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Published in:
Fisheries Research

Link to article, DOI:
10.1016/j.fishres.2020.105686

Publication date:
2020

Document Version
Peer reviewed version

Does the efficiency of a counter-herding device depend on seabed contact?

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Abstract

To prevent unwanted fish bycatch from entering the trawl, we modified a counter-herding device, FLEXSELECT, developed for a Northeast Atlantic *Nephrops* (*Nephrops norvegicus*) trawl fishery. FLEXSELECT, which was designed to direct fish away from the trawl by means of sweeping ropes in the herding area, has been shown to be highly effective on both roundfish and flatfish species. However, by adding sweeping elements we could be increasing the benthic impact of trawling. Therefore, in this study we investigated if the effect of FLEXSELECT can be maintained when raising the ropes off the seabed. A reduction in fish bycatch could still be achieved, but the effect of FLEXSELECT$_{raised}$ with respect to the previous design was significantly different for four of the seven species analysed. While for some species the effect was lower, it substantially increased for cod (*Gadus morhua*), making it highly relevant for the *Nephrops* fisheries, as well as for other fisheries in needs of avoiding cod catches. The results offer insights regarding species behavioural responses to FLEXSELECT$_{raised}$, to be used for future developments of counter-herding devices in commercial fisheries without the addition of seabed impact to the baseline gears.

Keywords

Anterior gear modification, counter-herding, fish behaviour, *Nephrops* fishery, cod reduction

Introduction

The efficiency of trawl gears in capturing fish depends strongly on how well they harness their behavioural responses. Indeed, the anterior spreading components of the trawl (i.e. doors and sweeps) generate a strong disturbance on the seabed and fish's avoidance of these components can lead them towards the trawl mouth ("herding"; reviewed in Winger et al. 2010). For example, demersal roundfish such as cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) were observed to respond to an approaching trawl by moving closer to the seabed and swimming away from the trawl doors and sweeps while keeping them at the edge of their visual field (Pitcher 1993; Wardle 1993). This behaviour brings individuals laying between the trawl doors to swim into the path of the trawl ("fountain manoeuvre"; reviewed by Winger et al. 2010). Timing and direction of the herding response vary among species, as they depend on the species-specific, anti-predator strategy (Fernö and Huse 2003). For example, roundfish tend to react early and swim away from the approaching threat, while benthic fish such as flatfish and monkfish (*Lophius* spp.), which use camouflage as an anti-predator strategy, tend to keep their position until direct or near contact with the gear components (Main and Sangster 1981; Ryer et al. 2010). Consequently, for benthic fish, herding occurs only if fish are stimulated mechanically using lengthy sweeps that provide sufficient time for the fish to swim into the trawl path (Winger et al. 2004; Ryer et al. 2010). Furthermore, herding can vary within species depending on the swimming capacity and endurance of the individuals, which differs according to size (Beamish 1966; He 1991; Videler 1993; Winger et al. 1999). To avoid being overtaken by the sweeps and, thus, reach the trawl path, fish must swim at a speed equal to or greater than the herding speed of the sweeps (Winger et al. 2010). This herding speed is determined by the forward towing speed of the trawl and the sweep angle (i.e. angle of attack of the sweep to the direction of tow). Because of their higher endurance and swimming capacity, larger individuals are more likely to sustain the herding speed and enter the trawl path, thus being exposed to capture (He 1993).

Underwater observations of bottom trawls and fish responses to the anterior gear components have helped to understand the stimuli that cause herding. An approaching trawl produces a number of stimuli, both visual, auditory and mechanical (i.e. vibrations; Winger et al. 2010). Even though many fish can detect sound, and herding responses have been described at light level below the threshold for visual perception (Engås and Ona 1990), it is believed that vision is the main sense in use when fish react in an ordered manner (Glass and Wardle 1989). When the ambient light level is sufficient, the trawl doors are the first conspicuous part of the trawl system sensed by the fish visually as the gear approaches (Korotkov 1984; Wardle 1986). They generate sediment clouds on their path which the fish keep avoiding even after the passage of the door (Main and Sangster 1981; Wardle 1983). It has been documented that the more the sediment cloud produced by the doors aligns with the sweeps, the stronger the herding response is (Korotkov 1984; Dickson 1993). Thus, the length and angle of the sweeps has been optimized to enhance their visual perception by exploiting the sediment cloud, as well as by providing sufficient time for the individuals to reach the trawl path (Strange 1984; Engås and Godø 1989). Furthermore, recent studies have proved that bottom contact of the sweeps is an important factor in the herding of roundfish, as attempts to rise the sweeps off the seabed have led to significant losses of cod and haddock catches (Sistiaga et al. 2015, 2016).

