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

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Abstract

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

Keywords

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

Introduction

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

Many devices have already been successful in reducing bycatch (Kelleher 2005). They typically exploit interspecific differences in terms of morphology and behaviour to improve selectivity inside and in front of the trawl (Glass 2000; Catchpole and Gray 2010). Examples which have improved selectivity inside the trawl include increased mesh sizes (e.g. Beutel et al. 2008; Frandsen et al. 2011), grids (Graham and Fryer 2006; Grimaldo et al. 2008), square mesh panels (e.g. Krag et al. 2008; Lomeli and Wakefield 2013), and species segregation into different compartments (e.g. Holst et al. 2009; Krag et al. 2009). Devices aiming at improving selectivity in front of the trawl typically do so by preventing certain species from entering the gear. For example, a raised footrope can reduce the catch of flatfish and juveniles of demersal fish (Hannah and Jones 2001; Krag et al. 2010); a topless gear allows the escape of roundfish species over the headline (He et al. 2007; Krag et al. 2015); and a modification of the sweeps interferes with the herding of fish towards the net mouth (Rose et al. 2010; Sistiaga et al. 2015). These devices have the advantage of minimizing fish interaction with the gear since they address the initial stimuli that cause fish capture in the first place. Therefore, they likely enhance species survival and fitness (Chopin and Arimoto 1995).

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

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

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

This study aimed to design and test the efficiency of a counter-herding device, FLEXSELECT, in reducing fish bycatch. We tested FLEXSELECT in the mixed trawl fishery targeting Norway lobster (*Nephrops norvegicus*), hereafter referred to as *Nephrops*. This fishery has a significant bycatch of both roundfish and flatfish. The fish bycatch involves economically important species but is usually of low quality due to its interaction with the crustaceans during the catching process (Karlsen et al. 2015) and can potentially choke the fishery once fish quotas are exhausted. In the frame of the landing obligation, fishermen need to reduce the fish fraction to be able to fully utilise *Nephrops* quotas. Furthermore, the small mesh sizes used lead to substantial quantities of undersized roundfish and flatfish being caught, thus leading to high proportions discarded (Kelleher 2005). Therefore, this fishery represents the perfect case study to investigate a counter-herding device. If effective, the advantages of FLEXSELECT are: i) a reduction of fish bycatch; ii) a reduction in the interaction of potential bycatch with the net, thus most likely enhancing its survival and fitness chances; and iii) the adaptation of the gear's selectivity to obtain the desired catch composition on a haul-by-haul basis. The efficiency of FLEXSELECT is expected to differ among species and sizes, thus the results concerning all relevant commercial species were examined length-based and discussed in relation to the different behavioural anti-predator strategies.

Materials and methods

FLEXSELECT design

The FLEXSELECT device consisted of four lines connected to a central metal ring (25 mm thick, 17 cm diameter, 3 kg), located at approximately 20 m ahead of the trawl mouth (Fig. 1). The two positioning lines (54 m) were made of mix wires (steel core and polypropylene cover, 6 strands, 14 mm in diameter, 0.21 kg/m). Two floats (115 g buoyancy) were attached at 2 and 5 m from the door/clump to prevent the long wires from twisting around the sweeps during the net deployment. The desired counter-herding effect was addressed with the two scaring lines (23.6 m) attached in front of the bridles. They consisted of thick ropes (polypropylene, 3 strands, 26 mm in diameter, 0.31 kg/m), meant to sweep the sea bottom and generate a sand cloud. Viking links and hammer locks (1.5 t lift, 0.7 kg), as well as swivels, were used to connect the FLEXSELECT lines to the gear components and to the central ring. These facilitated efficient coupling and decoupling of the FLEXSELECT lines to the gear. The challenge in designing FLEXSELECT was to make an efficient counter-herding stimulus without preventing the trawl from obtaining its intended geometry. It can be expected that heavier ropes would improve the herding efficiency as the interaction with the seafloor and sand cloud would be greater. However, a heavier device also increases the operational difficulties in terms of obtaining an optimal spread of the gear. Therefore, relative light materials were chosen.

