs on the
252 Nordmøre grid. At least 40 % of haddock up to approximately 15 cm pass through the grid
253 into the codend when fishing with the standard configuration. For haddock over 15 cm, this
254 risk gradually decreases with length, reaching zero for haddock over 18 cm. The fit statistics
255 showed that model (1) was capable of describing the experimental data well for both
256 configurations as the p-values were above 0.05 in each case (Table 2).

257 *3.5 Size selectivity and grid passage probability for redfish*

258 In the case of redfish, the fit statistics showed that model (1) described the experimental data
259 collected with both configurations well (Table 2). The grid contact values (C_{grid}) were high, at
260 over 70 %, with no significant difference between designs, resulting in the majority of the
261 small redfish (<12 cm) passing through the Nordmøre grid into the codend. For redfish
262 between 12 and 20 cm, grid passage probability decreases gradually with increasing fish size
263 (Fig. 3), and no redfish over 20 cm entered the codend. The grid passage probability curves
264 for the two configurations were not significantly different, as the 95 % confidence intervals of
265 the curves for their delta contained 0.0 for all sizes of redfish. The results imply that mounted
266 LEDs did not significantly affect size selection for this species.

267 *3.6 Size selectivity and grid passage probability for Deep-water shrimp*

268 The fit statistics showed that model (1) described the experimental data well for Deep-water
269 shrimp for the standard configuration, as the p-value was estimated to be >0.05 (Table 2). For
270 the LED configuration, the p-value was low. However, since there was no clear pattern in the
271 deviations between the data points and the fitted grid passage probability curve, this result
272 was attributed to over-dispersion in the data. This over-dispersion was probably due to the
273 amount of subsampling required during the shrimp data collection process (Table 1).
274 Therefore, the model (1) can also be used to describe the length-dependent grid passage
275 probability for this species (Fig. 3). The Nordmøre grid passage probability was very high for
276 both configurations tested (Fig. 3). This is also illustrated by the high C_{grid} values, which were
277 estimated to be 100 % in both cases, with relatively high values for the lower confidence
278 limits (Table 2). This was also reflected in the confidence limits for the grid passage
279 probability curves, which were very similar and contained 0.0 for all sizes of Deep-water
280 shrimp in the Delta plot (Fig. 3). The results show that LEDs have no effect on the grid
281 passage probability of Deep-water shrimp. While the grid passage probabilities are high, both
282 curves show a slight decrease with the size of the shrimp.

283 **4. Discussion**

284 Using the Barents Sea Deep-water shrimp fishery as a case study, it was investigated if it was
285 possible to change fish behavior in front of the Nordmøre grid, by triggering fish to utilize the
286 escape outlet above the grid, completely avoiding contact with the grid. Recent studies have
287 reported that fish display an avoidance response to certain colors of LEDs (Rose and
288 Hammond, 2014; Hannah et al., 2015). However, it was not known how effective LEDs
289 mounted on the Nordmøre grid would be in triggering the desired fish behavior in this fishery.
290 This study aimed to quantify the Nordmøre grid passage probability for different bycatch
291 species of different sizes, and to determine if mounting LEDs in the lower part of the grid
292 could reduce the amount of fish bycatch in the fishery.

293 The results of this study determined that there is a high grid passage probability for small
294 individuals of American plaice, cod, haddock and redfish, meaning that high numbers of
295 juveniles are likely to be retained by the codend. Adding green LEDs to the Nordmøre grid
296 did not reduce the risk for any of the species investigated passing through the Nordmøre grid.
297 In fact, adding LEDs to the grid did not significantly affect the size selectivity for any of the
298 bycatch species. While it was possible to answer the formulated research questions in this
299 study, the results do not suggest a technical measure for bycatch reduction in shrimp trawl
300 fisheries based on utilizing LEDs mounted on the base of the Nordmøre grid. The green LEDs
301 used in these trials did not result in a reduction of bycatch, thus confirming previous results
302 from the northeast Atlantic (Larsen et al., 2017). Hannah et al. (2015) reported that the
303 addition of green LED lamps around the grid increased the bycatch of eulachon by 104% and
304 slender sole (*Lyopsetta exilis*) by 77%, but the artificial light had no effect on ocean shrimp
305 (*Pandalus jordani*) and other fishes. Despite our results to some extent are in line with
306 Hannah et al. 2015, we did not find significant increase in bycatch for any of the species
307 examined. The possibility that the green LEDs affected the behavior of juvenile fish species
308 recorded in this study cannot be discounted.