With the growing need to improve the selectivity of towed gears, the wealth of knowledge regarding fish herding has been recently applied to reduce the catch of fish, rather than increasing it, in fisheries where fish species represent an unwanted bycatch (e.g. due to lack of quota availability; Feekings et al. 2012; EU 2013). For example, additional elements, such as ropes and plastic banners, have been added to the forward part of the trawl to scare and/or direct fish away from the trawl path (McHugh et al. 2015; Melli et al. 2018, 2019a). These anterior modifications have the advantage of preventing unwanted catches from going through the catch process, thus likely enhancing their survival (Winger et al. 2010; McHugh et al. 2017). In particular, Melli et al. (2018) tested for the first time the concept of a counter-herding device, which exploits the same stimuli that cause herding but direct them outside the trawl path. This counter-herding device, FLEXSELECT, which consisted of sweeping ropes placed in front of the trawl mouth, substantially reduced the catch of all the main commercial fish bycatch species, both roundfish and flatfish, in a *Nephrops* (*Nephrops norvegicus*) directed trawl fishery. The effect was found to be size-dependent for both roundfish and flatfish species, a result consistent with the knowledge on herding mechanisms, but also to vary substantially between species with supposed similar anti-predator behaviours (e.g. plaice, *Pleuronectes platessa*, and lemon sole, *Microstomus kitt*; Melli et al. 2018). Moreover, the effect was observed during both day- and nigh-time fishing, suggesting that the behavioural response triggered by FLEXSELECT was not only vision-dependent, but perhaps resulted also from the vibrations and sounds produced by the physical interaction of the device with the seabed (Melli et al. 2018).

Although reducing bycatch is one of the main challenges in improving the sustainability of trawl fisheries, so is the reduction of their seabed impact, especially of that deriving from the interaction of the anterior gear components with the seabed (Jones 1992; Løkkeborg 2005; Valdemarsen et al. 2007). Consequently, the addition of elements sweeping the seabed (such as a counter-herding device) should be considered critically, and floating alternatives need to be tested. Indeed, it has been hypothesised by Ryer (2008) that a floating counter-herding device would maintain its efficiency in reducing roundfish catches while not affecting those of flatfish and benthic species. Because there are fisheries where a reduction of roundfish species alone could be desirable, in this study we investigated the effect of raising the counter-herding device FLEXSELECT off the seabed.

Materials and Methods

Modification of FLEXSELECT design

The design of the originally tested FLEXSELECT (Melli et al. 2018), hereafter referred to as $\mathrm{FLEXSELECT}_{\mathrm{sweep}}$, was modified to raise the scaring lines off the seabed. The new device, termed $\mathrm{FLEXSELECT}_{\mathrm{raised}}$, was composed of the identical components as in $\mathrm{FLEXSELECT}_{\mathrm{sweep}}$: two positioning lines (54 m long, steel core and polypropylene cover, 6 strands, 14 mm in diameter, 0.21 kg/m) with two floats (115 g buoyancy) attached at 2 and 5 m behind the door/clump to prevent them from twisting around the sweeps; and two scaring lines (23.6 m long, polypropylene, 3 strands, 26 mm in diameter, 0.31 kg/m). Because the scaring lines already had neutral buoyancy in sea water, the raising effect was achieved by substituting the central metal ring (25 mm thick, 17 cm diameter, 3 kg) with a metal sledge (85L x 50W x 40H cm, 37 kg, stainless steel; Fig. 1) with 10 floats (8 x 850 gr lift, 2 x 8610 gr lift) attached on its upper side to facilitate the deployment and prevent it from digging into the seabed. Although from a commercial prospective, a metal sledge does not represent the easiest solution to raise the scaring lines off the seabed, we adopted such solution to use the central point of the device as an observation platform, equipped with GoPro cameras (Hero 3) and powerful narrow-beam LED lights (Big Blue TL4500P, 4500 lumen, 10° beam). The purpose of the observation platform was, firstly, to verify the suspension of the scaring lines above the seabed and their stability during towing, and, secondly, to observe fish response to the lines and understand the behavioural mechanisms involved in the effect of FLEXSELECT. The observation platform was equipped with two cameras aimed backwards (with respect to the towing direction) at each of the scaring lines (Fig. 1B). The two LED lights were placed approximately 15 cm below the GoPro cameras in the attempt of illuminating the 23.6 m long scaring lines. 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 observation platform.

