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Predicting optimal combinations of bycatch reduction devices in trawl gears: a meta-analytical approach

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Running title:

Towards a new generation of trawls

18   **Abstract**

19   Global efforts to reduce unwanted catches have led to the development of a vast array of
20   bycatch reduction devices (BRDs), in particular for mixed trawl fisheries. Some of these
21   BRDs could likely benefit from being combined. However, the number of possible
22   combinations would be prohibitive to be tested experimentally. Therefore, in this study we
23   propose a meta-analytical approach that combines the data available on BRDs tested
24   independently in a fishery and predict the theoretical selectivity of all possible
25   combinations of those devices. This allows to identify promising BRD combinations, worth
26   experimental investigation and flexible trawl configurations, where the selectivity can be
27   substantially modified by adding or removing one BRD, thus aiding fishermen in adapting
28   to high variability in catch composition and quota availability. To illustrate the approach, we
29   used BRDs developed for the well-studied *Nephrops* (*Nephrops norvegicus*, Nephropidae)
30   directed mixed trawl fishery in the Skagerrak and Kattegat seas. We predicted the
31   selectivity of 100 BRD combinations for *Nephrops*, cod (*Gadus morhua*, Gadidae) and
32   haddock (*Melanogrammus aeglefinus*, Gadidae), compared them in terms of absolute
33   selectivity and performance under realistic catch scenarios, from both single- and multi-
34   species perspectives, and identified 15 BRD combinations that could be worth future
35   experimental investigation. The meta-analytical approach makes best use of existing
36   knowledge and leads to new insights about the potential for improvement and flexibility in
37   trawl selectivity. This could benefit a variety of mixed trawl fisheries and help developing a
38   new generation of more flexible gears, with multiple BRDs integrated in their structure.

39   **Keywords**

40   *Combined selectivity, flexible trawl design, gear modifications, mixed trawl fisheries,*
41   *optimal gear design, trawl selectivity*

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65   **1. Introduction**

66   Addressing the issue of unwanted catches is one of the major challenges of fisheries
67   science and management (Pérez Roda et al., 2019; Karp et al, 2019). For decades, efforts
68   to reduce the capture of non-target species and/or undersized individuals have involved
69   the development of fishing gear modifications, herein termed Bycatch Reduction Devices
70   (BRDs; Kennelly and Broadhurst, 2002). These BRDs modify the selectivity of the gear,
71   i.e. its ability to retain the individuals encountered (Wileman et al., 1996), and exploit
72   differences in shape, size and behaviour among species to select out unwanted individuals
73   (e.g. Robertson, 1986; Isaksen et al., 1992; Fujimori et al., 2005; Graham and Fryer, 2006;
74   Broadhurst et al., 2012; Herrmann et al., 2015; Brinkhof et al., 2017; Lomeli et al., 2018;
75   Melli et al., 2018a). Together with ecosystem-based management approaches, BRDs have
76   contributed to successfully reducing global discards of unwanted catches (Worm et al.,
77   2009; Hall and Mainprize, 2005; Zeller et al., 2017). Nevertheless, continuous gear
78   development is required for the industry to be able to cope with the variability in catch
79   composition and management objectives (Kennelly and Broadhurst, 2002; O'Neill et al.,
80   2019).

81   In trawl fisheries, where proportions of unwanted catches are often high (Kelleher, 2005),
82   substantial effort has been devoted to developing and testing numerous BRDs and
83   alternative gear designs (reviewed by: Broadhurst, 2000; Catchpole and Revill, 2008;
84   Graham, 2010). Moreover, the process is expected to accelerate in coming years, with
85   multiple projects now directly involving the industry in the development and testing of gear
86   modifications (Armstrong et al., 2013; Mangi et al., 2016; Eliassen et al., 2019, Feekings et
87   al., 2019). To help promote awareness of the BRDs available and build future designs on
88   the existing information, the scientific community has dedicated effort towards sharing the

89 summarized results and/or data of the experimental trials through open-access databases
90 (e.g. http://www.discardless.eu/selectivity_manual; <http://www.seafish.org/geardb>;
91 <https://tool.gearingup.eu/>; O'Neill and Mutch, 2017; O'Neill et al., 2019). Moreover, results
92 from different studies have been combined through meta-analyses to extrapolate common
93 patterns useful in designing future gear modifications (e.g. ICES, 2007; Madsen, 2007;
94 Fryer et al., 2015; Fryer et al., 2017). Ideally, both scientists and fishermen could use this
95 information to choose the most appropriate gear design with respect to their specific catch
96 goals (O'Neill et al., 2019). However, for most mixed trawl fisheries, the optimal gear
97 design is not constant; it varies, within and between years, according to management
98 objectives (e.g. quota availability and discard bans), market values, as well as
99 environmental and biological fluctuations (Catchpole et al., 2005; Rochet and Trenkel,
100 2005; Feekings et al., 2012). Historically, fishermen have coped with such variability by
101 adopting different gears throughout the year or by changing fishing dynamics (i.e. fishing
102 grounds and period), more than relying on multiple and often complex BRDs (Broadhurst,
103 2000). Nonetheless, achieving a more flexible trawl design, where selectivity could be
104 temporarily changed without having to change gear or fishing ground, could be ultimately
105 beneficial to fishermen's incomes, while improving their capacity to align to the
106 management and environmental objectives for sustainable fisheries.

107 To push the boundaries of trawl selectivity, recent studies have begun to combine
108 sequential BRDs (e.g. Stepputtis et al., 2016; Brinkhof et al., 2018; Larsen et al., 2018a).
109 Indeed, a combination of BRDs could be more effective in reducing unwanted catches of
110 multiple species (Larsen et al., 2018a) or even achieving alternative selective profiles for
111 the target ones (Stepputtis et al., 2016). Despite these few studies, the potential benefit of
112 combining existing BRDs remains still widely unexplored. For example, some BRDs which

were designed to be easily added and removed from the anterior part of the trawl (e.g. McHugh et al., 2015; Melli et al., 2018a) could be combined with posterior BRDs to obtain flexible and convertible trawl selectivity. However, the combination of BRDs would need to be proven significantly more efficient in reducing unwanted catches than the single BRDs to be of interest to the industry. Given the number of BRDs, testing all possible combinations experimentally would be extremely expensive and time-consuming (Veiga-Malta et al., 2019). A cost-efficient alternative would be to identify the most promising combinations before testing them experimentally. Therefore, in this study we aimed at presenting a meta-analytical approach to (i) predict the selectivity of a gear with multiple BRDs, and (ii) compare the predicted combined selectivity to identify the most promising combinations. The meta-analytical approach presented here combines data available on BRDs that have been individually tested within a specific fishery to predict the selectivity of the potential BRD combinations. The theoretical performance and potential applicability of BRD combinations for the fishery is then investigated in terms of differences in size selectivity, catch profile and potential consequences on fishermen's incomes (Sala et al., 2015; Larsen et al., 2017; Veiga-Malta et al., 2019) to identify the most promising options.