309 In the standard Nordmøre grid setup the distance between the guiding panel and the grid is 0.5
310 m (Fig. 3), and the water flow (i.e. relative velocity) through it is more than 80 % of the
311 towing speed (Grimaldo and Larsen, 2005), i.e. more than 2.5 knots in our experiments. As
312 small fish have a limited swimming capacity in the aft part of a bottom trawl (Winger et al.,
313 2010), it is assumed that most of the small fish (ca. 10-20 cm) are unable to maneuver away
314 from the water flow through the lower part of the grid. This effect is supported by the high
315 C_{grid} values (Table 2). It is therefore concluded that other technical measures for reducing the
316 risk of bycatch in this fishery need to be found. He and Balzano (2013) state that exclusion of
317 fish bycatch by the Nordmøre grid can be attributed more to size and morphology than

318 behaviour of the animal and that small fish species in size are more difficult to exclude from
319 the trawl once they enter. Their rope grid design which is based on utilizing water flow and
320 swimming ability of fish reduced the catches of both small shrimps and finfish, especially
321 finfish larger than 16 cm (He and Balzano, 2013).

322 Norwegian-Russian legislation for northern fisheries requires improved selectivity in any type
323 of bottom trawls (Hønneland, 2014). Fishing fleets, supported by fisheries management, are
324 therefore constantly seeking solutions to improve the bycatch mitigation, i.e. the species
325 selectivity of the gear. In the case of the Deep-water shrimp fishery, increased selectivity
326 would benefit the industry, as it would result in less mechanical sorting on board, and a
327 reduction in area closures when bycatch levels exceeds given criteria. For the management of
328 the northeast Atlantic fisheries and as part of the priority list on fishery-related issues
329 regarding selectivity and discards, there is an ongoing revision of criteria for the intermixture
330 of juveniles and testing of new concepts to reduce such by-catches in the shrimp fisheries
331 north of 62°N (Gullestad et al., 2017).

332 Although the results of this study found that the addition of LEDs had no significant effect on
333 the amount of bycatch in the codend; as a result, the present findings are to all effects
334 negative. However, reporting this type of results does have a value both from the scientific
335 and the fishing industry viewpoint, because they enhance our understanding of fishing gear
336 selectivity besides reducing the risk of testing the same non-functioning concepts several
337 times. In addition, publishing negative as well as favorable results prevents forming a biased
338 picture (Csada et al., 1996). Therefore, even though the proposed solution did not deliver the
339 intended gain in bycatch reduction, we feel it still provides a useful contribution to the
340 literature.

341 The results for the standard configuration are important, as they quantify the risk of various
342 sizes of bycatch species being caught along with shrimp if they are abundant on the fishing

343 grounds. The results for this configuration are in line with those reported by Larsen et al.
344 (2017) who also tested this configuration as baseline to investigate the effect of other design
345 changes. The high C_{grid} values for bycatch species in the standard configuration both in the
346 this study and in Larsen et al. (2017) illustrate the challenge to avoid the small sized fish in
347 this shrimp fishery if they are abundant on the fishing grounds. Especially for the only flatfish
348 species in our study, American plaice, the values for C_{grid} were very high at 99-100 %,
349 meaning that only 0-1 % of the American plaice that entered the gear would escape through
350 the outlet without first contacting the grid. This is in keeping with the expectation that flatfish
351 show a preference for staying low in the gear, and therefore their length-dependent grid
352 passage probability does not exhibit the characteristic plateau (constant value for individuals
353 up to a certain size) seen for other species. The results for the standard configuration is
354 important for fisheries managers, who have two mitigation options: 1) closing fishing grounds
355 for a certain period, or 2) enforcing the use of codends that enable the release of fish with the
356 highest risk of passing through the grid. The first mitigation option has significant
357 consequences on the operational possibilities of the fleet, but is simpler to apply. The latter
358 mitigation strategy needs to be carefully considered, taking into account codend size selection
359 of the targeted shrimp.

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Table legends

Table 1: Overview of the 16 hauls with dates (day and month), hour and minute for the start of the hauls, towing time by minutes and number of length measurements obtained for fish and shrimp. The values in brackets represent the sampling factors (% in weight measured). Length measurements were taken for all fish caught. * indicates that data were not collected due to damage, making length measurement impossible. *nC* is the number of individuals in the codend and *nG* is the number of individuals in the grid cover. Hauls 5 to 12 were made with LED lamps.