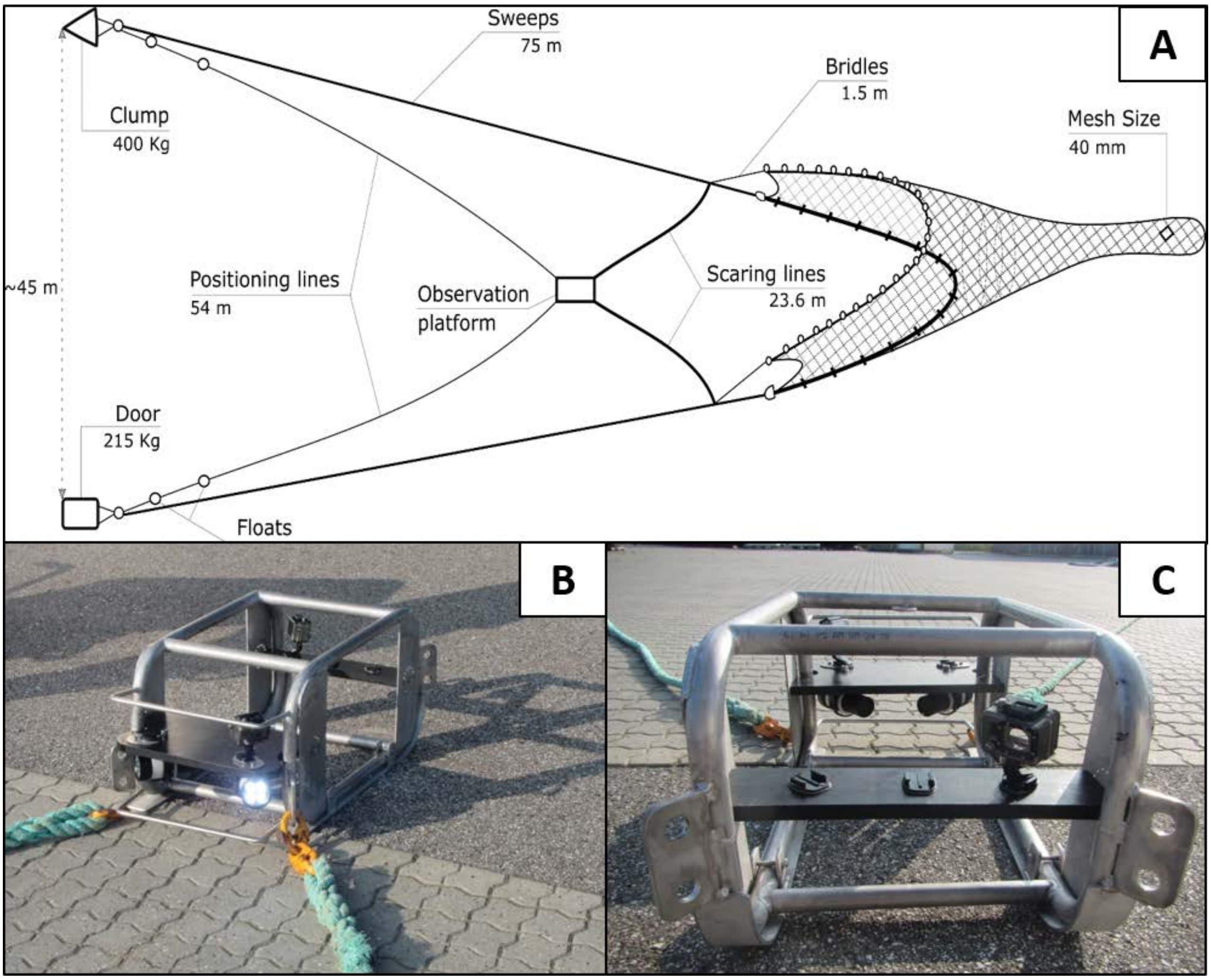

Figure 1. A) The port side trawl in a twin-rig system with $FLEXSELECT_{raised}$ (adapted from Melli et al. 2018). Proportions are not respected to facilitate the identification of all components; B) observation platform (back view) with scaring lines; C) observation platform (front view). During the experimental trials floats were attached to the top of the observation platform.

Experimental trial

The experimental trial was conducted on board the research vessel "Havfisken" (17 m, 373 kW), between August 31st and September 8th 2017. The vessel was equipped for three-wire, twin-trawling, with two identical Combi trawls (40 m long footrope, 420 meshes circumference at the trawl mouth, 80 mm mesh size; see Appendix A for technical drawing) towed in parallel. The twin-rig was spread with two Type 2 Thyborøn doors (1.78 m^2, 197 kg) and a 400 kg triangular chain central clump. The trawl doors and clump were equipped with distance sensors (Simrad PI), providing the spread of the two trawls during towing. The trawls were rigged with 75 m long, single wire sweeps with 4.3 cm (diameter) rubber cookies. The trawls were equipped with small mesh codends constructed from the same weave of netting (41.7±1.3 mm square mesh, 50 meshes measured on dry netting with Omega Mesh Gauge). The only difference between the two trawls was that $FLEXSELECT_{raised}$ was mounted on one of them, while the other trawl worked as a baseline. To prevent any systematic effect of the $FLEXSELECT_{raised}$ position in the twin-rig system on the catch, the device was shifted from one trawl to the other approximately every sixth haul. Fishing was conducted on commercial fishing grounds in Kattegat and Skagerrak (ICES Division 3.a; 57°50ˈN 10°58ˈE; in an area of approximately 120 square nautical miles) at depths between 33 m and 87 m. Hauls were performed during daytime, i.e. between one hour after sunrise and one hour before sunset. The total catch of each trawl was emptied into a sea-stabilized weighting tank, the total weight was recorded and the catch was then sorted by species. The total length (TL) of all commercial fish species and the carapace length (CL) of *Nephrops* were measured and rounded down to the nearest centimetre and millimetre, respectively.

