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1 **FLEXSELECT: counter-herding device to reduce bycatch in crustacean trawl**
2 **fisheries**

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25 **Abstract**

26 FLEXSELECT is a simple counter-herding device which aims at reducing the bycatch of fish by
27 scaring them away from the trawl path without affecting the catches of the target species.
28 FLEXSELECT was tested in the Norway lobster (*Nephrops norvegicus*) directed trawl fishery, as
29 this includes bycatch of both roundfish and flatfish. Length-based data were collected for
30 *Nephrops*, four roundfish species (cod, haddock, whiting and hake) and two flatfish species
31 (plaice and lemon sole) and length-based catch comparisons performed. No significant effect
32 on the target species, *Nephrops*, was detected, whereas a reduction of 39% (CI: 29-46 %) was
33 obtained for the overall number of fish. Catches of all the six fish species examined were
34 significantly reduced by FLEXSELECT, with the efficiency varying considerably among species
35 and over length classes. No significant diel differences were found for either roundfish or
36 flatfish species. FLEXSELECT prevents bycatch species from interacting with the trawl, thus
37 most likely enhancing their survival and fitness. Moreover, its fast attachment system makes
38 FLEXSELECT a flexible tool, adaptable to different fisheries and catch goals.

39 **Keywords**

40 *Bycatch reduction, Nephrops, scaring lines, catch comparison, trawl selectivity*

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46 **Introduction**

47 The capture and subsequent discarding of unwanted species and sizes is recognized as
48 damaging to both fisheries and marine conservation objectives (Kelleher 2005). Therefore,
49 fishermen are faced with the challenge of improving the species and size selectivity of their
50 fishing gears. Globally, considerable effort has been taken to reduce discards through both
51 technical and managerial measures. Within Europe, the latest measure has been the landing
52 obligation (discard ban) introduced as part of the reformed European Union Common Fisheries
53 Policy (European Commission 2013). The landing obligation, directed at all quota regulated
54 species, introduces a strong incentive for the fishing industry to reduce unwanted catches since
55 these are now counted towards quotas. Additionally, the loss of space on board and the
56 increased handling costs of this less valuable fraction of the catch may further incentivise
57 fishermen to be more selective. Nonetheless, fishing typically involves high variability in catch
58 compositions, thus increasing the challenge to reduce unwanted bycatch. Highly flexible
59 devices, which are easy to attach to and remove from the gear, are needed to adapt the
60 selectivity of fishing gears to haul-by-haul variations observed in catch compositions.

61 Many devices have already been successful in reducing bycatch (Kelleher 2005). They typically
62 exploit interspecific differences in terms of morphology and behaviour to improve selectivity
63 inside and in front of the trawl (Glass 2000; Catchpole and Gray 2010). Examples which have
64 improved selectivity inside the trawl include increased mesh sizes (e.g. Beutel et al. 2008;
65 Frandsen et al. 2011), grids (Graham and Fryer 2006; Grimaldo et al. 2008), square mesh panels
66 (e.g. Krag et al. 2008; Lomeli and Wakefield 2013), and species segregation into different
67 compartments (e.g. Holst et al. 2009; Krag et al. 2009). Devices aiming at improving selectivity

68 in front of the trawl typically do so by preventing certain species from entering the gear. For
69 example, a raised footrope can reduce the catch of flatfish and juveniles of demersal fish
70 (Hannah and Jones 2001; Krag et al. 2010); a topless gear allows the escape of roundfish
71 species over the headline (He et al. 2007; Krag et al. 2015); and a modification of the sweeps
72 interferes with the herding of fish towards the net mouth (Rose et al. 2010; Sistiaga et al.
73 2015). These devices have the advantage of minimizing fish interaction with the gear since they
74 address the initial stimuli that cause fish capture in the first place. Therefore, they likely
75 enhance species survival and fitness (Chopin and Arimoto 1995).

76 During fishing, the doors and sweeps of the trawl are the first parts of the gear that interact
77 with the fish. These components determine the overall geometry of the trawl, as the doors
78 spread the gear and the sweeps connect the doors to the trawl. However, doors and sweeps
79 also herd fish into the path of the trawl by exploiting their natural anti-predator behaviour
80 (Glass and Wardle 1989; Engås and Ona 1990; Winger et al. 2010). The herding process starts
81 with an anti-predator reaction triggered by the approaching trawl. The doors and sweeps
82 produce vibrations and a sand cloud, thus stimulating fish's avoidance behaviour. Their
83 reactions are often considered to be mainly vision-dependent, as herding has been observed to
84 cease at low light levels (Wardle 1993; Kim and Wardle 1998); however other stimuli associate
85 to trawling (e.g. sound) may enable herding at lower light levels (Engås and Ona 1990). The
86 type of reaction is then determined by species-specific anti-predator strategies. Flatfish,
87 specialized in camouflage, are reticent to flee until the predator is very close (Ryer 2008).
88 When they flee, it is to keep a safe distance from the predator and resettle on the seafloor to
89 hide. On the contrary, roundfish tend to respond at greater distances, swimming away

90 (Noettestad and Axelsen 1999; He 2011). Despite these differences, all individuals in the area
91 between the doors that flee are herded towards the trawl mouth. Nonetheless, for herding to
92 be effective, fish must have sufficient time and endurance to reach the trawl mouth (Winger et
93 al. 2010). Thus, it is a fish's swimming capacity that determines its herding potential. If a fish's
94 endurance is lower than the time required to cover the distance to the trawl mouth, it is
95 overrun by the sweeps and escapes capture (e.g., Mathai et al. 1984; Winger et al. 2004;
96 Sistiaga et al. 2015). Swimming performances are known to vary among species and sizes, to
97 depend on individual fitness, and to be influenced by environmental parameters like
98 temperature (Winger et al. 2010).

99 Ryer (2008) hypothesized that herding of roundfish in a flatfish-directed trawl fishery could be
100 reduced with a counter-herding design, e.g. a second inverted stimulus, positioned between
101 the sweeps. However, Ryer (2008) also highlighted how the implementation of such a counter-
102 herding device would entail significant engineering challenges. For example, different tensions
103 were expected on the components of the device when the spread of the trawl doors changes
104 according to bottom topography and sediment characteristics. For this reason, no scientific test
105 of a counter-herding design has, to our knowledge, been performed until now.

106 This study aimed to design and test the efficiency of a counter-herding device, FLEXSELECT, in
107 reducing fish bycatch. We tested FLEXSELECT in the mixed trawl fishery targeting Norway
108 lobster (*Nephrops norvegicus*), hereafter referred to as *Nephrops*. This fishery has a significant
109 bycatch of both roundfish and flatfish. The fish bycatch involves economically important
110 species but is usually of low quality due to its interaction with the crustaceans during the

111 catching process (Karlsen et al. 2015) and can potentially choke the fishery once fish quotas are
112 exhausted. In the frame of the landing obligation, fishermen need to reduce the fish fraction to
113 be able to fully utilise *Nephrops* quotas. Furthermore, the small mesh sizes used lead to
114 substantial quantities of undersized roundfish and flatfish being caught, thus leading to high
115 proportions discarded (Kelleher 2005). Therefore, this fishery represents the perfect case study
116 to investigate a counter-herding device. If effective, the advantages of FLEXSELECT are: i) a
117 reduction of fish bycatch; ii) a reduction in the interaction of potential bycatch with the net,
118 thus most likely enhancing its survival and fitness chances; and iii) the adaptation of the gear's
119 selectivity to obtain the desired catch composition on a haul-by-haul basis. The efficiency of
120 FLEXSELECT is expected to differ among species and sizes, thus the results concerning all
121 relevant commercial species were examined length-based and discussed in relation to the
122 different behavioural anti-predator strategies.