Sea Trial

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

FLEXSELECT was mounted on one trawl while the other worked as a control. This setting assured that both trawls encountered similar species compositions and abundances over time. To prevent any systematic effect of the trawl position (side of the vessel) on the catch, the FLEXSELECT device was shifted from one trawl to the other approximately every sixth haul. The distance between the inner wingtip of the two trawls, about 50 m, was assumed sufficient to prevent overestimation of the control catch due to fish escaping from the FLEXSELECT device. The twin rig was spread with two Type 2 Thyborøn doors (1.78 m^2, 197 kg), with an additional weight of 25 kg to obtain a better spreading force, and a 400 kg triangular central clump. The trawls were rigged with 75 m long single wire sweeps with 4.3 cm (diameter) rubber cookies. The trawl doors and clump were equipped with distance sensors (Simrad PI), which continuously provided information about the spread of the two trawls during towing. Since only one trawl was equipped with the counter-herding device and thus potentially limited in its spread, the two values were constantly monitored during towing.

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

Statistical analyses

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

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

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

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

where STj and SCj are the averaged door-to-clump distances for the test and control trawls in haul j, respectively.

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

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

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

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

Results

During the sea trial, 30 hauls were conducted, of which 26 were valid and included in the statistical analyses (Table 1). Four hauls were excluded due to initial technical problems related to the gears spread, with the test trawl spreading significantly less than the control. This difference was probably caused by a partial twisting of the positioning lines around the sweeps and it was solved through the addition of floats to the positioning lines (see FLEXSELECT design). Of the 26 valid hauls, eight were carried out at night and 18 during daylight hours. The towing time varied from 30 to 135 min, and the depth from 33 to 87 m. The total catches of the control trawl varied between 90.5 and 1539 kg, while the catches in the experimental trawl ranged from 55 to 1145 kg. The mean difference in spread between the trawls was used to account for small differences in swept area by calculating a corrected baseline for no effect on the catch comparison rates and catch ratios. Trawl-spread values were not available for two hauls (25 and 26) due to a malfunctioning of the sensor on the central clump. However, the door spread was consistent with those obtained at similar depths thus the hauls were not excluded from the analyses.

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

Target species: *Nephrops*

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

Fish species

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

Roundfish

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

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

Flatfish

Similarly, the catch comparison curves for the two flatfish species analysed described the main trends in the data relatively well (Fig. 4). *p*–values for both species were above 0.5, indicating a good model representation of the data. The catch ratio curves show that lemon sole catches were significantly reduced for length classes which were well represented in the data, whereas only small plaice (below 35 cm) were significantly affected by FLEXSELECT (Fig. 4).

Day- and night-time comparison

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

Discussion

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

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

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

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

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

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

No diel differences were observed in FLEXSELECT’s effect, despite several studies having demonstrated that both roundfish (Walsh and Hickey 1993) and flatfish (Ryer and Barnett, 2006) do not respond with an ordinated herding when the light level is below species visual perception thresholds. Nevertheless, a lack of diel variation in FLEXSELECT’s efficiency is desirable, as *Nephrops* fisheries typically take place under different light levels, depending on the season and the area (Feekings et al. 2015).

On the basis of the results obtained, we conclude that FLEXSELECT represents an effective bycatch reduction measure, potentially adaptable to different fisheries. Contrary to most other selective devices, FLEXSELECT can be used on a haul-by-haul level, deciding its use on the basis of the catch composition. This flexibility allows both an occasional and a more permanent use. For example, FLEXSELECT can be used in specific periods or areas to avoid catching fish during the spawning seasons, to reduce catches when prices are low, or as an alternative to temporary area closures (Dunn et al. 2011). Moreover, the device can be deployed on a more permanent base to reduce fish catches in those fisheries in which these represent an undesirable catch. Among these, shrimp trawl fisheries could benefit from using FLEXSELECT, after its adaptation to the gear geometry, as it may not only reduce fish bycatch but also minimize its interaction with the net and the rest of the catch. Indeed, this “preventive” approach has recently gained interest to address bycatch in these fisheries (McHugh et al. 2017). Therefore, the applicability of FLEXSELECT is much wider than the *Nephrops*-directed mixed trawl fishery presented here and should be tested in other fisheries as well. Moreover, we believe the efficacy of FLEXSELECT could be optimized by modifying the intensity of the stimulus it produces, for example by using heavier components or by increasing their visibility. Nonetheless, before modifications can be introduced in the design, the mechanism through which FLEXSELECT works needs to be better understood. It is unclear from the results of this study if FLEXSELECT’s scaring lines stimulate fish to rise vertically in the water column and escape over the headline, or if they deviate their path to the wing tips. In the latter case, FLEXSELECT's effect could be increased by changing the position of the central ring, thus altering the angles created by the lines. The angle respect to the towing direction is indeed recognized as an important factor in determining herding (Winger et al. 2010) and thus, we expect also for counter-herding. Further studies are necessary to identify which species can be prevented from entering the trawl and which are more effectively released later inside the trawl. This study focused on the main commercial species in the case study fishery, as they are included in the landing obligation and thus represent a priority for the fishermen. However, FLEXSELECT's effect likely extends to other species which are commercially less relevant but may still be important in an ecosystem context.