We conducted two separate experiments, one where the observation platform was equipped with LED lights and one where it was not. Indeed, although artificial illumination was required for collecting video footage due to the limited ambient light at the fishing depth and high turbidity in the fishing area (Aarup et al. 1996), artificial lights could alter fish behavioural responses (reviewed by Nguyen and Winger 2019) and, thus, the efficiency of $FLEXSELECT_{raised}$. For this reason, the effect of $FLEXSELECT_{raised}$ was first modelled separately for each experiment, and only when no significant difference was detected, were data pooled together.

Statistical analyses

To identify any species- or size-specific differences between floating and sweeping scaring lines, we conducted the analyses in three steps. First, we estimated the length-dependent relative catch efficiency of the trawl with $\text{FLEXSELECT}_{\text{raised}}$, with and without LED lights, with respect to the baseline trawl. Second, in the absence of significant differences caused by the LED lights, we conducted an overall analysis including all hauls. Third, we indirectly assessed the difference in length-dependent relative catch efficiency of the trawl with the $\text{FLEXSELECT}_{\text{raised}}$ and with the $\text{FLEXSELECT}_{\text{sweep}}$ (Melli et al. 2018) by estimating the ratio between the catch ratio curves obtained from the two trials (Veiga-Malta et al. 2019). This final step was only possible because the gear used as baseline in this study was identical to that used in Melli et al. (2018).

To estimate the effect of $\text{FLEXSELECT}_{\text{raised}}$, with and without LED lights, as well as overall, we used length-based count data of each species in each trawl 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 in the catching process due to within- and between-haul variation (Millar 1993). For each species, only hauls with 10 or more individuals were included in the analysis following Krag et al. (2014). 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 B.