The meta-analytical approach presented is applicable to any well-studied fishery worldwide, where multiple BRDs have been developed and documented. To illustrate it, we chose BRDs developed for the *Nephrops* (*Nephrops norvegicus*, Nephropidae) directed mixed trawl fishery in the Skagerrak and Kattegat (North-east Atlantic; between Denmark, Norway and Sweden). This fishery, one of the most economically-important in Europe (Graham and Ferro, 2004; Krag et al., 2008), catches a wide range of species, including roundfish and flatfish (Kelleher, 2005; Krag et al., 2008). The diversity of unwanted species and sizes caught in this fishery has led to the development of a vast

array of BRDs (see for review Graham and Ferro, 2004; Catchpole and Reville, 2008). Many of these BRDs could potentially be combined to obtain different catch profiles, both in terms of species and sizes, and flexible trawl configurations.

2. Materials and Methods

2.1 Criteria for the selection of BRDs

To predict the species-specific selectivity of a combination of BRDs it is first necessary to know the species-specific, population-independent, selectivity of each BRD included. This is described by a species-specific selection curve that expresses the probability of retaining an individual of length l given that it was available to the gear (Wileman et al., 1996). Population-independent size-selectivity, also known as absolute selectivity, can be estimated using data-collection methods such as the covered-codend method and paired gear methods where a non-selective codend is used as a control (Wileman et al., 1996; Millar, 2009). Therefore, we selected studies where these methods were used. Moreover, since the efficiency of BRDs is often species dependent (e.g. Melli et al., 2018a), and their applicability further influenced by a number of factors (Feekings et al., 2012), we included multiple species in the analysis. Subsequently, we selected studies that provided size selectivity for the main target species as well as several bycatch species. Homogeneity in length-range, within species, among the studies included was also essential, as the dataset with the most restrictive range will affect the predictive power for the relative combinations. Finally, we selected BRDs that were strongly effective on at least one of the species of interest, and could be assumed to function independently in the trawl, i.e. applied to different sections of the trawl, without interfering with each other. In particular, this last criteria for the selection of BRDs aimed at preventing the risk for unpredictable synergies or contrasts deriving from applying multiple BRDs to the same trawl section, e.g.

161 a device that counters the herding response (e.g. Melli et al., 2018a) with one that
162 prevents the herding stimulus (e.g. Sistiaga et al., 2015; 2016). However, this assumption
163 does not imply that impairment in the efficiency of the BRDs due to, for example, an
164 increased state of fatigue in the individuals interacting with sequential BRDs, was
165 excluded. Such risk can only be acknowledged and investigated experimentally after the
166 most promising BRD combinations have been identified.

167 2.2 Estimation of bootstrap set for individual BRDs

168 Once the BRDs were selected, the original data for each independently-tested BRD were
169 re-analysed, according to the model used in the original study (see Appendix 1), while
170 applying a double-bootstrap method with 1000 repetitions to consider both within- and
171 between-hauls variation in size selectivity (Millar, 1993). The purpose of this step was to
172 obtain a bootstrap set for each BRD and each species. Besides being used to estimate
173 Efron 95% confidence intervals (CIs; Efron, 1982) for the population-independent
174 selectivity curve of each individual BRD, the resulting bootstrap set was necessary to
175 estimate the uncertainties for the population-independent combined selectivity, as
176 described in the following section. These and all the following steps were conducted using
177 the software SELNET (Herrmann et al., 2012).

178 2.3 Prediction of combined selectivity

179 For a standard trawl gear (i.e. without BRDs), size-selectivity is mostly determined by the
180 characteristics of the codend, in particular mesh size and shape (Glass, 2000; Herrmann
181 et al., 2009). However, for an individual to end up being retained in the codend it has to be
182 retained during the previous steps of the capture process. Therefore, the size selectivity of
183 a trawl gear can be considered as a sequence of selective processes. Indeed, if we divide
184 the trawl in four main sections s , the likelihood for an individual of length l being retained in

the codend requires that it is herded into the trawl, and passed through the body and extension sections without escaping (Fig. 1). Assuming the retention probability $r(l)_s$ of each section to be independent, we modelled the overall retention probability $r_{Combined}(l)$ as the product of the population-independent, size selection processes in each section of the trawl:

191

$$r_{Combined}(l) = \prod_{s=1}^4 r(l)_s = r_{Herding}(l) \times r_{Body}(l) \times r_{Extension}(l) \times r_{Codend}(l) \quad (1)$$

where $r_{Herding}(l)$, $r_{Body}(l)$, $r_{Extension}(l)$ and $r_{Codend}(l)$ are the population-independent size selectivity in the respective sections of the trawl, conditioned entering the section.

To estimate 95% Efron CIs for each $r_{Combined}(l)$, we used the bootstrap sets obtained in section 2.2 for each original design. Because these bootstrap sets were obtained independently, a new bootstrap set of results for $r_{Combined}(l)$ could be created using:

$$r_{Combined}(l)_i = r_{Herding}(l)_i \times r_{Body}(l)_i \times r_{Extension}(l)_i \times r_{Codend}(l)_i \quad i \in [1 \dots 1000] \quad (2)$$

where i denotes the bootstrap repetition index (Herrmann et al., 2018). In Eq. (2) the 1000 bootstrap sets generated from the original datasets were multiplied to obtain the new bootstrap set for the combined configuration. Based on this final bootstrap set, 95% Efron Percentile CIs for $r_{Combined}(l)$ were estimated.

2.4 Comparison of BRD combinations

To investigate if and how a combination of BRDs was significantly better with respect to the single BRDs or other BRD combinations, we quantified changes in (i) absolute selectivity, by using the delta selectivity (Larsen et al., 2018b); (ii) catch profile, by

206 estimating the cumulative catch curve (Veiga-Malta et al., 2019); and (iii) potential
207 consequences for the fishery, using performance indicators (Sala et al., 2015).

208 2.4.1 Delta selectivity

209 The delta selectivity consists of subtracting the predicted, species-specific, absolute
210 selectivity of two BRD combinations to identify size-ranges where there was a significant
211 change in selectivity (Larsen et al., 2018b). If $r_B(l)$ is the size selectivity of a trawl used as
212 a baseline, for example one having a simple codend or a single BRD, and $r_C(l)$ the size
213 selectivity of the combination of interest, then the difference in selectivity, $\Delta r(l)$ is:

$$214 \quad \Delta r(l) = r_C(l) - r_B(l) \quad (3)$$

215 Uncertainties for $\Delta r(l)$ were estimated using the approach described in (section 2.3) while
216 subtracting the two independently generated bootstrap sets. In general, $\Delta r(l)$ spans
217 between -1.0 and 1.0, where values above 0.0 imply that the combination has a higher
218 retention probability for individuals of length l than the baseline, while values below 0.0
219 imply a lower retention probability. The difference in retention probability is significant
220 when the Efron 95% CIs do not overlap the 0.0 baseline for equality.