123 **Materials and methods**

124 **FLEXSELECT design**

125 The FLEXSELECT device consisted of four lines connected to a central metal ring (25 mm thick,
126 17 cm diameter, 3 kg), located at approximately 20 m ahead of the trawl mouth (Fig. 1). The
127 two positioning lines (54 m) were made of mix wires (steel core and polypropylene cover, 6
128 strands, 14 mm in diameter, 0.21 kg/m). Two floats (115 g buoyancy) were attached at 2 and 5
129 m from the door/clump to prevent the long wires from twisting around the sweeps during the
130 net deployment. The desired counter-herding effect was addressed with the two scaring lines
131 (23.6 m) attached in front of the bridles. They consisted of thick ropes (polypropylene, 3

132 strands, 26 mm in diameter, 0.31 kg/m), meant to sweep the sea bottom and generate a sand
133 cloud. Viking links and hammer locks (1.5 t lift, 0.7 kg), as well as swivels, were used to connect
134 the FLEXSELECT lines to the gear components and to the central ring. These facilitated efficient
135 coupling and decoupling of the FLEXSELECT lines to the gear. The challenge in designing
136 FLEXSELECT was to make an efficient counter-herding stimulus without preventing the trawl
137 from obtaining its intended geometry. It can be expected that heavier ropes would improve
138 the herding efficiency as the interaction with the seafloor and sand cloud would be greater.
139 However, a heavier device also increases the operational difficulties in terms of obtaining an
140 optimal spread of the gear. Therefore, relative light materials were chosen.

141 **Sea Trial**

142 The experimental trial was conducted on board the research vessel “Havfisken” (17 m, 373
143 kW), during 5-20 September 2016. The vessel was equipped for three-wire, twin-trawling, with
144 two identical Combi trawls (40 m long footrope, 420 meshes circumference) towed in parallel.
145 The two trawls were equipped with identical 40 mm square mesh codends to retain the entire
146 population encountered. Actual mesh sizes were measured on dry netting (41.65 ± 1.33). Each
147 codend was horizontally divided into two compartments due to a second experiment not
148 included in the present study.

149 FLEXSELECT was mounted on one trawl while the other worked as a control. This setting
150 assured that both trawls encountered similar species compositions and abundances over time.
151 To prevent any systematic effect of the trawl position (side of the vessel) on the catch, the
152 FLEXSELECT device was shifted from one trawl to the other approximately every sixth haul. The

153 distance between the inner wingtip of the two trawls, about 50 m, was assumed sufficient to
154 prevent overestimation of the control catch due to fish escaping from the FLEXSELECT device.
155 The twin rig was spread with two Type 2 Thyborøn doors (1.78 m², 197 kg), with an additional
156 weight of 25 kg to obtain a better spreading force, and a 400 kg triangular central clump. The
157 trawls were rigged with 75 m long single wire sweeps with 4.3 cm (diameter) rubber cookies.
158 The trawl doors and clump were equipped with distance sensors (Simrad PI), which
159 continuously provided information about the spread of the two trawls during towing. Since
160 only one trawl was equipped with the counter-herding device and thus potentially limited in its
161 spread, the two values were constantly monitored during towing.

162 Fishing was conducted in commercial grounds in the Skagerrak Sea, at depths between 33 m
163 and 87 m. To investigate the diel effects, hauls were performed during day- and night-time,
164 avoiding one hour before and after sunrise and sunset. The total catch was weighed and sorted
165 by species. The total length of all commercial fish species and the carapace length of *Nephrops*
166 were measured and rounded down to the nearest centimetre and millimetre, respectively.

167 **Statistical analyses**

168 The only difference between the two trawls was the attachment of FLEXSELECT to one of them.
169 Therefore, any difference in the catch between the two trawls was assumed to be caused by
170 FLEXSELECT presence. Its effect was assessed for each species separately, comparing the
171 catches of the test trawl (T) and the control trawl (C) while accounting for potential length
172 dependencies. Count data for the different length groups of each species were used to
173 estimate the curvature of a model for the size-dependent catch comparison rate $cc(l)$ with 95%

174 Efron confidence intervals (Efron 1982). The confidence intervals were based on double
 175 bootstrapping (1000 repetitions), accounting for uncertainty due to within- and between-haul
 176 variation in the catching process. For each species, only hauls with 10 or more individuals were
 177 included in the analysis following Krag et al. (2014). Separate analyses were conducted for day-
 178 and night-time hauls to enable inferring potential diel differences in the efficiency of the
 179 FLEXSELECT device. We adapted the catch comparison analysis methodology based on paired
 180 catch data described by Krag et al. (2015) while adopting recent improvements in model
 181 average estimation described by Herrmann et al. (2017). The analyses were performed using
 182 the software SELNET (Herrmann et al. 2012). The statistical procedure is described step-by-step
 183 in Appendix 1.

184 The baseline for no effect on the catch comparison rate is a value of 0.5 for paired catch
 185 comparison data (Krag et al. 2014). However, this assumed that the two trawls fished an area
 186 of similar size. We considered that, according to the proportions of the trawls used in this
 187 study, a difference in spread between the two trawls higher than 4 m could have consequences
 188 on the overall geometry of the trawls. Therefore, those hauls were excluded from the analyses.
 189 For smaller differences we calculated a bias-corrected baseline cc_0 that accounted for little
 190 changes in the towed area:

$$191 \quad (1) \quad cc_0 = \frac{\sum_{j=1}^h ST_j}{\sum_{j=1}^h (ST_j + SC_j)}$$

192 where ST_j and SC_j are the averaged door-to-clump distances for the test and control trawls in
 193 haul j , respectively.

194 Catch ratios (cr) and 95% Efron confidence intervals were calculated to directly quantify the
 195 differences in catch between the test and control trawls. Catch ratios were obtained using the
 196 relationship between cr and cc (Herrmann et al. 2017):

$$197 \quad (2) \quad cr(l) = \frac{cc(l)}{1-cc(l)}$$

198 A value of 1.0 for $cr(l)$ indicates that there is no difference in catch between the two trawls,
 199 meaning that, for a given species and length, FLEXSELECT would have failed to modify the
 200 catch. However, similarly to the baseline value for the $cc(l)$, a bias-corrected baseline cr_0 equal
 201 to 0.98 was calculated applying Equation 1 and 2.

202 Finally, to provide length-averaged values for the effect of FLEXSELECT on the species
 203 examined, we calculated the average catch ratio ($cr_{average}$) by summing all individuals caught
 204 per trawl in each haul (Herrmann et al. 2017). However, since the effect was not constant
 205 throughout length classes, it is important to notice that $cr_{average}$ values are specific for the
 206 population structure encountered during the experimental trial. Therefore, these values
 207 cannot be extrapolated to other scenarios in which the size structure of the fish population
 208 may be different.

209 **Results**

210 During the sea trial, 30 hauls were conducted, of which 26 were valid and included in the
 211 statistical analyses (Table 1). Four hauls were excluded due to initial technical problems related
 212 to the gears spread, with the test trawl spreading significantly less than the control. This
 213 difference was probably caused by a partial twisting of the positioning lines around the sweeps

214 and it was solved through the addition of floats to the positioning lines (see FLEXSELECT
215 design). Of the 26 valid hauls, eight were carried out at night and 18 during daylight hours. The
216 towing time varied from 30 to 135 min, and the depth from 33 to 87 m. The total catches of the
217 control trawl varied between 90.5 and 1539 kg, while the catches in the experimental trawl
218 ranged from 55 to 1145 kg. The mean difference in spread between the trawls was used to
219 account for small differences in swept area by calculating a corrected baseline for no effect on
220 the catch comparison rates and catch ratios. Trawl-spread values were not available for two
221 hauls (25 and 26) due to a malfunctioning of the sensor on the central clump. However, the
222 door spread was consistent with those obtained at similar depths thus the hauls were not
223 excluded from the analyses.