Haul ID	Date	Start haul	Towing time	Redfish		American Plaice		Cod		Haddock		Deep-water Shrimp	
				<i>nC</i>	<i>nG</i>	<i>nC</i>	<i>nG</i>	<i>nC</i>	<i>nG</i>	<i>nC</i>	<i>nG</i>	<i>nC</i> (% measurd)	<i>nG</i> (% measured)
1	19.11.	05:31	70	15	77	55	74	29	45	14	11	210 (8.18)	264 (54.50)
2	19.11.	07:44	120	328	627	58	97	149	72	67	94	227 (5.30)	40 (65.24)
3	19.11.	14:43	136	56	125	35	132	23	32	5	16	213 (6.92)	0 (100)
4	19.11.	17:51	121	29	86	92	95	50	51	18	10	212 (6.39)	7 (39.66)
5 ^{LED}	20.11.	15:13	119	67	250	84	100	27	19	14	36	202 (9.31)	35 (100)
6 ^{LED}	20.11.	18:05	101	19	137	148	187	15	18	17	16	269 (9.22)	167 (100)
7 ^{LED}	20.11.	23:45	99	37	125	214	162	46	43	19	19	293 (4.08)	46 (56.25)
8 ^{LED}	21.11.	02:22	121	22	197	205	194	70	47	15	18	240 (7.74)	33 (66.67)
9 ^{LED}	21.11.	05:41	114	62	249	188	212	107	53	13	21	268 (3.50)	159 (76.62)
10 ^{LED}	21.11.	08:25	181	423	576	107	123	179	53	46	53	226 (2.44)	70 (56.59)
11 ^{LED}	21.11.	12:17	101	43	290	55	118	50	32	16	20	212 (2.32)	18 (39.95)
12 ^{LED}	21.11.	19:54	36	29	347	164	215	20	24	16	17	215 (2.73)	93 (56.54)
13	22.11.	00:52	87	11	146	87	148	24	23	10	11	212 (3.23)	*
14	22.11.	04:07	89	21	102	30	111	53	36	6	4	191 (3.92)	*
15	22.11.	06:20	89	37	115	98	190	85	68	4	9	226 (5.54)	27 (63.37)
16	22.11.	10:36	40	154	106	23	33	90	22	14	25	230 (2.67)	8 (59.76)

Table 2: Size selectivity parameters and fit statistic results for all analyzed species based on fitting the model (2-3) to the experimental data. Values in brackets are 95 % confidence limits. DOF = Degrees of freedom.

Species	Parameter	Without LEDs	With LEDs
American Plaice	C_{grid}	1.00 (0.96-1.00)	0.99 (0.95-1.00)
	$L50_{grid}$ (cm)	19.46 (18.29-20.98)	19.44 (18.55-20.91)
	SR_{grid} (cm)	8.26 (6.68-9.53)	8.36 (6.84-9.38)
	DOF	39	42
	Deviance	25.54	54.07
	p-value	0.9524	0.1004
	Cod	C_{grid}	0.83 (0.70-1.00)
$L50_{grid}$ (cm)		18.55 (15.93-21.46)	18.84 (16.89-20.77)
SR_{grid} (cm)		5.06 (1.15-7.31)	3.92 (2.04-5.95)
DOF		35	32
Deviance		15.98	8.69
p-value		0.9976	1.0000
Haddock		C_{grid}	0.51 (0.44-1.00)
	$L50_{grid}$ (cm)	17.84 (14.34-18.07)	15.22 (14.22-14.22)
	SR_{grid} (cm)	0.50 (0.50-4.88)	4.55 (0.10-5.49)
	DOF	13	10
	Deviance	12.12	16.69
	p-value	0.5176	0.0816
	Redfish	C_{grid}	0.78 (0.70-0.94)
$L50_{grid}$ (cm)		13.98 (13.23-14.61)	13.85 (11.86-15.09)
SR_{grid} (cm)		2.42 (2.42-3.24)	4.07 (2.18-5.96)
DOF		39	36
Deviance		25.54	36.79
p-value		0.9524	0.4323
Deep-water Shrimp		C_{grid}	1.00 (0.97-1.00)
	$L50_{grid}$ (mm)	48.87 (28.07-197.42)	58.46 (35.87-198)
	SR_{grid} (mm)	16.45 (0.10-41.74)	20.46 (3.27-90.22)
	DOF	16	18
	Deviance	23.65	104.05
	p-value	0.0974	< 0.001

Figure 1: Selective system consisting of a Nordmøre grid followed by the codend seen from above (A) and the experimental setup (B) in a side view. A cover is installed over the escape outlet in the upper panel and an inner net is inserted in the codend. Small circles represent Ø200 mm plastic floats.

Figure 2: The two trawl configurations tested: Standard configuration without LEDs (top) and standard configuration with four Lindgren-Pitman Electralume[®] LEDs mounted on the lower part of grid (bottom) pointing in the towing direction and 45° downwards.

Figure 3: Grid passage probability for all species. Dots illustrate experimental rates, solid curves represent the fitted model, and the dashed curves are the 95 % confidence bands for the curves. Results are presented for the configuration without LEDs (left column), the configuration with LEDs (middle column) and the difference in the length-dependent grid passage probability (Delta) (right column). For bycatch species length is total length in cm whereas length is carapace length in mm for Deep-water shrimp. Grey solid curves represent total summed (and raised in the case of Deep-water shrimp) population size structure retained by the gear.