221 2.4.2 Cumulative catch curve

222 The cumulative catch curve expresses what would be the catch profile under a specific
223 scenario of population encountered by the gear (Veiga-Malta et al., 2019). To estimate
224 cumulative catch curves for the BRD combinations we applied the predicted combined
225 selectivity to realistic, species-specific population scenarios. These scenarios were
226 estimated from the datasets of the BRDs included in the case-study, using the catch of the
227 non-selective control gears (see Appendix 2). For each species, we selected three
228 scenarios with different size-structures and modes (i.e. most frequent length class

229 represented) in the population. For each scenario $nPop_l$, uncertainties (95% Efron CIs)
230 were obtained based on a double bootstrap method to include both between- and within-
231 hauls variability in the structure of the population (see Appendix 2).

232 Using the size-selection curves predicted in section 2.3 for each BRD combination, and
233 applying them to $nPop_l$, we obtained simulated catches, $nCatch(l)$. We then expressed
234 these catches as a cumulative distribution function for the catch:

$$235 \quad CDF\_nCatch(L) = \frac{\sum_{l=0}^L \{r_{combined}(l) \times nPop_l\}}{\sum_l \{r_{combined}(l) \times nPop_l\}} \quad (4)$$

236 For each $CDF\_nCatch(L)$ we calculated 95% CIs based on the bootstrap sets for
237 $r_{combined}(l)$ and $nPop_l$ using the approach previously described for $r_{combined}(l)$.

238 The cumulative catch curve provides insights about how the efficiency of the single BRDs
239 or BRD combinations may be impaired by the structure of the population encountered.
240 BRD combinations whose efficiency is significantly affected by the population structure
241 have non-overlapping CIs for the different $CDF\_nCatch(L)$. Moreover, the cumulative catch
242 curves show the proportion of the catch of a species that would be below the Minimum
243 Conservation Reference Size (MCRS; i.e. minimum size at which the individual can be
244 sold for human consumption) under that population scenario.

245 2.4.3 Performance indicators

246 The population scenarios estimated in the previous section were also used to quantify the
247 performance of the BRD combinations, from the fishermen's perspective. While the size of
248 an individual typically defines whether it is commercially saleable or not, quotas and
249 catches are typically expressed in weight. Thus, for a fisherman, the performance of a
250 gear is determined by the proportion of weight retained with respect to that of other

251 designs (Sala et al., 2015). Therefore, we converted the number of individuals per length-
 252 class into weights and used them to calculate, for each species and each population
 253 scenario, the percentage (in weight) of undersized and commercial-sized individuals
 254 retained. This conversion was conducted by using a length-weight relationship, $w(l) = a \times$
 255 l^b where w is the weight (in g) / the length (in cm) and a and b are the coefficients for the
 256 specific species, season and study-area.

257 To estimate these performance indicators, we first applied the size-selection curves
 258 predicted in section 2.3 for each BRD combination to the population scenarios expressed
 259 in weight, $w(l) \times nPop_l$, and obtained simulated catches in weight, $w(l) \times r_{combined}(l) \times$
 260 $nPop_l$. We then calculated the percentage of weight retained for individuals below (wP^-)
 261 and above (wP^+) the species-specific MRCS, respectively, for a specific combination of
 262 BRDs. The indicators were calculated by:

$$\begin{aligned}
 263 \quad wP^- &= 100 \times \frac{\sum_{l < MCRS} \{a \times l^b \times r_{combined}(l) \times nPop_l\}}{\sum_{l < MCRS} \{a \times l^b \times nPop_l\}} \\
 264 \quad wP^+ &= 100 \times \frac{\sum_{l > MCRS} \{a \times l^b \times r_{combined}(l) \times nPop_l\}}{\sum_{l > MCRS} \{a \times l^b \times nPop_l\}} \quad (5)
 \end{aligned}$$

265

266 Both indicators (wP^- , wP^+) were estimated with uncertainties for each species and
 267 population scenario, using the bootstrap set for $r_{combined}(l)$ and $nPop_l$. Specifically, by first
 268 calculating the values for the indicators based on the result of each bootstrap repetition for
 269 $r_{combined}(l)$ and $nPop_l$ synchronous in (5) to obtain a bootstrap set for the indicator values.
 270 Efron 95% CIs were estimated for each of the indicators based on the resulting bootstrap
 271 set.

272 Because uncertainties are typically wider at the tails of the length range represented in the
273 data, and since the conversion into weights accentuates the influence of the larger and
274 less represented length classes when estimating the indicators, we restricted the length
275 range for each of the species analysed according to the data included. In particular, we set
276 the minimum length of the range as the smallest length class including at least five
277 individuals in all the single BRD datasets. Similarly, we determine the maximum length as
278 the largest length class with at least five individuals in all the datasets. This approach
279 prevented the less-represented length classes from compromising the information
280 contained in the main bulk of data.

281 Finally, to investigate the proportion of weight retained of bycatch species with respect to
282 the main target species, and compare the performance of different BRD combinations, we
283 used a multispecies population scenario (see Appendix 2). The performance indicators
284 calculated for this scenario were used to discuss the most promising BRD combinations
285 for the case-study fishery, depending on hypothetical catch goals (e.g. maximum quota
286 saving or maximum economic output).

287 **3. Application to a case-study fishery**

288 The *Nephrops*-directed mixed trawl fishery in the Skagerrak-Kattegat (ICES sub-division
289 IIIa) typically uses Combi trawls (i.e. wide-body trawl model for mixed bottom fisheries;
290 Cosmos Trawl A/S) to target both *Nephrops* and valuable fish species (ICES, 2014). Most
291 of these species are quota-regulated at the vessel level (Individual Transferable Quota
292 system; Squires et al., 1998) and are subjected to the EU landing obligation (i.e. discard
293 ban; EU, 2013). Among the legal gear options, most of the fleet adopts a 90 mm diamond
294 mesh codend with a 3 m long escape panel of larger meshes (140, 180 or 270 mm

295 depending on fishing area and mesh shape; ICES, 2014) inserted in the upper netting of
296 the codend, 4 m ahead of the codline (see Krag et al., 2016). The escape panel was
297 designed to reduce the catch of undersized fish, in particular gadoids (Frandsen et al.,
298 2009; Briggs et al., 2010). However, under the landing obligation, quota for fish species
299 can be exhausted prior to that of the main target species, *Nephrops*, potentially choking
300 the fishery (Catchpole et al., 2017).