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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

Table 2

Number of individuals and number of hauls per species included in the analyses, for the three analyses performed. Species that were subsampled are indicated with the actual number of individuals measured (in brackets) and the 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)

Table 3

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

	Pooled			Day-time			Night-time		
	p-value	Deviance	DoF	*p*-value	Deviance	DoF	*p*-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

Table 4

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

	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

Figure 1: FLEXSELECT design.

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.

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

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.

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

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.

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

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.

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

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.

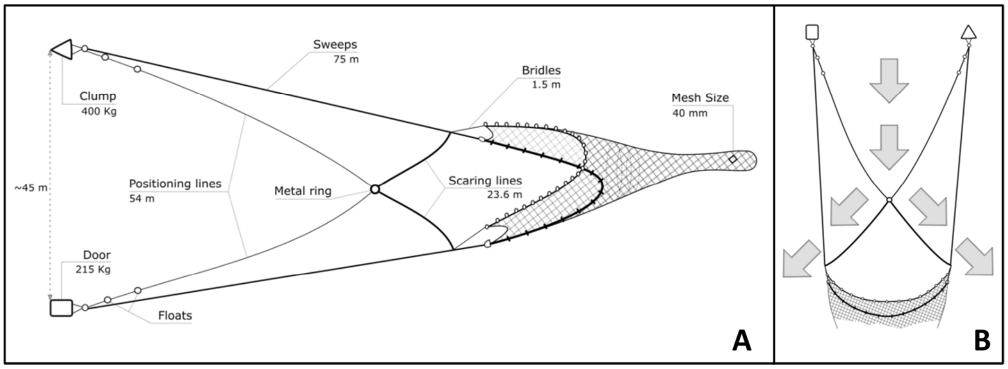

Figure 1. A) The port trawl in a twin-rig with FLEXSELECT mounted. Proportions are not respected to facilitate the identification of all FLEXSELECT components. B) Desired counter-herding effect. The grey arrows represent the direction of fish escape.

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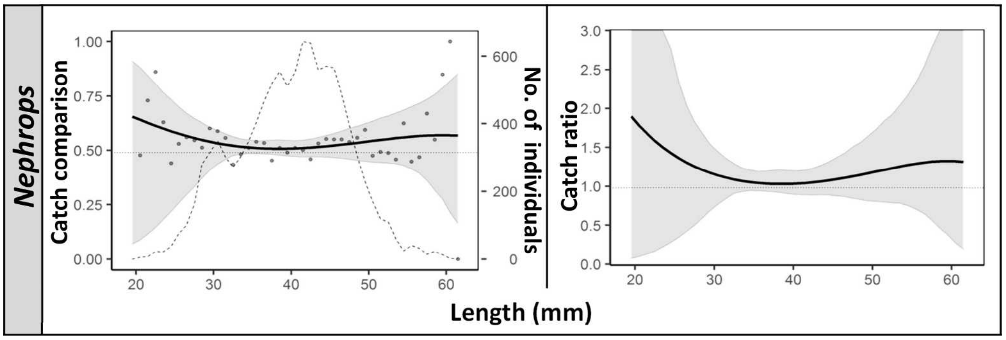

Figure 2. Catch comparison rates and catch ratios for Nephrops. On the left: the curve (solid line) represents the modeled catch efficiency fitted to the experimental points (dots). The grey band represents 95% confidence intervals and the dashed line the length distribution observed in the catch. The 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.