To quantify the differences in catch between the test and baseline trawls, we calculated catch ratios (cr) and 95% Efron confidence intervals from the relationship between cr(l) and cc(l) (Herrmann et al. 2017):

(1) $$cr(l) = \frac{cc(l)}{1.0 - cc(l)}$$

The advantage of using the catch ratio is that if the catch efficiency of both trawls is equal, i.e. no effect of the FLEXSELECT device, the $cr(l)$ would be 1.0. A $cr(l)$ = 1.25 would mean that the test trawl catches on average 25% more individuals of length l than the baseline trawl. In contrast, a $cr(l)$ = 0.75 would mean that the test trawl catches 25% less individuals of length l than the baseline trawl.

To investigate if and to which extent raising the scaring lines off the seabed affected the efficiency of FLEXSELECT, we estimated the ratio between the catch ratio curves estimated for $FLEXSELECT_{raised}$ and $FLEXSELECT_{sweep}$:

(2) $$cr(l)_{raised/sweep} = \frac{cr(l)_{raised}}{cr(l)_{sweep}}$$

where $cr(l)_{raised}$ quantifies the effect on the catch of $FLEXSELECT_{raised}$, and $cr(l)_{sweep}$ that of $FLEXSELECT_{sweep}$ (Melli et al. 2018), both in respect to the same baseline gear. The 95% Efron CIs for $cr(l)_{raised/sweep}$ were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) from each catch ratio model estimated for either FLEXSELECT design. Since both bootstrap populations were obtained independently, a new population of results with 1000 bootstrap iterations was created for $cr(l)_{raised/sweep}$ following (Herrmann et al. 2018):

(3) $$cr(l)_{raised/sweep} = \frac{cr(l)_{raised\,i}}{cr(l)_{sweep\,i}} \quad i \in [1 \dots 1000]$$

where *i* represents the bootstrap repetition index.

Results

A total of 24 hauls were conducted, of which 21 were included in the analysis (Table 1). The three hauls excluded had large marine litter (e.g. netting, cable) twisted around the scaring lines or entangled with the observation platform and were, thus, not included in the analysis as a precaution. No significant difference was found between the test and baseline trawls in terms of average spread (t-test on paired data; $t(20)=2.09$; $p=0.05$), contrary to what was observed with the $FLEXSELECT_{sweep}$ (Melli et al. 2018). Of the 21 valid hauls, 11 were carried out with LED lights on the observation platform, and 10 without.

The effect of the $FLEXSELECT_{raised}$ was quantified for seven commercial species: the target species, *Nephrops*; four roundfish species, cod, haddock, whiting and hake (*Merluccius merluccius*); and two flatfish species, lemon sole (*Microstomus kitt*) and plaice (*Pleuronectes platessa*). No significant difference between hauls with and without LED lights was detected (see Supplementary Material).

Underwater observations

Approximately 10 hours of video footage collected during the hauls with LED lights were of sufficient quality to allow qualitative observations of the scaring lines and fish behavioural responses. As expected, the scaring lines suspended above the seabed, approximately 20-30 cm (estimated from recognizable benthic organisms such as *Pennatulacea* spp.). However, despite the powerful LED lights used, only the first 2 out of the 23.6 m of the scaring lines were visible (Fig. 2A). Therefore, it is not possible to conclude that the entire lines were raised off the seabed. Nonetheless, no oscillation in the visible part of the scaring lines was observed in the footage, and considering the neutral buoyance of the ropes, we expect most of the lines to have been off the seabed.