301 To investigate the multispecies performance of BRD combinations for this fishery we
302 chose three species: the main target species, *Nephrops*; cod (*Gadus morhua*, Gadidae),
303 recognized as the main potential choke species for the area; and haddock
304 (*Melanogrammus aeglefinus*, Gadidae), a species with low risk of choking the fishery
305 (North Sea Advisory Council, 2018).

306 3.1 BRDs selected

307 We identified seven datasets to be included in the meta-analytical approach: a total of five
308 independently tested BRDs, selected due to their effect on the species of interest, and two
309 simple codends of 90 and 120 mm diamond mesh size, common mesh sizes used within
310 the fishery (Table 1). All the datasets were collected with similar trawl designs, fishing
311 dynamics (e.g. towing speed) and fishing area. Figure 2 illustrates the BRDs designs: a
312 counter-herding device (Melli et al., 2018a), a modification of the upper netting panel in the
313 trawl body (Krag et al., 2014), a horizontally-divided trawl codend (Melli et al., 2018b; Melli
314 et al., 2019b); a 90 mm diamond mesh codend with a 120 mm Square Mesh Panel (SMP;
315 Krag et al., 2013), and a 120 mm diamond mesh codend with a 180 mm SMP (Krag et al.,
316 2015). Each of these BRDs was effective on at least one of the bycatch species analysed,
317 without completely excluding all commercial fish from the catch (like for example a grid

318 would; Frandsen et al., 2009). This choice was made to respect the multispecies feature of
319 the *Nephrops*-directed mixed trawl fishery in the Skagerrak-Kattegat.

320 The selectivity of the two simple codends (i.e. 90 and 120 mm diamond mesh size) were
321 included as options to be combined with the BRDs in the herding zone, trawl body and/or
322 upper and lower codend after the separation inserted in the trawl extension. The specifics
323 of each codend and eventual SMP are summarized in Table 2. In addition, we included the
324 option of leaving the codend open by considering zero retention for those individuals
325 entering that codend.

326 The model used for each BRD and codend selectivity, its parameters and fit statistics are
327 summarised in Appendix 1.

328 3.1.1 Nomenclature system

329 To generate an ID for each of the BRD combinations we adopted a nomenclature system
330 where the letter define the section of the trawl (H=herding zone; B=trawl body; E=trawl
331 extension; C=codend). For the first three sections (H, B and E), where only one BRD
332 option was included in the study, we used a binary number system to identify the absence
333 (0) or presence (1) of the BRD. In the codend section (C), the five codend options were
334 numbered from 0 to 4, with C0 being the baseline codend (90 mm diamond mesh), C1 the
335 120 mm diamond mesh codend, C2 the 90 mm diamond mesh with a 120 mm SMP, C3
336 the 120 mm diamond mesh with a 180 mm SMP, and C4 the open codend. As a result, the
337 ID for a combination of the counter-herding device and a codend of 90 mm diamond mesh
338 with a 120 mm SMP (C2), with no modification on the body and extension sections, was
339 named H1B0E0C2. When the horizontal separation in the trawl extension was present
340 (E1) the two codends, lower and upper respectively, were specified in the ID. For example,
341 a BRD combination with the modification of the upper netting panel in the trawl body, the

vertical separation in the trawl extension leading to a 90 mm diamond lower codend and an open upper codend was identified as H0B1E1C0C4.

3.2 Predicted combined selectivity

Due to the BRDs selected, and because the modification introduced in the Extension section was a separation into two compartments, Eq. (1) becomes:

$$r_{Combined}(l) = r_{Herd\textit{ing}}(l) \times r_{Body}(l) \times [r_{Extension}(l) \times r_{CodendL}(l) + (1.0 - r_{Extension}(l)) \times r_{CodendU}(l)] \quad (6)$$

where $r_{Extension}(l)$ expresses the probability of an individual of length l to enter the lower compartment, $r_{CodendL}(l)$ is the size selectivity of the lower codend and $r_{CodendU}(l)$ of the upper one. When no separation is included in the trawl (E0), $r_{Extension}(l)$ equals one, meaning that all individuals enter one codend. When no BRD is inserted in the Herding zone (H0) and Body section (B0), $r_{Herd\textit{ing}}(l)$ and $r_{Body}(l)$ are assumed to equal one, meaning that the individuals entering that section are retained as they would in a standard trawl.

We predicted the selectivity of all possible combinations, obtaining a total of 100 predictions for *Nephrops* and cod. Since data for haddock were unavailable for C2, the number of possible combinations for haddock was 64. For all the species, four combinations had $r_{Combined}(l)$ equal to 0.0, relative to the theoretical option of fishing with an open codend (C4) when no separation in the extension was included (E0). Thus, the final number of species-specific, combined selectivity curves was 96 for *Nephrops* and cod, and 60 for haddock (see the Supplementary Material for representation of all predicted selectivity curves).

363 Figure 3 illustrates examples of the predicted selectivity of different combinations of BRDs
364 for the three species considered. The first two rows show the selectivity of a trawl with one
365 BRD; for example H0B0E1C0C1 introduced a second codend with larger meshes (C1) by
366 modifying the trawl extension with a vertical separation. The third and fourth rows show
367 examples of two BRDs combined, such as a large mesh panel in the trawl body and a
368 codend with a SMP inserted (H0B1E0C3). The fifth and sixth rows show examples of three
369 and four BRDs combined, respectively.

370 For each predicted selectivity curve, the 95% Efron CIs reflected the strength of the data
371 and the consistency (between-hauls variation) of the effect in the original datasets. Thus,
372 combinations of BRDs with high binomial noise in one or more of the original datasets
373 resulted in wide CIs. In particular, this is the case for the tails of the length-range of each
374 species, where the dataset with the most restricted length-range limited the inferential
375 power for that combination. This result prevented predictions that were not supported by
376 the original experimental data. Examples can be observed in Fig. 3, where the combined
377 selectivity curves of H1 and H1B1 for *Nephrops* resembled a bell-shaped curve (Dickson
378 et al., 1995; Lövgren et al., 2016) with a high retention of the central length classes and a
379 low retention of the smaller and larger classes. However, as expressed by the wide CIs,
380 the effect on the larger classes is inconclusive and should not be interpreted.

381 Moreover, combined selectivity curves for *Nephrops* involving the counter-herding device
382 (H1) exceeded retention rates of 1.0 (Fig. 3). This was caused by the use of the catch ratio
383 (see Appendix 1) to describe the effect of the counter-herding device, which in some cases
384 increased the number of individuals entering the trawl, although not significantly (Melli et
385 al., 2018a).