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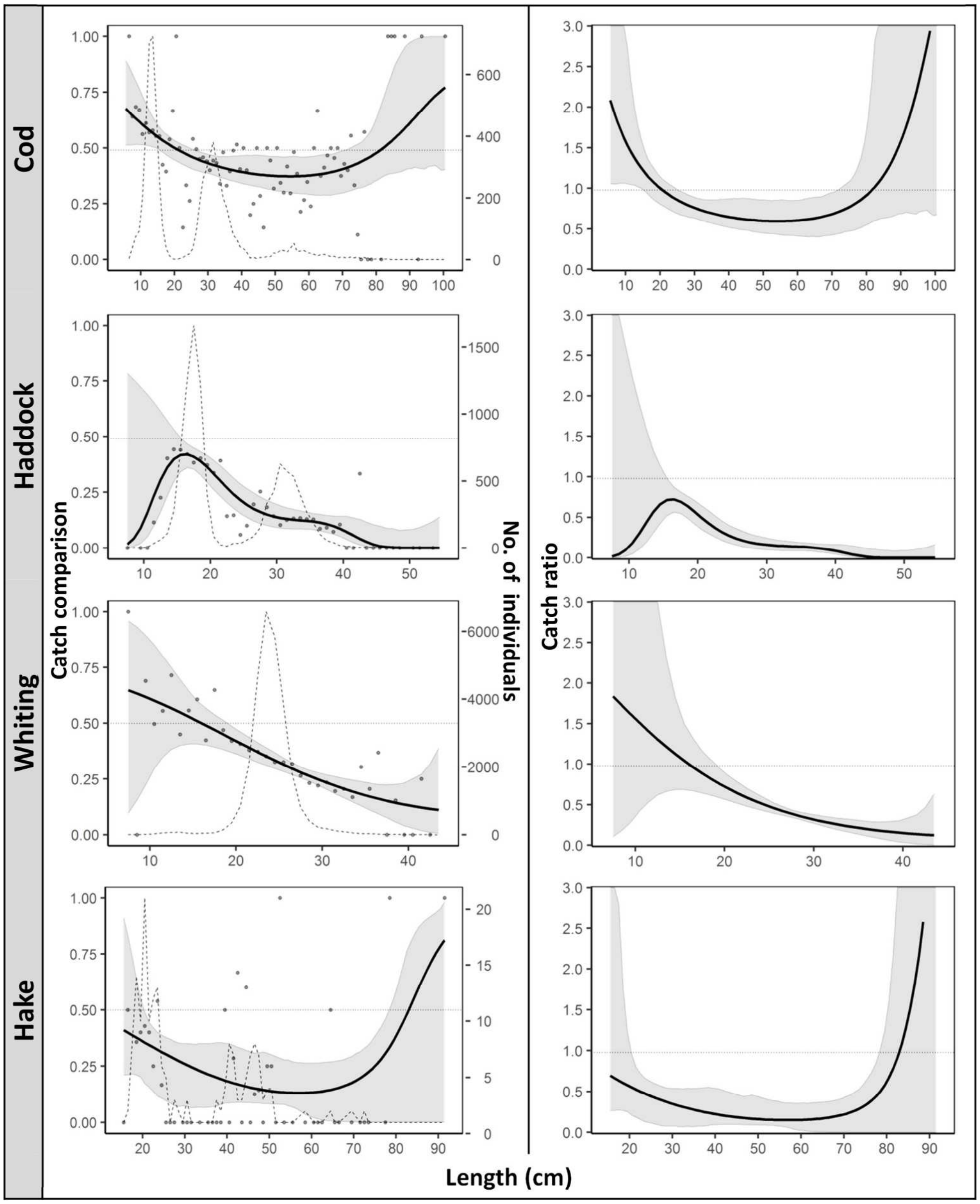

Figure 3. Catch comparison rates and catch ratios for the four roundfish species. On the left: catch comparison curves (solid lines) representing the modeled catch efficiencies fitted to the experimental points (dots). The grey bands show 95% confidence intervals and the dashed lines the length distributions 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.