224 Seven commercial species were included in the analysis: the target species, *Nephrops*; four
225 roundfish species, cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), whiting
226 (*Merlangius merlangus*) and hake (*Merluccius merluccius*); and two flatfish species, plaice
227 (*Pleuronectes platessa*) and lemon sole (*Microstomus kitt*). All species were sampled in both
228 night- and day-time except for *Nephrops*, whose presence outside of their burrows was limited
229 to day-time, and hake, which in general was caught in few numbers (less than 10 individuals
230 per haul) during night-time (Table 2). Due to the intense activity of the *Nephrops*-directed
231 fishery in the period of the study, very few fish were encountered while fishing in the closest
232 *Nephrops* grounds. Consequently, some of the hauls were conducted in proximity to the
233 *Nephrops* grounds but in deeper water, where higher abundances of fish were expected.

234 **Target species: *Nephrops***

235 The catch comparison curve for *Nephrops* described well the experimental data for length
236 classes 25-55 cm (Fig. 2). For the lengths where fewer individuals were caught, the catch
237 comparison rates were subject to increasing binominal noise, as shown by the increasing size
238 of the confidence intervals. The ability of the catch comparison curves to describe the
239 experimental data is also demonstrated by the fit statistics (Table 3). The *p*-value for *Nephrops*
240 is >0.05 , meaning that the model can be trusted to represent the experimental data (see
241 Appendix 1). The catch ratio between the test and the control trawls did not detect any
242 significant effect of FLEXSELECT on the target species, as the confidence intervals overlapped
243 the baseline in all the length classes (Fig. 2).

244 **Fish species**

245 For the six fish species examined, FLEXSELECT reduced the catch in numbers by 39% (CI: 29-
246 46%). When considering the Minimum Conservation Reference Sizes (MCRS, previously
247 Minimum Landing Sizes), catches of individuals above and below the limit were reduced by
248 49% (CI: 39-57%) and 29% (CI: 19-39%), respectively (Table 4). The catch ratio averaged over
249 length showed significant effects for all fish species except for cod (Table 4). This could possibly
250 be due to the high number of small cod caught during the trial. The reduction in catch was
251 strongest for lemon sole (65%), followed by hake (63%), haddock (57%) and whiting (46%).
252 However, these reductions in catch are specific for the population structure encountered
253 during the experiment and cannot be generalized. In particular, the roundfish examined
254 present length-based differences in their response to FLEXSELECT, thus the averaged rates
255 depend on the length classes most abundant in the data.

256 Roundfish

257 The catch comparison curves for all the four roundfish species analysed described the main
258 trends in the data relatively well, without systematic deviations between the experimental
259 points and the modelled curves (Fig. 3). For cod, haddock and whiting, the model fits provided
260 p -values < 0.05 (Table 3), indicating potential problems with the model in describing the
261 experimental data (see Appendix 1). However, considering that no structure was detected in
262 the deviations between the data and the modelled catch comparison curves for any of the
263 species, the low p -values may be due to overdispersion in the data. Therefore, we were
264 confident in applying the model to describe the catch comparison rates also for these species.

265 A significant catch reduction was detected for at least some of the length classes of all the four
266 roundfish species analysed (Fig. 3). Haddock and whiting showed the largest response and a
267 strong length-dependent effect, with larger individuals escaping from the experimental trawl in
268 higher numbers than smaller individuals. The effect on cod was significant for individuals
269 between 25 cm and 71 cm, as the catch ratio was significantly lower than 0.98. On the
270 contrary, small individuals (below 14 cm) were more effectively caught by the test trawl. Hake,
271 despite the small amount of individuals sampled, showed a strong response to the FLEXSELECT
272 device for all the length classes represented.

273 Flatfish

274 Similarly, the catch comparison curves for the two flatfish species analysed described the main
275 trends in the data relatively well (Fig. 4). p -values for both species were above 0.5, indicating a
276 good model representation of the data. The catch ratio curves show that lemon sole catches

277 were significantly reduced for length classes which were well represented in the data, whereas
278 only small plaice (below 35 cm) were significantly affected by FLEXSELECT (Fig. 4).

279 **Day- and night-time comparison**

280 Potential differences in catch efficiency between night- and day-time were investigated by
281 overlapping the respective confidence intervals (Fig. 5). A lower number of night-time hauls
282 compared to day-time hauls were performed, thus the number of individuals is generally lower
283 in the night-time analyses. In particular, the amount of data for lemon sole during night-time
284 was small ($n=45$) and the dispersion so high that the resulting p -value was lower than 0.05
285 (Table 3). Despite this, all the model fits seem to represent the experimental points well, and
286 no systematic pattern was observed in the residuals. No significant differences between day-
287 and night-time were found for any of the species examined, as the confidence intervals
288 overlapped for all the length classes represented. An exception was observed for haddock,
289 where the two confidence intervals did not overlap for one length class (17 cm).

290 **Discussion**

291 This study showed that the bycatch of fish species can be substantially reduced by FLEXSELECT
292 without affecting the catch of the target species *Nephrops*. The device was effective on all the
293 six fish species analysed, with the intensity of the effect varying across species and length
294 classes. FLEXSELECT reduced the overall number of fish by 39% (CI: 29-46%), a percentage that
295 increases to 49% (CI: 39-57%) when considering only individuals above MCRS due to the
296 length-dependency of the effect. Although the individuals above MCRS have a higher economic
297 value, a reduction of bigger and thus heavier individuals enhances higher quota savings.

298 Therefore, this result is consistent with FLEXSELECT application to the *Nephrops*-directed mix
299 trawl fishery, in which a reduction of fish bycatch is desirable after exhaustion of fish quotas. In
300 such periods, fish in general represents an unwanted bycatch. Moreover, FLEXSELECT could be
301 combined with traditional selective devices (e.g. square mesh panels), which are efficient in
302 releasing juveniles, to achieve a larger overall reduction of bycatch. Furthermore, a proportion
303 of the small individuals captured during the trial were retained due to the small mesh size used
304 in the codend (40 mm square mesh). These individuals would typically escape the standard
305 commercial fishing gears used in *Nephrops*-directed fisheries (80-90 mm diamond mesh),
306 although after potentially damaging interactions with the trawl.

307 The effects of FLEXSELECT were diverse, both between and within the groups of roundfish and
308 flatfish. As expected, roundfish were effectively stimulated and escaped capture from the trawl
309 with the counter-herding device. In fact, we designed FLEXSELECT following the same principle
310 of stimuli which causes herding and makes trawls efficient gears. Gadoids which can be
311 encountered in high densities, like whiting and haddock, were previously described forming
312 shoals that facilitate an ordered herding behaviour (Jones et al. 2008); similarly, they were
313 efficiently counter-herded by FLEXSELECT. Their catches were reduced on average by 46% and
314 57%, respectively. The strong length-dependency evident for both species is likely related to
315 different swimming performances across length classes, with bigger individuals being able to
316 sustain higher speeds for longer periods (He 1993). A plausible explanation is that bigger
317 individuals were led away from the trawl path by FLEXSELECT scaring lines, whereas smaller
318 individuals followed a different escape strategy or were overrun, remaining in the trawl path.