386 3.3 Comparison of BRD combinations

387 3.3.1 Delta selectivity

388 To understand if and how the addition of BRDs could significantly affect the species-
389 specific absolute selectivity of a BRD combination, we subtracted their predicted selectivity
390 (Delta selectivity, Fig. 4). Three examples, with increasing complexity (i.e. No. of BRDs),
391 are provided with respect to the relative simpler version of trawl (Fig. 4). In particular, the
392 addition of a counter-herding device to a trawl with a 90 mm diamond codend was
393 predicted to significantly reduce the retention rate of cod (24–72 cm; green curve) and
394 haddock (15–60 cm; blue curve), without affecting that of *Nephrops* (red curve; Fig. 4a).
395 The further addition of the BRD in the trawl extension (i.e. separation into two codends) in
396 the trawl extension did not change the retention of haddock but significantly reduced that
397 of cod (19–73 cm; Fig. 4b). However, the retention of *Nephrops* was also significantly
398 affected (22–70 mm; Fig. 4b). Finally, the addition of a large-mesh panel in the upper
399 netting of the trawl body did not further reduce the retention of either *Nephrops* or
400 haddock, but it significantly reduced that of cod (11–70 cm; Fig. 4c). Thus, if one single
401 BRD can be effective in substantially reducing the retention of haddock, the addition of
402 more BRDs can be useful to reduce that of cod. However, additional BRDs can
403 significantly affect the retention of the main target species, *Nephrops*.

404 3.3.2 Cumulative catch curves

405 In terms of catch profile for each species, the cumulative catch curves indicated that the
406 proportion of catch composed of undersized individuals (i.e. < MCRS), can vary
407 significantly when using the BRD combinations under different population scenarios (Fig.
408 5). For example, the proportion of undersized *Nephrops* predicted to be caught under the
409 population scenarios P2 and P3 with the combination H1B0E1C0C1 was less than 10%,

410 whereas under the population scenario P1 it reached approximately 45% (Fig. 5). The
411 efficiency of most BRD combinations in selecting out undersized individuals was found to
412 be significantly affected by the structure of the population encountered, as represented by
413 the non-overlapping CIs of the cumulative catch curves (Fig. 5). The highest proportion of
414 undersized individuals was always caught when the mode of the population structure was
415 close to the MCRS. For example, in the third population scenario for cod (P3), where the
416 mode in the population is at 25 cm (MCRS for cod in the Skagerrak/Kattegat is 30 cm),
417 approximately 80% of the catch with the combination H1B0E1C0C1 consisted of
418 undersized individuals (Fig. 5). Similarly, under the second population scenario, the
419 proportion of undersized haddock in the catch was approximately 60% (Fig. 5). If on one
420 hand this is the result of the higher density of undersized individuals in the population
421 scenario, on the other it can highlight that the BRDs included in the combination were less
422 effective in improving the selectivity in proximity of the MCRS. For example, with the
423 combination H1B0E1C0C1, cod below 30 cm are not counter-herded and enter more
424 frequently the lower compartment, thus they are less likely to encounter the 120 mm mesh
425 size of the upper codend (Melli et al., 2018a; Melli et al., 2018b). However, a high
426 proportion of undersized individuals can also imply that the combination of BRDs has a
427 length-dependent efficiency, i.e. it is more effective in reducing the catch of larger
428 individuals (e.g. haddock; Melli et al., 2018a). Consequently, the proportion of undersized
429 individuals in the catch is high because the commercial-sized ones have been selected
430 out. To distinguish between these two cases, the cumulative catch curve should be
431 complemented by the performance indicators, which provide the proportion of undersized
432 and commercial-sized retained with respect to the population encountered.

433 3.3.3 Performance indicators

434 To estimate the performance indicators from a fisherman's perspective, the number of
435 individuals per length class in each population scenario was converted to weight per length
436 class. For cod and haddock, we used length-weight relationships available on [fishbase.org](https://www.fishbase.org)
437 (Froese and Pauly, 2014) for ICES Division IIIa (cod: $a = 0.00587$ and $b = 3.140$; haddock:
438 $a = 0.0065$ and $b = 3.1083$). For *Nephrops* we used the data from the Data Collection
439 Framework (DCF) and International Bottom Trawl Survey (IBTS) programs in Skagerrak
440 and Kattegat ($a = 0.000765$ and $b = 2.98025$). Prior to conversion, the length ranges were
441 restricted (see section 2.4.3) as follow: 20.5–59.5 mm for *Nephrops*, 20.5–76.5 cm for cod
442 and 18.5–43.5 cm for haddock. Moreover, to estimate the proportion of weight retained of
443 individuals below and above the MCRS, we used the MCRS for the ICES division IIIa: 32
444 mm carapace length for *Nephrops*, and 30 cm and 27 cm total length for cod and haddock,
445 respectively.

446 The performance indicators were estimated for all the possible combinations of the BRDs
447 considered and for each of the population scenarios, i.e. P1-P3 per species and a
448 multispecies scenario (Supplementary Material). A subset of BRD combinations, with
449 decreasing retention of cod, is presented in Table 3. The results showed that, from the
450 fishermen's perspective, most BRDs combinations were predicted to have a consistent
451 effect across population scenarios, with very few combinations having non-overlapping CIs
452 between scenarios (Table 3). Moreover, the number of BRDs combined was found to not
453 necessarily significantly reduce the proportion of weight retained. For example, the
454 addition of one (e.g. H1B0E0C0) or even two BRDs (e.g. H0B0E1C2C0) did not
455 significantly reduce the proportion of undersized cod retained, with respect to a simple
456 trawl with no BRDs (H0B0E0C0; Table 3). Similarly, combinations consisting of three

BRDs (e.g. H1B0E1C2C1) did not significantly reduce the weight retained of neither undersized nor commercial-sized cod with respect to combinations consisting of two BRDs (e.g. H1B0E0C2 or H1B1E0C0; Table 3). In contrast, an almost complete elimination of cod catches was achieved only from combinations of four BRDs (e.g. H1B1E1C2C4), the maximum level of complexity considered in this study.