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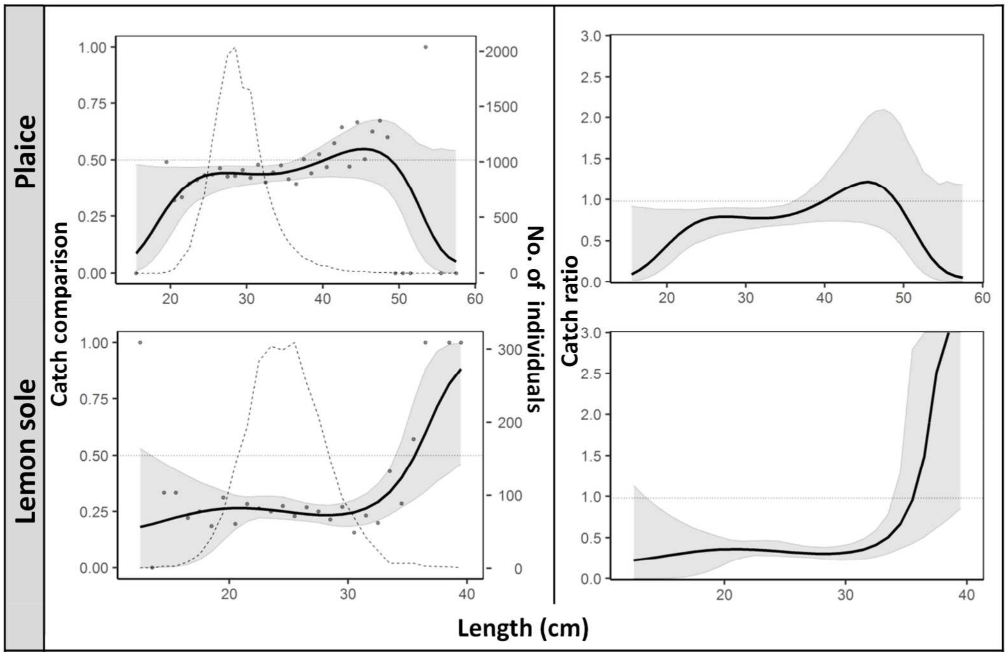

Figure 4. Catch comparison rates and catch ratios for the two flatfish species. On the left: catch comparison curves (solid lines) representing the modeled catch efficiencies fitted to the experimental points (dots). The grey bands show 95% confidence intervals and the dashed lines the length distributions 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.

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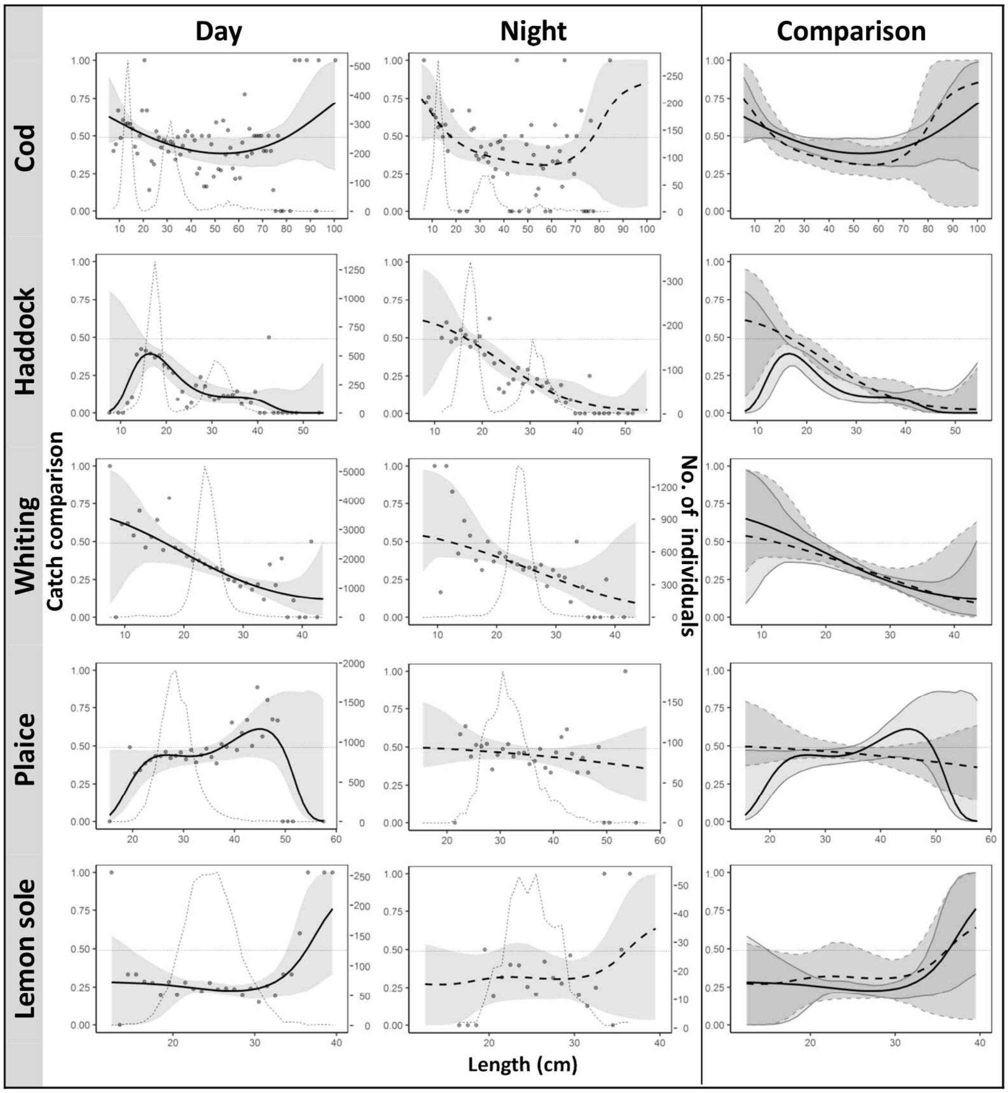