319 A similar effect also emerged between cod and hake, although varying in the strength of the
320 response. The response of hake to FLEXSELECT's scaring lines was strong for most of the length
321 classes encountered (21-77 cm), despite the low number of individuals. Cod also showed a
322 response to FLEXSELECT for a similar range of classes (25-71 cm) however the effect was
323 smaller and more variable. We compared this result with other modifications introduced in the
324 trawl mouth area to determine if a higher reduction of cod catches can be achieved. Krag et al.
325 (2015) obtained a significant reduction in cod catches for individuals bigger than 35 cm using a
326 topless trawl, but this was strongly affected by the height of the headline and thus not
327 applicable to every trawl. A higher reduction was achieved by raising the footrope (Krag et al.
328 2010), as cod in general tend to stay close to the seafloor. Unfortunately, this solution is not
329 applicable in a crustacean fishery without affecting the catches of the target species.
330 Furthermore, small cod (<14 cm) were caught in significantly higher numbers in the trawl with
331 FLEXSELECT. Juvenile cod are known to stay closer to the seafloor than adult cod, and are often
332 observed to escape below the fishing line after coming in contact with it (Winger et al. 2010).
333 Thus, it is possible that these individuals came in contact with the FLEXSELECT lines and were
334 subsequently exposed to capture by the trawl. In commercial gears, this result does not
335 represent a major concern, as juveniles of these sizes would not be caught by the range of
336 mesh sizes used in *Nephrops* directed fisheries. On the contrary, an adaptation of FLEXSELECT
337 may be used in scientific surveys to sample small length classes, usually underestimated due to
338 this difference in catchability (Harley and Myers 2001).

339 Different effects were also detected between the two flatfish species examined. Flatfish anti-
340 predator strategy is based on camouflage, and normally their swimming capacities are limited

341 (Ryer et al. 2008). However, little is known about inter-specific differences, and previous
342 studies have focused on a limited number of species. In our experiment, lemon sole was the
343 most affected species, with a reduction of 65% (in numbers). On the contrary, plaice was
344 affected only for individuals smaller than 35 cm, and only a slight reduction in catches was
345 obtained. A first potential explanation may be a size-dependent behaviour caused by
346 swimming capacity constraints. Winger et al. (2004) observed that the escape strategy of small
347 plaice (<30 cm) consists mainly of fast swimming bursts alternated with resting periods, while
348 larger individuals (greater than or equal to 30 cm) prefer continuous swimming. Thus, as most
349 lemon soles captured in this study were of 20-30 cm, a swimming strategy similar to small
350 plaice seems likely. Nonetheless, the effect of FLEXSELECT on lemon sole was considerably
351 higher than the effect on small plaice, suggesting additional differences between the species.
352 The degree of burial, for example, may be an important factor in determining reactivity and the
353 timing of the first response. More studies are necessary to enlighten species-specific
354 behaviours in flatfish and their potential applicability to bycatch reduction devices. For
355 example, our results suggest that plaice is only slightly affected by the counter-herding device,
356 thus fisheries that target specifically this species may use FLEXSELECT to reduce the bycatch of
357 roundfish.

358 No diel differences were observed in FLEXSELECT's effect, despite several studies having
359 demonstrated that both roundfish (Walsh and Hickey 1993) and flatfish (Ryer and Barnett,
360 2006) do not respond with an ordinated herding when the light level is below species visual
361 perception thresholds. Nevertheless, a lack of diel variation in FLEXSELECT's efficiency is

362 desirable, as *Nephrops* fisheries typically take place under different light levels, depending on
363 the season and the area (Feekings et al. 2015).

364 On the basis of the results obtained, we conclude that FLEXSELECT represents an effective
365 bycatch reduction measure, potentially adaptable to different fisheries. Contrary to most other
366 selective devices, FLEXSELECT can be used on a haul-by-haul level, deciding its use on the basis
367 of the catch composition. This flexibility allows both an occasional and a more permanent use.

368 For example, FLEXSELECT can be used in specific periods or areas to avoid catching fish during
369 the spawning seasons, to reduce catches when prices are low, or as an alternative to
370 temporary area closures (Dunn et al. 2011). Moreover, the device can be deployed on a more

371 permanent base to reduce fish catches in those fisheries in which these represent an
372 undesirable catch. Among these, shrimp trawl fisheries could benefit from using FLEXSELECT,
373 after its adaptation to the gear geometry, as it may not only reduce fish bycatch but also

374 minimize its interaction with the net and the rest of the catch. Indeed, this “preventive”
375 approach has recently gained interest to address bycatch in these fisheries (McHugh et al.

376 2017). Therefore, the applicability of FLEXSELECT is much wider than the *Nephrops*-directed
377 mixed trawl fishery presented here and should be tested in other fisheries as well. Moreover,
378 we believe the efficacy of FLEXSELECT could be optimized by modifying the intensity of the
379 stimulus it produces, for example by using heavier components or by increasing their visibility.

380 Nonetheless, before modifications can be introduced in the design, the mechanism through
381 which FLEXSELECT works needs to be better understood. It is unclear from the results of this

382 study if FLEXSELECT’s scaring lines stimulate fish to rise vertically in the water column and
383 escape over the headline, or if they deviate their path to the wing tips. In the latter case,

384 FLEXSELECT's effect could be increased by changing the position of the central ring, thus
385 altering the angles created by the lines. The angle respect to the towing direction is indeed
386 recognized as an important factor in determining herding (Winger et al. 2010) and thus, we
387 expect also for counter-herding. Further studies are necessary to identify which species can be
388 prevented from entering the trawl and which are more effectively released later inside the
389 trawl. This study focused on the main commercial species in the case study fishery, as they are
390 included in the landing obligation and thus represent a priority for the fishermen. However,
391 FLEXSELECT's effect likely extends to other species which are commercially less relevant but
392 may still be important in an ecosystem context.

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520

List of tables

521

Table 1: Overview of the valid hauls.

522

Table 2: Number of individuals and number of hauls per species included in the analyses.

523

Table 3: Fit statistics for the modeled catch comparison rates.

524

Table 4: Catch ratios averaged over length classes.

525

526

527

Table 1

Overview of the valid hauls, showing the total catch (kg) in the test and control trawls. Hauls were distinguished by time of the day (D=day-time, N=night-time). The position of the test trawl was inverted every 4-6 hauls from Starboard (S) to Port (P). The total spread (Door spread) and the spread of each trawl are also reported. No data from the clump sensor were available for hauls 25 and 26.

Haul Nr.	Trawl time (hh:mm)	D/N	Depth (m)	Wind (m/s)	Test trawl	Doors spread (m)		Test trawl spread (m)		Control trawl spread (m)		Tot. Catch (Kg) Test	Tot. Catch (Kg) Control
						Mean	Sd	Mean	Sd	Mean	Sd		
1	00:50	N	33	5	S	81.09	1.09	39.94	0.83	41.14	0.38	425	658
2	01:00	D	86	3	S	90.71	2.29	43.57	1.99	47.14	1.07	255	605
3	01:05	D	87	3	S	94.75	2.76	46.25	1.28	48.50	1.93	294	732
4	01:00	D	78	3	S	94.64	2.93	46.79	1.62	47.85	1.57	1101	1539
5	00:50	D	85	8	P	95.00	3.39	47.20	1.48	47.80	1.92	491	833
6	00:40	D	87	9	P	91.23	2.98	45.58	1.26	45.65	1.81	381	538
7	00:45	D	84	9	P	96.30	3.87	47.04	1.46	49.26	2.65	402	603
8	02:15	D	61	8	P	83.44	3.01	41.29	1.16	42.15	1.99	102	199
9	01:00	N	90	3	P	93.06	3.62	46.79	1.85	46.27	1.92	199	410
10	01:35	N	78	3	P	94.98	3.49	45.94	1.77	49.05	1.96	425	508
11	00:30	N	85	3	S	83.13	3.07	42.30	0.78	40.83	3.36	244	466
12	00:50	D	84	3	S	81.03	2.31	41.07	0.84	39.97	1.57	1145	1299
13	00:30	N	77	3	S	80.50	3.63	40.05	1.58	40.45	2.39	296	408
14	00:45	D	80	2	S	83.62	3.10	41.97	2.35	41.65	1.25	275	394
15	00:45	D	84	2	S	74.33	1.14	36.92	0.52	37.42	0.95	402	680
16	01:30	D	54	2	P	88.12	2.04	43.50	1.23	44.62	1.05	130	171
17	01:30	D	46	1	P	87.81	3.72	42.71	1.89	45.10	2.10	228	223.5
18	01:00	D	45	0	P	87.47	1.88	42.11	1.12	45.36	0.98	55	90.5
19	01:00	D	48	0	P	85.19	0.86	41.29	0.71	43.90	1.42	69	105
20	00:47	D	77	5	P	86.77	3.56	42.72	3.24	43.92	1.08	350	590
21	00:45	D	86	6	P	86.70	3.22	43.17	1.57	43.53	2.05	435	615
22	00:46	D	85	7	S	88.93	3.83	43.85	1.86	45.08	2.08	267	480
23	00:45	N	85	7	S	79.78	3.27	39.58	1.20	40.20	2.13	311	449
24	00:45	N	86	6	S	76.70	3.77	38.00	1.38	38.70	2.51	207	132
25	00:30	D	85	6	S	80.65	0.45	-	-	-	-	247	388
26	00:46	N	85	4	S	78.50	5.07	-	-	-	-	292	278