3.3.4 Most promising combinations

The performance indicators proved to be the fastest measure to determine if the BRD combination could represent a viable option for the case-study fishery. Indeed, we excluded any BRD combinations that would cause a loss of commercial-sized *Nephrops*, across population scenarios, greater than 15% with respect to a trawl with no BRDs and a 90 mm diamond mesh codend. Fifteen combinations were subsequently identified which could be suitable for the case-study fishery (Table 4). Of these 15 combinations, only 10 included predictions for haddock, due to the lack of data for the 90 mm diamond mesh size codend with a 120 mm SMP (C2). Most of these combinations had a lower codend of 90 mm diamond mesh size, whenever the horizontal separation was introduced. Only one of the selected BRD combinations had a different lower codend, C2, in combination with a 90 mm diamond codend as upper codend (Table 4). Furthermore, out of the 15 BRD combinations identified, 10 included the counter-herding device (Melli et al., 2018a) and six the large mesh size in the upper netting of the trawl body (Krag et al., 2014). Only three of the identified combinations included the maximum level of complexity (i.e. No. of BRDs) possible in this study. This was mainly caused by the potential loss of commercial-sized *Nephrops* associated with each additional BRD introduced in the trawl.

When comparing the performance of the BRD combinations identified under a multispecies catch scenario (see Appendix 2), the results highlighted potential strategies

481 for the fishing vessels operating in the Skagerrak and Kattegat (Fig. 6). In Figure 6, the #0
482 indicates a simple trawl with no BRDs and a 90 mm diamond mesh codend. Under the
483 catch scenario considered, all the selected combinations had similar predicted retention
484 rates for the main target catches, i.e. commercial-sized *Nephrops*, which did not differ
485 significantly from the one of a simple trawl with a 90 mm diamond mesh codend. This
486 baseline design retained 75.3% (66.2–84.0) undersized cod and a highly variable
487 percentage of undersized haddock (10.7–67.7%). Moreover, catches of commercial-sized
488 bycatch were 97.4% (96.4–98.2) and 62.0% (26.0–92.0) for cod and haddock,
489 respectively. With respect to this baseline, most of the identified BRD combinations had
490 desirable catch profiles: they caught less than 50% of the weight of undersized bycatch of
491 both cod and haddock (highlighted sections in Fig. 6). One exception, the combination #6
492 (H1B0E0C0), was predicted to retain on average 60.6% (48.3–73.0) of the weight of
493 undersized cod in this population scenario (see Appendix 2 for description of the scenario).

494 In terms of commercial-sized individuals, all the BRD combinations identified as most
495 promising minimized the percentage of commercial-sized haddock retained, with the
496 exception of combination #1 (H0B0E1C0C1). These results show that, with the BRDs
497 included in this study, which are among the most effective for the case-study fishery, it is
498 impossible to substantially reduce catches of cod, without affecting those of commercial-
499 sized haddock (Fig. 6). Nonetheless, since cod is a potential choke species for the case-
500 study fishery under the EU landing obligation (North Sea Advisory Council, 2018), a
501 reduction of cod, and thus haddock, may be necessary to continue fishing for *Nephrops*
502 when the cod quota is approaching exhaustion. We could identify several combinations of
503 BRDs that could potentially help the fishery to significantly reduce catches of this species.
504 The results showed that an almost complete avoidance of cod could be achieved by

505   combing up to four BRDs (#15; Fig. 6). In particular, by including a BRD in each of the four
506   sections of the trawl considered in this study, this combination achieved overall retention
507   below 25% and 1% of the weight of cod and haddock, respectively, a result that until now
508   has only been achieved by introducing a grid in the trawl codend at the cost of all
509   commercial catches of fish (Frandsen et al., 2009; Drewery et al., 2010). In contrast, even
510   though the BRD combinations identified here would reduce commercial catches of some
511   species (e.g. haddock) they are likely to allow the retention of others, such as monkfish
512   (*Lophius piscatorius*) and flatfish species, less affected by these types of BRDs (Krag et
513   al., 2008; Fryer et al., 2017; Melli et al., 2018a).

514   If fishermen were to minimize the bycatch of undersized roundfish, while maintaining the
515   majority of the income deriving from commercial-sized cod, for example when cod quota is
516   available, the BRD combinations #2 (H0B0E1C0C2) and #7 (H1B0E1C0C1) could
517   represent the best options (Fig. 6). Although many other BRD combinations achieved
518   similar results, these two had the advantage of retaining on average the same percentage
519   of undersized *Nephrops* as the baseline design (see Supplementary Material for all
520   Performance Indicators). In particular, #2 retained 83.0 % (78.3–87.6) of commercial cod
521   catches and although data for haddock were not available for this BRD combination,
522   haddock catches can be expected to be low due to its high escape rate through 120 mm
523   SMPs (Krag et al., 2008; Fryer et al., 2015).

524   Finally, the meta-analytical approach allowed to identify three convertible BRD
525   combinations that could lead to a flexible trawl configuration. In particular, the BRD
526   combination #2 retained most of the commercial-sized cod while reducing the catch of
527   undersized fish (Fig. 6), a catch profile useful at maximizing catch value when cod quota is

528 available. However, when the quota comes close to exhaustion, combination #2 can be
529 converted into combination #8 by simply adding the counter-herding device and to #10 by
530 leaving the upper codend open. This substantially modifies the trawl selectivity without
531 requiring a trip to the harbour.

532 **4. Discussion**

533 The meta-analytical approach described in this study makes best use of the existing
534 knowledge on BRDs and leads to new insights about the potential for improvement in trawl
535 selectivity. By using the data already available we were able to predict the combined
536 selectivity of multiple BRDs and quickly inspect a great number of potential BRD
537 combinations, without the time and cost outlay associated with experimental investigation.
538 The use of this approach could ultimately speed up the identification of promising gear
539 designs, thus aiding the industry in pursuing individual catch goals (O'Neill et al., 2019).
540 Moreover, the meta-analytical approach allows to determine if an increase in complexity in
541 the gear design, i.e. no. of BRDs combined, would result in a significant reduction of
542 unwanted catches. Indeed, because simplicity is often key when considering the uptake of
543 a gear design by fishermen (Broadhurst, 2000; Kennelly and Broadhurst, 2002), and
544 because each additional selection process can lead to a loss of target catch, the number
545 of BRDs should be kept to a minimum. To do so, the approach proposed in this study
546 starts from a simple gear design and adds levels of complexity (i.e. BRDs) until there is no
547 significant improvement in selectivity, for each species, with the addition of further BRDs.
548 Finally, by combining BRDs, we can expand the boundaries of trawl selectivity, moving
549 away from the standard S-shaped selectivity curve (Wileman et al., 1996) and achieving
550 alternative selective profiles more in line with the most recent management objectives (e.g.
551 balanced harvesting; Law et al., 2015; Stepputtis et al., 2016).