FIG. 1

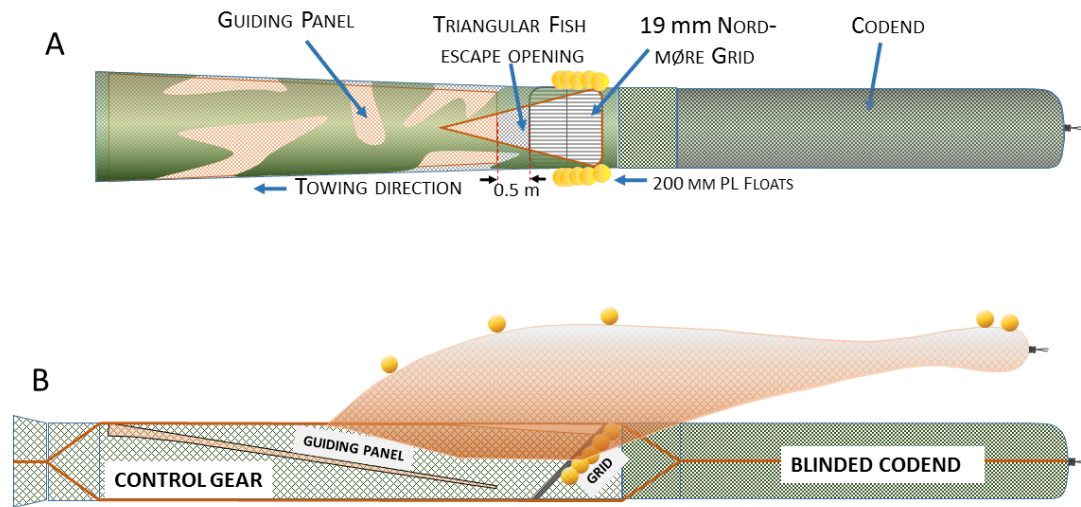


FIG. 2

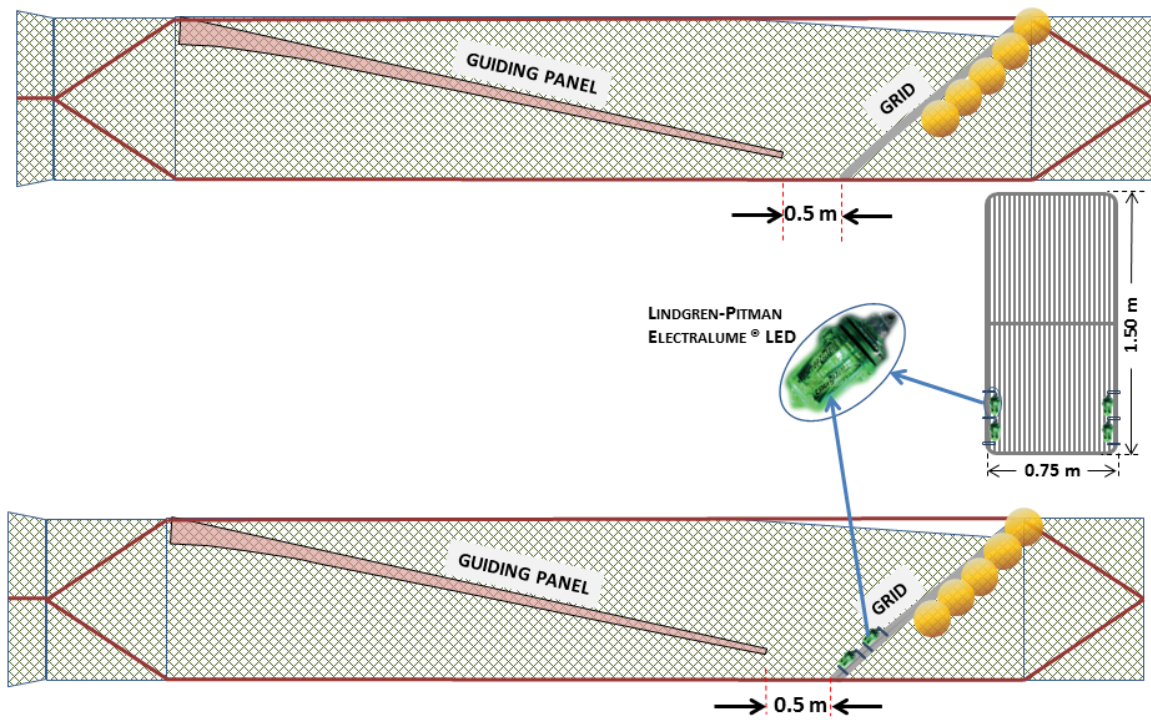


FIG. 3