528 **Table 2**

529 Number of individuals and number of hauls per species included in the analyses, for the three analyses performed.
 530 Species that were subsampled are indicated with the actual number of individuals measured (in brackets) and the
 531 raised total number (see Appendix 1).

	Pooled		Night-time		Day-time	
	Hauls	Nr	Hauls	Nr	Hauls	Nr
Nephrops	6	10618 (6266)	1	21	5	10597 (6245)
Cod	23	6749	7	1928	16	4821
Haddock	20	9865	7	2242	13	7623
Whiting	26	28567 (23341)	8	5479	18	23088 (17862)
Hake	5	178	-	-	5	178
Lemon sole	19	2474	6	345	13	2129
Plaice	23	15676 (13867)	8	1725	15	13951 (12142)

532

533 **Table 3**

534 Fit statistics for the modeled catch comparison rates. DoF denotes degree of freedom and is calculated by subtracting
 535 the number of model parameters from the number of length classes in the dataset analyzed.

	<i>p</i> -value	Pooled			Day-time			Night-time		
		Deviance	DoF	<i>p</i> -value	Deviance	DoF	<i>p</i> -value	Deviance	DoF	
Nephrops	0.06	53.74	39	-	-	-	-	-	-	
Cod	0.03	100.75	76	0.02	101.25	74	0.31	64.99	60	
Haddock	0.01	61.50	39	< 0.01	67.60	37	0.72	28.86	34	
Whiting	0.01	51.08	31	< 0.01	56.74	31	0.19	33.15	27	
Hake	0.21	52.32	45	-	-	-	-	-	-	
Plaice	0.07	44.87	32	0.09	41.07	30	0.23	30.95	26	
Lemon sole	0.42	22.70	22	0.69	18.22	22	0.03	28.48	16	

536

537

538 **Table 4**

539 Catch ratios averaged over length classes with 95% confidence intervals. The percentages for the total catch of the fish
 540 species analyzed, both below and above the MCRS, and the percentages per species are reported. The baseline for no
 541 effect of FLEXSELECT is 0.98. Percentages in the text are obtained by subtracting the catch ratio from 0.98 and
 542 multiplying the difference by 100.

543

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546

	Mean	CI Low	CI High
Tot fish	0.59	0.52	0.69
Fish<MCRS	0.69	0.59	0.79
Fish>MCRS	0.49	0.41	0.59
Cod	0.96	0.85	1.13
Haddock	0.41	0.30	0.54
Whiting	0.52	0.45	0.61
Hake	0.35	0.22	0.49
Plaice	0.79	0.64	0.89
Lemon sole	0.33	0.28	0.41

Figures captions

547

548 Figure 1: FLEXSELECT design.

549 **Figure 1. A)** The port trawl in a twin-rig with FLEXSELECT mounted. Proportions are not respected to facilitate the
550 identification of all FLEXSELECT components. **B)** Desired counter-herding effect. The grey arrows represent the
551 direction of fish escape.

552

553 Figure 2: Catch comparison rates and catch ratios for the target species *Nephrops*.

554 **Figure 2.** Catch comparison rates and catch ratios for *Nephrops*. On the left: the curve (solid line) represents the
555 modeled catch efficiency fitted to the experimental points (dots). The grey band represents 95% confidence intervals
556 and the dashed line the length distribution observed in the catch. The dotted horizontal line, located at 0.49, describes
557 equivalence in catch rates between the two trawls. On the right: catch ratio curve (solid line) with 95% confidence
558 intervals (grey band). The dotted horizontal line, located at 0.98, describes equivalence in catch rates between the
559 two trawls.

560

561 Figure 3: Catch comparison rates and catch ratios for the four roundfish species.

562 **Figure 3.** Catch comparison rates and catch ratios for the four roundfish species. On the left: catch comparison curves
563 (solid lines) representing the modeled catch efficiencies fitted to the experimental points (dots). The grey bands show
564 95% confidence intervals and the dashed lines the length distributions observed in the catch. The dotted horizontal
565 lines, located at 0.49, represent the baseline for no effect. On the right: catch ratio curves (solid line) with 95%
566 confidence intervals (grey bands). The dotted horizontal lines, located at 0.98, describe equivalence in catch between
567 the two trawls.

568

569 Figure 4: Catch comparison rates and catch ratios for the two flatfish species.

570 **Figure 4.** Catch comparison rates and catch ratios for the two flatfish species. On the left: catch comparison curves
571 (solid lines) representing the modeled catch efficiencies fitted to the experimental points (dots). The grey bands show
572 95% confidence intervals and the dashed lines the length distributions observed in the catch. The dotted horizontal
573 lines, located at 0.49, represent the baseline for no effect. On the right: catch ratio curves (solid line) with 95%
574 confidence intervals (grey bands). The dotted horizontal lines, located at 0.98, describe equivalence in catch between
575 the two trawls.

576

577 Figure 5: Catch comparison curves for day-time hauls, night-time hauls and overlap comparison.

578 **Figure 5.** Catch comparison curves for day-time hauls (1st column), night-time hauls (2nd column) and overlap
579 comparison (3rd column). The experimental points (dots) and catch distribution (dashed lines) per each group of hauls
580 is reported. The modelled fits for day-time (bold full lines) and night-time (bold dashed lines) are shown with the
581 respective 95% confidence intervals (grey bands). The bands borders are dashed for night-time confidence intervals.
582 The dotted horizontal lines, at 0.49, describe equivalence in catch rates between the two trawls.

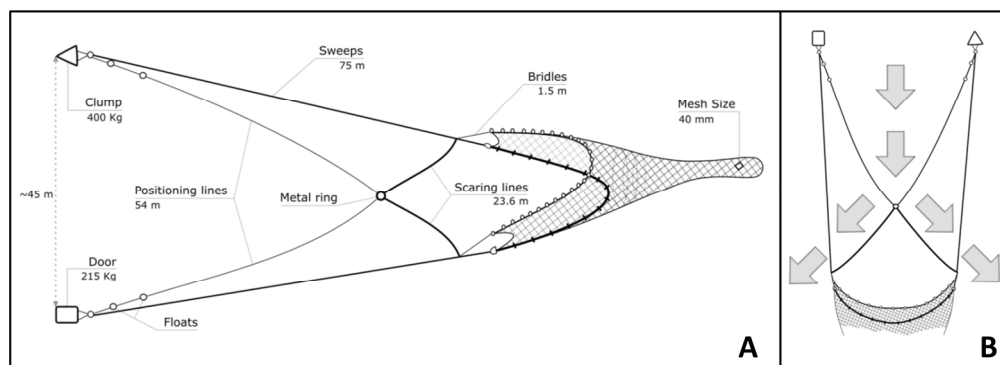


Figure 1. A) The port trawl in a twin-rig with FLEXSELECT mounted. Proportions are not respected to facilitate the identification of all FLEXSELECT components. B) Desired counter-herding effect. The grey arrows represent the direction of fish escape.