552 The case-study presented herein, led to the identification of 15 potentially applicable
553 combinations that could help the fishery to cope with the requirements of the European
554 landing obligation (ICES, 2013) and, thus, are worth experimental validation. This result
555 was achieved by only including five BRDs into the meta-analysis out of those available for
556 the *Nephrops*-directed mixed trawl fishery. Other strongly effective BRDs, such as grids in
557 the trawl extension (Graham and Fryer, 2006; Frandsen et al., 2009), could be considered
558 in future analyses, especially when including more fish species to better investigate the
559 overall effect on fishermen's income. The designs identified as most promising, here and
560 in future applications of the meta-analytical approach, are relative to the case-study
561 considered; nonetheless, there are several well-studied fisheries in the world where
562 multiple BRDs have been developed due to high temporal and spatial variability in bycatch
563 rates (Catchpole et al., 2005; Rochet and Trenkel, 2005) that could benefit from the
564 application of the meta-analytical approach described. This is the case, for example, for
565 trawl fisheries such as the Australian penaeid-trawl fishery (Broadhurst, 2000; Broadhurst
566 et al., 2012), the US West coast groundfish bottom trawl fishery (Lomeli et al., 2017; 2018;
567 2019), the Gulf of Maine pink shrimp trawl fishery (He and Balzano, 2007; He and
568 Balzano, 2012), and the Irish Sea *Nephrops* fishery (Briggs, 1992; Cosgrove et al., 2019).
569 To maximize the advantage of predicting the combination of multiple sequential BRDs, the
570 choice of BRDs should be limited to highly efficient designs, targeting different species and
571 size-groups.

572 It is important to highlight that the scope of the approach presented is the identification of
573 promising combinations and that experimental validation of the predictions is essential.
574 Indeed, the predicted combined selectivity curves are based on the assumption of
575 independence among the BRDs, meaning that when combined the BRDs would perform

576 as they do when applied individually. However, a certain level of impairment in
577 performance should be expected, depending on the type of modifications introduced. For
578 example, anterior BRDs (e.g. Melli et al., 2018a) can potentially increase the resuspension
579 of sediment and, thus, affect the visibility inside the trawl (O'Neill and Ivanović, 2015). This
580 might have consequences on the vision-dependent behaviours of the individuals in the
581 trawl, thus affecting their response to the posterior BRDs (e.g. mesh penetration; Glass et
582 al., 1993). Moreover, individuals that are stimulated or enter in contact with multiple
583 sequential BRDs may be subjected to increased states of fatigue and/or stress, with
584 potential implications on their ability to contact the BRDs and escape (Winger et al., 2010).
585 The introduction of each BRD may also alter or divert the water flow in the trawl, with
586 consequences on the hydrodynamic performance and selective properties of the gear and
587 BRDs (e.g. Riedel and DeAlteris, 1995). Finally, when testing the combination of BRDs
588 experimentally, a certain degree of divergence from the prediction should be expected due
589 to the potentially necessary scaling in size of the trawl and BRDs, with respect to the
590 experimental trawl used for data collection. Nonetheless, the meta-analytical approach
591 substantially reduces the amount of experimental work by narrowing the list of BRD
592 combinations to be tested.

593 Finally, a major outcome of the meta-analytical approach was to identify flexible gear
594 configurations that could be quickly converted from one to the other, with substantial
595 changes in selectivity. A flexible trawl configuration would allow fishermen to adjust their
596 selectivity on a day-to-day or even haul-to-haul level, creating a multi-purpose trawl where
597 selectivity could be adjusted to match the variability in management objectives, market
598 values, and temporal and spatial variability in catch composition (Catchpole et al., 2005;
599 Rochet and Trenkel, 2005; Feekings et al., 2012). The advantage deriving from such

600 flexibility, especially under strong economic drivers such as discard bans (Karp et al.,
601 2019), could offset the additional complexity in gear design and number of BRDs. The
602 entire trawl design could even be re-thought with potential BRDs already integrated in its
603 structure. This would likely reduce the risk for loss of target catch or impairment of the gear
604 geometry deriving from applying the BRDs to the trawl as a second thought. With this
605 meta-analytical approach, we hope to facilitate the identification of compatible gear
606 configurations and initiate further discussion about multi-purpose trawl designs.

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612 **6. Data availability statement**

613 The data that support the findings of this study are either published or available from the
614 corresponding author upon reasonable request.

615 **7. References**

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List of Tables

Table 1 Summary of the datasets included in the meta-analysis.

Reference	Trawl section	ID	Type of data	Description
Melli et al., 2018a	Herding	H0/H1	Paired gears	Counter-herding device
Krag et al., 2014	Body	B0/B1	Paired gears	Trawl with 800 mm diamond meshes in the upper netting of trawl body
Melli et al., 2018b and Melli et al., 2019b	Extension	E0/E1	Covered-Codend	Horizontally divided trawl codend
Krag et al., 2013	Codend	C0	Covered-Codend	90 mm diamond mesh codend; cod and <i>Nephrops</i>
Krag et al., 2016	Codend	C0	Covered-Codend	90 mm diamond mesh codend; haddock
Krag et al., 2015	Codend	C1	Covered-Codend	120 mm diamond mesh codend
Krag et al., 2013	Codend	C2	Covered-Codend	90 mm diamond mesh codend with 120 mm square mesh panel
Krag et al., 2015	Codend	C3	Covered-Codend	120 mm diamond mesh codend with 180 mm square mesh panel

Table 2 Summary of codend specifications. Circum. = circumference in the codend; Twine thickness = twine thickness of the netting; SMP = square mesh panel; m = metre, mm = millimetre.

Codend	Length (m)	Circum. (No. meshes)	Codend mesh size (mm)	Twine thickness	SMP mesh size (mm)	SMP Length (m)	Cover mesh size (mm)
C0	7	100	95	4 mm, Double	-	-	40
C1	6	92	127	5 mm, Double	-	-	40
C2	7	100	95	4 mm, Double	126	3	40
C3	6	92	127	5 mm, Double	180	3	40

872 **Table 3** Performance indicators of a simple trawl design with no BRDs (H0B0E0C0) and six
873 examples of BRD combinations for cod, under three population scenarios (P1, P2 and P3). 95 %
874 Efron CIs are shown within parenthesis. wP⁻ = Percentage (in weight) of undersized cod retained;
875 wP⁺ = Percentage (in weight) of commercial-sized cod retained. The examples are ordered
876 according to their mean wP⁻, colours are used to highlight the efficiency of the BRD combination in
877 reducing catches of cod: red = low effect; yellow = medium effect; green = high effect.