A total of 1586 fish were observed with sufficient clarity to assess the presence or absence of a response to the scaring lines. Most observations consisted of roundfish or Atlantic hagfish, *Myxine glutinosa*, while very few flatfish could be identified (n=13). Of the individuals observed, 817 showed a clear change in swimming speed or direction while in the field of view (recorded as "presence of response") and 760 appeared to hold their position (recorded as "absence of response"). Individuals that were already swimming when entering the field of view and did not alter their swimming speed or direction were excluded. Few individuals (n=9) were observed physically interacting with the scaring lines (i.e. were hit by the line before swimming away; Fig 2B). Considering the limited view of the scaring lines in the footage, we chose not to further categorize the responses observed. Indeed, the part of scaring lines visible in the footage (i.e. the first meters close to the observation platform) was oriented almost in parallel to the towing direction while the angle would gradually increase while approaching the bridles; therefore, the orientation of fish response may vary at different points of the scaring lines. In the section of the scaring lines observed, responses were oriented in multiple directions (see Appendix C for screenshots illustrating the most common directions observed) and no clear pattern was noticed.

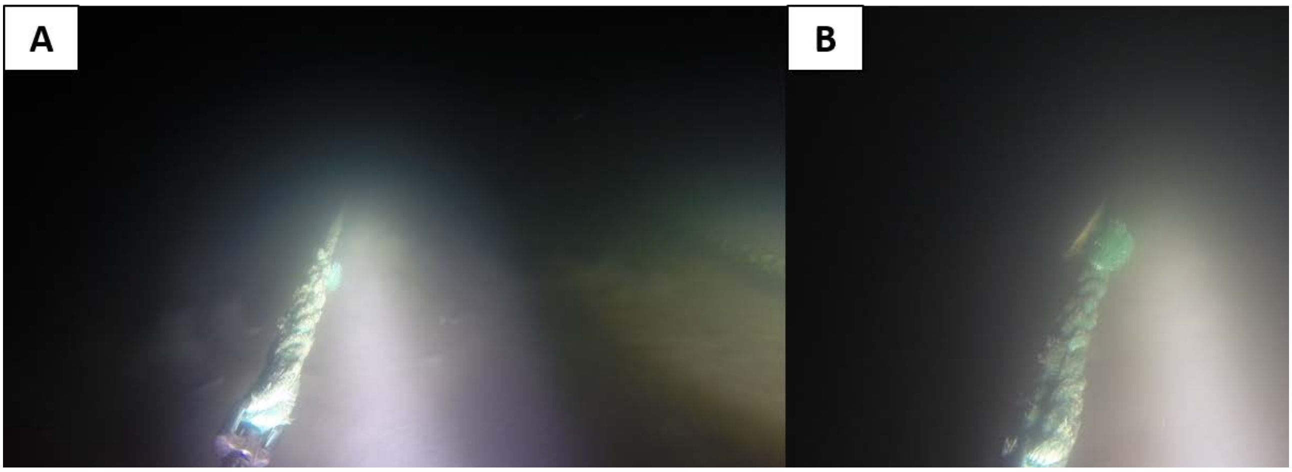

Figure 2. Screenshots from the underwater video footage collected with the observation platform equipped with LED lights. A) Visible part of the scaring lines; B) Fish entering in contact with one of the scaring lines.

FLEXSELECT$_{raised}$ effect on *Nephrops* catches

The model estimated for *Nephrops* on the pooled data of all the valid hauls (Table 2) described well the main trend in the data (Fig. 3). For length classes where fewer individuals were caught, in particular above 55 mm CL, increased dispersion is observed in the experimental data and well-reflected by the increasing width of the 95% Efron CIs (Fig. 3). The model fit provided a *p*-value < 0.05 (Table 3), indicating potential problems with the model in describing the experimental data. However, after inspection of the residuals, which did not show any structure in the deviations between the data and the modelled curve, we concluded that the low *p*-value is due to over-dispersion in the data (Wileman et al. 1996), a result frequently obtained for subsampled species (e.g. Melli et al. 2018, 2019b). We were, therefore, confident that the combined model represent well the experimental data.

The catch ratio between the FLEXSELECT$_{raised}$ and baseline trawls showed a significant loss of *Nephrops*, both below and above the Minimum Conservation Reference Size (MCRS) of 32 mm CL, as the confidence intervals did not overlap the baseline for equal catch (1.0), for length classes between 24 and 45 mm CL (Fig. 3).