174x62mm (300 x 300 DPI)

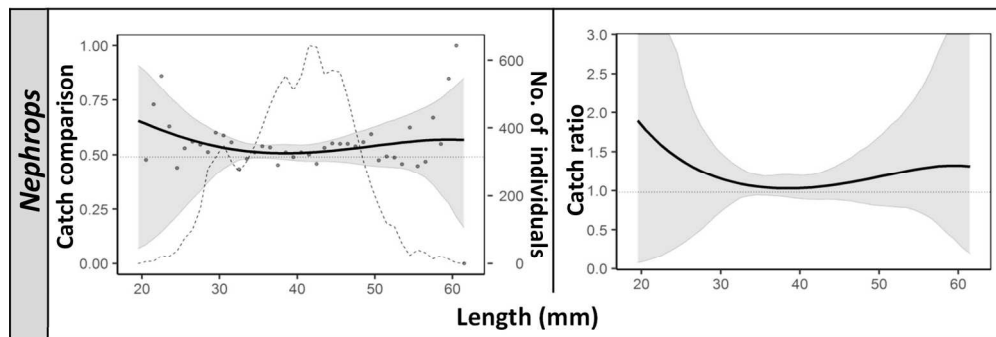


Figure 2. Catch comparison rates and catch ratios for *Nephrops*. On the left: the curve (solid line) represents the modeled catch efficiency fitted to the experimental points (dots). The grey band represents 95% confidence intervals and the dashed line the length distribution observed in the catch. The dotted horizontal line, located at 0.49, describes equivalence in catch rates between the two trawls. On the right: catch ratio curve (solid line) with 95% confidence intervals (grey band). The dotted horizontal line, located at 0.98, describes equivalence in catch rates between the two trawls.

182x61mm (300 x 300 DPI)

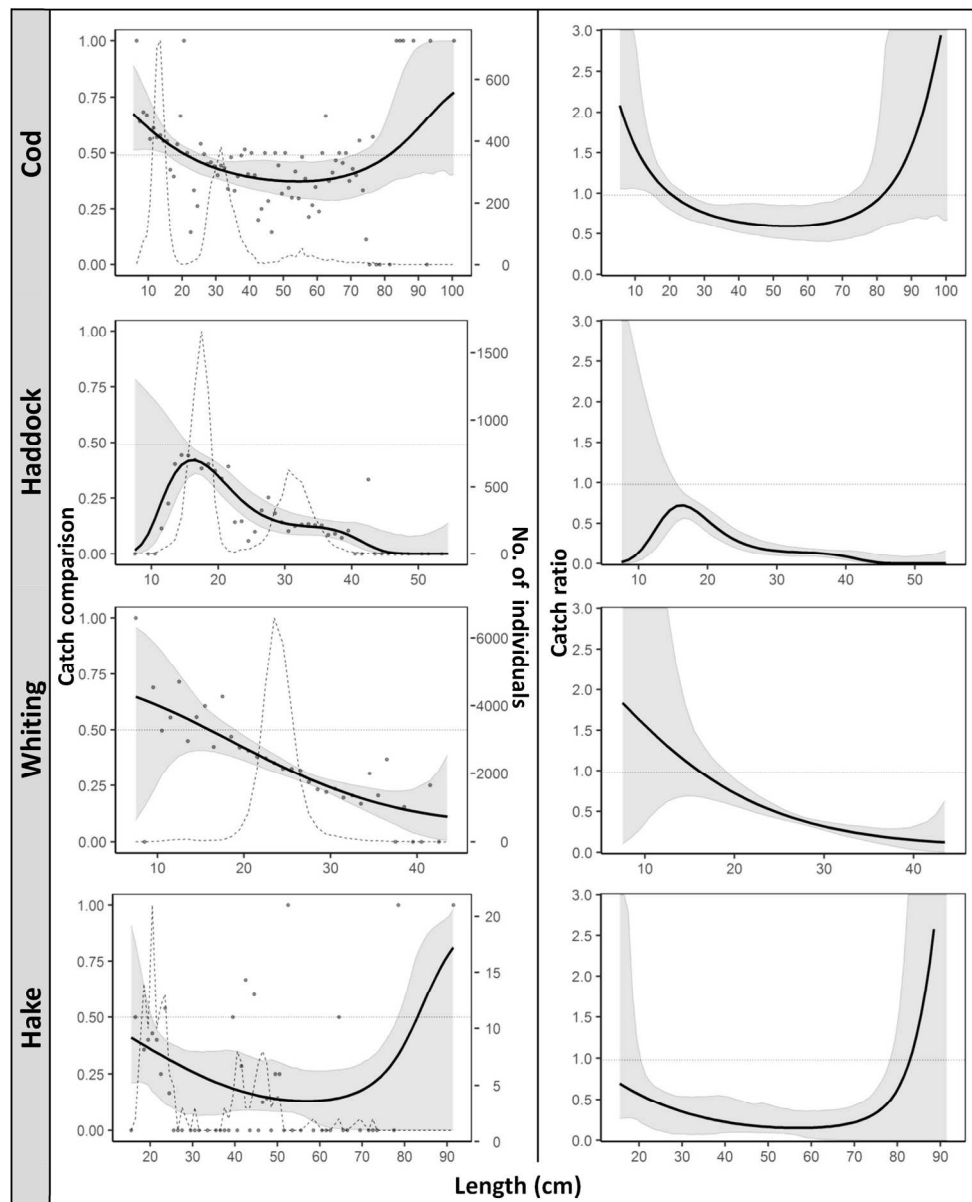


Figure 3. Catch comparison rates and catch ratios for the four roundfish species. On the left: catch comparison curves (solid lines) representing the modeled catch efficiencies fitted to the experimental points (dots). The grey bands show 95% confidence intervals and the dashed lines the length distributions observed in the catch. The dotted horizontal lines, located at 0.49, represent the baseline for no effect. On the right: catch ratio curves (solid line) with 95% confidence intervals (grey bands). The dotted horizontal lines, located at 0.98, describe equivalence in catch between the two trawls.