Figure 5. Catch comparison curves for day-time hauls (1st column), night-time hauls (2nd column) and overlap comparison (3rd column). The experimental points (dots) and catch distribution (dashed lines) per each group of hauls is reported. The modelled fits for day-time (bold full lines) and night-time (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)

Appendix 1

Estimation of the catch comparison curve

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

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

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

where the summation is over hauls *h*.

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

(2) $$g(\boldsymbol{v}) = -\sum_l \sum_{j=1}^{h}\left\{\left(\frac{nTU_{lj}}{qTU_j}+\frac{nTD_{lj}}{qTD_j}\right)\times \ln\left(cc(l,\boldsymbol{v})\right) + \left(\frac{nCU_{lj}}{qCU_j}+\frac{nCD_{lj}}{qCD_j}\right)\times \ln(1-cc(l,\boldsymbol{v}))\right\}$$

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

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

$$(3) \qquad cc(l,\boldsymbol{v}) = \frac{\exp(f(l,\boldsymbol{v}))}{1.0+\exp(f(l,\boldsymbol{v}))}$$

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

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

Leaving out one or more of the parameters $v_0 \dots v_4$ in equation (4) provided 31 additional models that were considered as potential models to describe *cc*(*l*,***v***). Model averaging, ranking the models according to how likely they were compared to each other (Burnham and Anderson, 2002), was then applied to describe *cc*(*l*,***v***). To obtain a combined model, the individual models were ranked and weighted according to their Akaike's Information Criterion (AIC) values (Akaike 1974; Burnham and Anderson 2002; Herrmann et al. 2017). Models with AIC values within +10 the value of the model with the lowest AIC, were considered to contribute to *cc*(*l*,***v***) (Katsanevakis 2006; Herrmann et al. 2017). One advantage of using this combined model approach is that we avoid having to choose one specific model among the different candidates. The ability of the combined model to describe the experimental data was assessed based on the *p*-value, which expresses the likelihood for obtaining at least as large a discrepancy as that observed between the fitted model and the experimental data, by coincidence. Therefore, for the combined model to be a candidate model, the *p*-value should not be < 0.05 (Wileman et al. 1996). In cases with poor fit statistics (p-value < 0.05; deviance >> degrees of freedom), the deviations between the experimental observed points and the fitted curve were examined to determine whether this was caused by structural problems in describing the experimental data or due to data overdispersion.

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

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

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

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

Estimation of the catch ratio curve

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

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

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

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

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

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

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

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

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

Using equation (8) and incorporating the calculation of *cr(l,**v**)* for each relevant length class into the double bootstrap procedure describedabove, we estimated the confidence limits for the catch ratio.

Estimation of length-integrated catch ratio

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

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

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

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