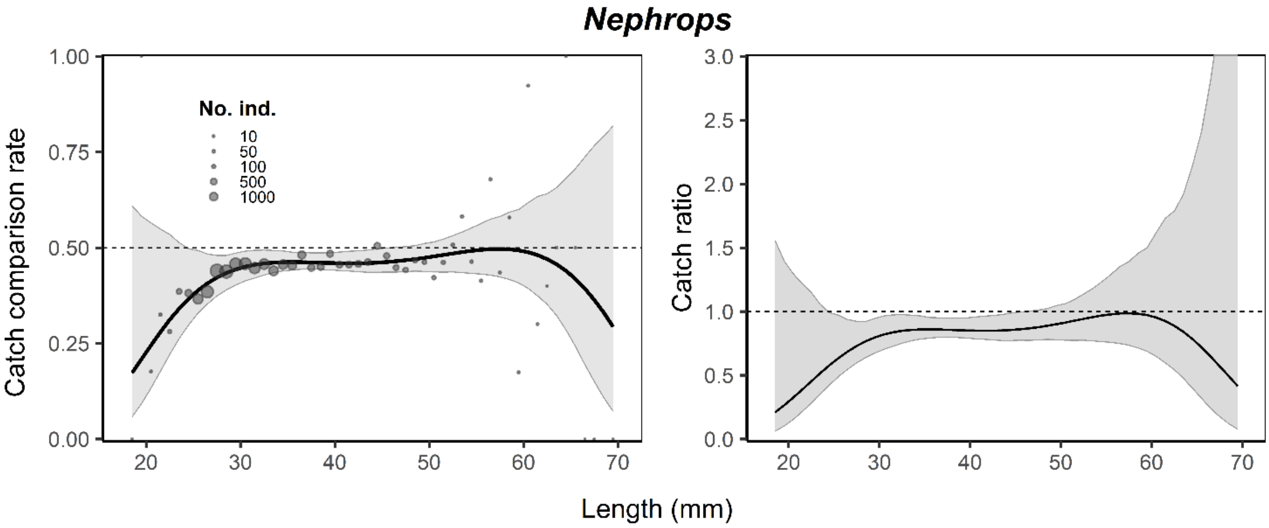

Figure 3. Catch comparison rates and catch ratios for the target species *Nephrops*. The curve (solid line) represents the combined model fitted to the experimental points (dots). The size of the dots is relative to the total number of individuals of that length class caught in either trawl. The grey ribbon represents 95% Efron Confidence Intervals. The dashed horizontal line describes equivalence in catch between the two trawls.

FLEXSELECT$_{raised}$ effect on fish catches

The models estimated for the six fish species analysed on the pooled data of all the valid hauls (Table 2) described well the main trends in the data, without systematic deviations between the experimental points and the modelled catch comparison curves (Fig. 4 and 5). The model fits for cod and whiting provided *p*-values < 0.05, indicating potential problems with the model in describing the experimental data (Table 3). This outcome has been frequently observed for cod (e.g. Krag et al. 2015; Melli et al. 2018) and for species subsampled, such as whiting (Melli et al. 2018, 2019b). The residual deviations between the data and the modelled curves were carefully investigated for each species but no systematic structure was detected. Thus, we attributed the poor fit-statistics of these cases to over-dispersion in the data and trusted the models to represent sufficiently well the experimental data (Wileman et al., 1996).