184x226mm (300 x 300 DPI)

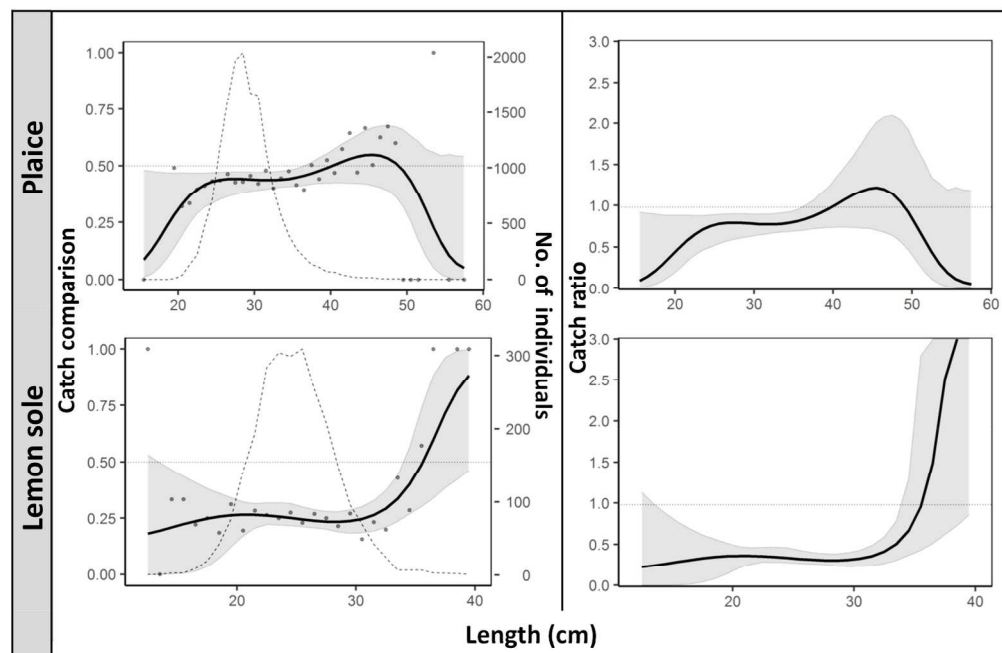


Figure 4. Catch comparison rates and catch ratios for the two flatfish species. On the left: catch comparison curves (solid lines) representing the modeled catch efficiencies fitted to the experimental points (dots). The grey bands show 95% confidence intervals and the dashed lines the length distributions observed in the catch. The dotted horizontal lines, located at 0.49, represent the baseline for no effect. On the right: catch ratio curves (solid line) with 95% confidence intervals (grey bands). The dotted horizontal lines, located at 0.98, describe equivalence in catch between the two trawls.

182x118mm (300 x 300 DPI)

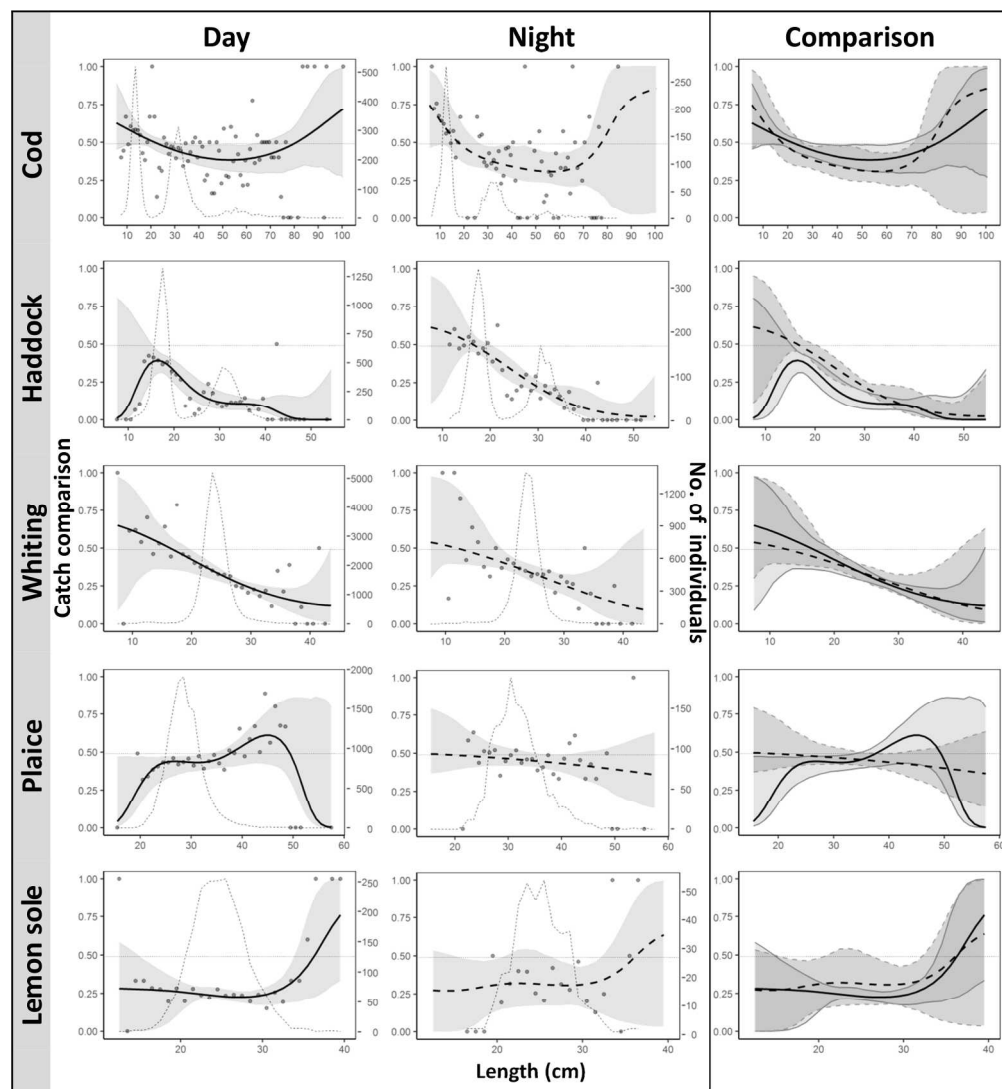


Figure 5. Catch comparison curves for day-time hauls (1st column), night-time hauls (2nd column) and overlap comparison (3rd column). The experimental points (dots) and catch distribution (dashed lines) per each group of hauls is reported. The modelled fits for day-time (bold full lines) and night-time (bold dashed lines) are shown with the respective 95% confidence intervals (grey bands). The bands borders are dashed for night-time confidence intervals. The dotted horizontal lines, at 0.49, describe equivalence in catch rates between the two trawls.

188x204mm (300 x 300 DPI)

1 Appendix 1

2 Estimation of the catch comparison curve

3 The effect of FLEXSELECT was assessed for each species separately based on comparing the
 4 catch in the test trawl (T) with the catch in the control trawl (C) while accounting for a
 5 potential length dependent effect. Due to a second experiment, not included in the present
 6 study, each trawl was divided into an upper (U) and lower (D) codend. Consequently, the
 7 number of individuals n of length class l being measured in a trawl haul j consisted of four
 8 numbers (counts) nTU_{lj} , nTD_{lj} , nCU_{lj} and nCD_{lj} . Each compartment had an associated species-
 9 specific sampling factor qTU_{lj} , qTD_{lj} , qCU_{lj} and qCD_{lj} , generally equal to 1.0, except for a few
 10 hauls where catches of *Nephrops*, plaice and whiting were subsampled.

11 For each species, the experimental catch comparison rate cc_l for length l was given by:

$$12 \quad (1) \quad cc_l = \frac{\sum_{j=1}^h \left(\frac{nTU_{lj}}{qTU_{lj}} + \frac{nTD_{lj}}{qTD_{lj}} \right)}{\sum_{j=1}^h \left(\frac{nTU_{lj}}{qTU_{lj}} + \frac{nTD_{lj}}{qTD_{lj}} + \frac{nCU_{lj}}{qCU_{lj}} + \frac{nCD_{lj}}{qCD_{lj}} \right)}$$

13 where the summation is over hauls h .

14 The length-dependent count data of each species were used to estimate a model for size
 15 dependent catch comparison rate $cc(l)$ averaged over hauls using maximum likelihood
 16 estimation by minimizing the following equation:

$$17 \quad (2) \quad g(\mathbf{v}) = -\sum_l \sum_{j=1}^h \left\{ \left(\frac{nTU_{lj}}{qTU_{lj}} + \frac{nTD_{lj}}{qTD_{lj}} \right) \times \ln(cc(l, \mathbf{v})) + \left(\frac{nCU_{lj}}{qCU_{lj}} + \frac{nCD_{lj}}{qCD_{lj}} \right) \times \ln(1 - cc(l, \mathbf{v})) \right\}$$

18 where \mathbf{v} represents the parameters describing the catch comparison curve $cc(l, \mathbf{v})$.