		wP ⁻ (%)	wP ⁺ (%)	w DiscardRatio (%)
H0B0E0C0	P1	66.6 (53.9 – 77.6)	98.7 (98.0 – 99.3)	2.8 (1.6 – 4.9)
	P2	78.2 (70.5 – 86.1)	96.0 (94.3 – 97.2)	8.1 (5.4 – 11.1)
	P3	69.0 (57.0 – 78.5)	94.0 (91.7 – 96.4)	59.9 (48.3 – 66.8)
H0B0E1C2C0	P1	52.7 (41.4 – 63.0)	95.5 (93.7 – 97.1)	2.3 (1.3 – 4.0)
	P2	63.6 (56.2 – 71.2)	90.7 (88.0 – 93.2)	7.0 (4.7 – 9.8)
	P3	54.7 (44.4 – 63.2)	86.7 (83.0 – 91.7)	56.2 (43.2 – 63.7)
H1B0E0C0	P1	55.8 (41.7 – 67.5)	63.4 (50.0 – 81.4)	3.6 (1.8 – 6.3)
	P2	61.7 (50.1 – 73.8)	63.2 (51.3 – 79.0)	9.5 (6.0 – 13.3)
	P3	57.6 (43.4 – 68.6)	62.9 (52.2 – 77.8)	65.0 (52.4 – 71.7)
H1B1E0C0	P1	33.6 (23.4 – 42.7)	38.8 (28.3 – 51.9)	3.6 (1.7 – 6.8)
	P2	33.0 (24.7 – 42.4)	35.9 (27.8 – 48.1)	9.0 (5.4 – 13.6)
	P3	34.2 (24.0 – 43.6)	33.3 (26.4 – 44.9)	67.6 (51.8 – 76.0)
H1B0E1C2C1	P1	12.4 (7.6 – 16.6)	55.0 (41.9 – 71.3)	1.0 (0.5 – 1.8)
	P2	15.8 (10.9 – 20.5)	47.4 (36.3 – 61.3)	3.5 (2.0 – 5.4)
	P3	12.6 (7.8 – 16.5)	40.9 (32.2 – 55.5)	38.6 (22.9 – 49.7)
H0B1E0C2	P1	6.1 (3.2 – 10.9)	52.9 (43.4 – 64.6)	0.5 (0.2 – 1.0)
	P2	9.4 (5.8 – 15.6)	43.1 (35.9 – 55.1)	2.3 (1.2 – 3.9)
	P3	6.2 (3.0 – 10.6)	34.6 (25.3 – 49.6)	26.9 (11.5 – 40.9)
H1B1E1C2C4	P1	1.2 (0.6 – 2.4)	8.3 (5.1 – 11.5)	0.6 (0.3 – 1.5)
	P2	1.8 (1.0 – 3.1)	6.8 (4.4 – 9.7)	2.8 (1.3 – 5.2)
	P3	1.3 (0.6 – 2.3)	5.4 (3.3 – 8.6)	32.1 (14.9 – 49.3)

887 **Table 4** Summary of the BRD combinations identified as most promising for the case-study fishery.
888 H = Herding zone; B = Trawl body; E = Trawl extension.

Combination	ID	BRDs included				
		H	B	E	Lower codend	Upper codend
H0B0E1C0C1	1	-	-	x	90 mm diamond	120 mm diamond
H0B0E1C0C2	2	-	-	x	90 mm diamond	90 mm + 120 mm SMP
H0B0E1C0C3	3	-	-	x	90 mm diamond	120 mm + 180 mm SMP
H0B1E0C0	4	-	x	-	90 mm diamond	-
H0B1E1C0C2	5	-	x	-	90 mm diamond	90 mm + 120 mm SMP
H1B0E0C0	6	x	-	-	90 mm diamond	-
H1B0E1C0C1	7	x	-	x	90 mm diamond	120 mm diamond
H1B0E1C0C2	8	x	-	x	90 mm diamond	90 mm + 120 mm SMP
H1B0E1C0C3	9	x	-	x	90 mm diamond	120 mm + 180 mm SMP
H1B0E1C0C4	10	x	-	x	90 mm diamond	open
H1B0E1C2C0	11	x	-	x	90 mm + 120 mm SMP	90 mm diamond
H1B1E0C0	12	x	x	-	90 mm diamond	-
H1B1E1C0C1	13	x	x	x	90 mm diamond	120 mm diamond
H1B1E1C0C2	14	x	x	x	90 mm diamond	90 mm + 120 mm SMP
H1B1E1C0C3	15	x	x	x	90 mm diamond	120 mm + 180 mm SMP

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Figure 1 Schematic drawing of the four independent trawl sections considered in this study.

Figure 2 Schematic drawings of the BRDs included in the study. **a)** Counter-herding device from Melli et al., 2018a; **b)** Large meshes in the upper netting of the trawl body from Krag et al., 2014; **c)** Horizontally divided trawl codend from Melli et al., 2018b; **d)** C0: 90 mm diamond codend from Krag et al., 2013; C1: 120 mm diamond codend from Krag et al., 2014; C2: 90 mm diamond codend with 120 mm SMP from Krag et al., 2013; C3: 120 mm diamond codend with 180 mm SMP from Krag et al., 2014.

Figure 3 Predicted selectivity curves (full lines) with 95% Efron CIs (ribbons) of six BRD combinations for the three species of interest. Lengths are in centimetres (total length) for fish species and millimetres (carapace length) for *Nephrops*.

Figure 4 Delta selectivity with 95% Efron CIs (solid lines with ribbons) of increasing numbers of BRDs combined, for *Nephrops* (red), cod (green) and haddock (blue). (a) Counter-herding device+90 mm diamond codend (1 BRD) with respect to a trawl with a simple 90 mm diamond codend; (b) Addition of a second codend (2 BRDs) with respect to the 1-BRD selectivity; (c) Addition of a large mesh size in the trawl body (3 BRDs) with respect to the previous 2-BRDs combination. Lengths are in centimetres (total length) for fish species and millimetres (carapace length) for *Nephrops*.

Figure 5 On the left column, cumulative catch curves with 95% Efron CIs (solid lines with ribbons) for the combination H1B0E1C0C1 under three population scenarios for (a) *Nephrops*, (b) cod and (c) haddock. The vertical dashed line indicates the MCRS for the species. On the right column, structure of the three population scenarios with 95% Efron CIs (solid lines with ribbons). Lengths are in centimetres (total length) for fish species and millimetres (carapace length) for *Nephrops*.

Figure 6 Two species comparisons of the performance of the most promising BRD combinations (15 for *Nephrops* and cod, and 10 for haddock) under the multispecies catch scenario. The numbers represents the ID of the combination as expressed in Table 4. On the left column, percentage (in weight) of undersized fish retained (wP^-). On the right column, percentage (in weight) of commercial-sized fish retained (wP^+). The first two rows show the percentage (in weight) of fish retained with respect to the percentage (in weight) of target catches (i.e. commercial-sized *Nephrops*). Dashed lines (vertical and horizontal) delineate 50% retention. Highlighted sections indicate desirable performances. MCRS = Minimum Conservation Reference Size.