19 A fundamental step is to find a model for $cc(l, \mathbf{v})$ sufficiently flexible to account for the
 20 curvature for all the different species and considering potential differences between day
 21 and night hauls. We adapted a flexible model for $cc(l, \mathbf{v})$ often applied for catch comparison
 22 studies (Krag et al., 2014, 2015):

$$23 \quad (3) \quad cc(l, \mathbf{v}) = \frac{\exp(f(l, \mathbf{v}))}{1.0 + \exp(f(l, \mathbf{v}))}$$

24 where f is a polynomial of order k with coefficients v_0, \dots, v_k so $\mathbf{v} = (v_0, \dots, v_k)$. We used $f(l, \mathbf{v})$ of
 25 the following form:

$$26 \quad (4) \quad f(l, \mathbf{v}) = \sum_{i=0}^4 v_i \times \left(\frac{l}{100}\right)^i = v_0 + v_1 \times \frac{l}{100} + v_2 \times \frac{l^2}{100^2} + \dots + v_4 \times \frac{l^4}{100^4}$$

27 Leaving out one or more of the parameters $v_0 \dots v_4$ in equation (4) provided 31 additional
 28 models that were considered as potential models to describe $cc(l, \mathbf{v})$. Model averaging,
 29 ranking the models according to how likely they were compared to each other (Burnham
 30 and Anderson, 2002), was then applied to describe $cc(l, \mathbf{v})$. To obtain a combined model, the
 31 individual models were ranked and weighted according to their Akaike's Information
 32 Criterion (AIC) values (Akaike 1974; Burnham and Anderson 2002; Herrmann et al. 2017).
 33 Models with AIC values within +10 the value of the model with the lowest AIC, were
 34 considered to contribute to $cc(l, \mathbf{v})$ (Katsanevakis 2006; Herrmann et al. 2017). One
 35 advantage of using this combined model approach is that we avoid having to choose one
 36 specific model among the different candidates. The ability of the combined model to
 37 describe the experimental data was assessed based on the p -value, which expresses the
 38 likelihood for obtaining at least as large a discrepancy as that observed between the fitted
 39 model and the experimental data, by coincidence. Therefore, for the combined model to be
 40 a candidate model, the p -value should not be < 0.05 (Wileman et al. 1996). In cases with

41 poor fit statistics (p -value < 0.05; deviance >> degrees of freedom), the deviations between
 42 the experimental observed points and the fitted curve were examined to determine
 43 whether this was caused by structural problems in describing the experimental data or due
 44 to data overdispersion.

45 Confidence intervals (CI) for the size-dependent effect of FLEXSELECT were estimated using
 46 a double bootstrap method (Millar 1993). The procedure accounted for uncertainty due to
 47 between-haul variation by selecting h hauls with replacement from the h hauls available
 48 during each bootstrap repetition. Within-haul uncertainty in the size structure of the catch
 49 data was accounted for by randomly selecting individuals with replacement from each of
 50 the selected hauls separately from the four codends. The number of individuals selected
 51 from each haul was the number of individuals length measured in that haul in each of the
 52 codends, respectively. One thousand bootstrap repetitions were performed, and the Efron
 53 95% CI (Efron 1982) was calculated for the catch comparison curve. Incorporating this
 54 combined model approach in each of the bootstrap repetitions enabled us to account for
 55 additional uncertainty in the catch comparison curve due to model averaging (Herrmann et
 56 al. 2017).

57 The baseline for no effect of FLEXSELECT on the catch comparison rate is a value of 0.5 for
 58 paired catch comparison data (Krag et al. 2014). However, this assumed that the two trawls
 59 fish an area of similar size. Therefore, an additional baseline cc_0 that accounts for potential
 60 differences due to differences in door to clump distance is also applied:

61 (5)
$$cc_0 = \frac{\sum_{j=1}^h ST_j}{\sum_{j=1}^h (ST_j + SC_j)}$$

62 where ST_j and SC_j are respectively the averaged door to clump distance for the test and
63 control trawl in haul j .

64 **Estimation of the catch ratio curve**

65 The catch comparison rate $cc(l, \mathbf{v})$ cannot be used to quantify directly the effect of
66 FLEXSELECT on an individual of length l . Instead, we used the catch ratio $cr(l, \mathbf{v})$, that gives a
67 direct relative value of the catch efficiency between the test and control trawl. For the
68 experimental data, the catch ratio for a length class l is expressed as follows:

$$69 \quad (6) \quad cr_l = \frac{\sum_{j=1}^h \left(\frac{nTU_{lj}}{qTU_j} + \frac{nTD_{lj}}{qTD_j} \right)}{\sum_{j=1}^h \left(\frac{nCU_{lj}}{qCU_j} + \frac{nCD_{lj}}{qCD_j} \right)}$$

70 Simple mathematical manipulation based on (1) and (6) yields the following general
71 relationship between the catch ratio and the catch comparison:

$$72 \quad (7) \quad cr_l = \frac{cc_l}{1 - cc_l}$$

73 which also means that the same relationship exists for the functional forms:

$$74 \quad (8) \quad cr(l, \mathbf{v}) = \frac{cc(l, \mathbf{v})}{1 - cc(l, \mathbf{v})}$$

75 One advantage of using the catch ratio in the way it is defined by (6) and (8) is that if the
76 catch efficiency of both trawls is equal, i.e. no effect of the FLEXSELECT device, the $cr(l, \mathbf{v})$
77 would be 1.0. A $cr(l, \mathbf{v}) = 1.25$ would mean that the test trawl catches on average 25% more
78 fish or *Nephrops* with length l than the control trawl. In contrast, a $cr(l, \mathbf{v}) = 0.75$ would mean
79 that the test trawl catches 25% less fish of length l than the control trawl. Similar to the
80 process for the catch comparison rate, we corrected the baseline for no effect of

81 FLEXSELECT by accounting for differences in the area fished between test and control trawl
 82 (9) (i.e. differences in door to clump distance):

$$83 \quad (9) \quad cr_0 = \frac{\sum_{j=1}^h ST_j}{\sum_{j=1}^h SC_j}$$

84 Using equation (8) and incorporating the calculation of $cr(l, \mathbf{v})$ for each relevant length class
 85 into the double bootstrap procedure described above, we estimated the confidence limits
 86 for the catch ratio.

87 **Estimation of length-integrated catch ratio**

88 A length-integrated average value for the catch ratio can be estimated by:

$$89 \quad (10) \quad cr_{average} = \frac{\sum_l \sum_{j=1}^h \left(\frac{nTU_{lj}}{qTU_j} + \frac{nTD_{lj}}{qTD_j} \right)}{\sum_l \sum_{j=1}^h \left(\frac{nCU_{lj}}{qCU_j} + \frac{nCD_{lj}}{qCD_j} \right)}$$

90 where the outer summation covers the length classes in the catch during the experimental
 91 fishing period. By incorporating $cr_{average}$ into each of the bootstrap iterations described
 92 above, we were able to assess the 95% confidence limits for $cr_{average}$. We used $cr_{average}$ to
 93 provide length-averaged values for the effect of FLEXSELECT on the catch efficiency. In
 94 contrast to the length-dependent evaluation of the catch ratio, $cr_{average}$ values are specific
 95 for the population structure encountered during the experimental trial. Therefore, these
 96 values are specific for the size structure at the time the trial was carried out, and cannot be
 97 extrapolated to other scenarios in which the size structure of the fish population may be
 98 different.

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