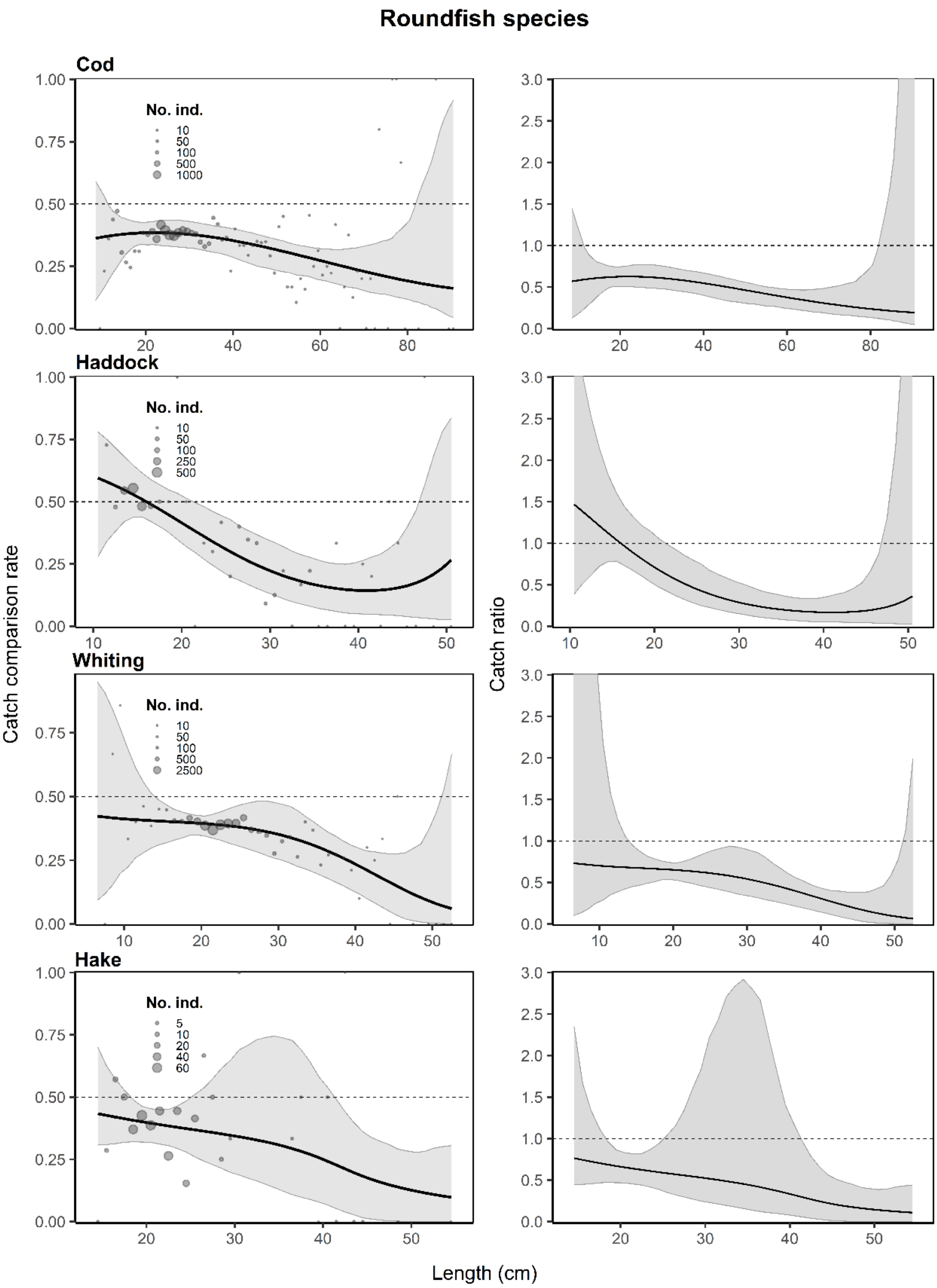

Figure 4. Catch comparison rates and catch ratios for the four roundfish species analysed. The curve (solid line) represents the combined model fitted to the experimental points (dots). The size of the dots is relative to the total number of individuals of that length class caught in either trawl. The grey ribbon represents 95% Efron Confidence Intervals. The dashed horizontal line describes equivalence in catch between the two trawls.

The catch ratio curves showed a significant reduction in the catches of the test trawl with FLEXSELECT$_{raised}$ for all the commercial fish species analysed (Fig. 4 and 5). Specifically, the catches of cod, haddock and whiting were substantially reduced at lengths between 11–81, 21–46 and 14–50 cm, respectively. Few hake were caught during the experiment, as reflected by the wider CIs (Fig. 4). Nonetheless, a significant reduction was detected for lengths between 18–24 and 41–55 cm. All roundfish species showed a length-dependent effect of FLEXSELECT$_{raised}$, with a stronger reduction of larger individuals rather than smaller individuals (Fig. 4). In contrast, for the two flatfish species, the significant reduction in catch was limited to smaller individuals, between 15–31 cm and 10–29 cm for plaice and lemon sole, respectively (Fig. 5).

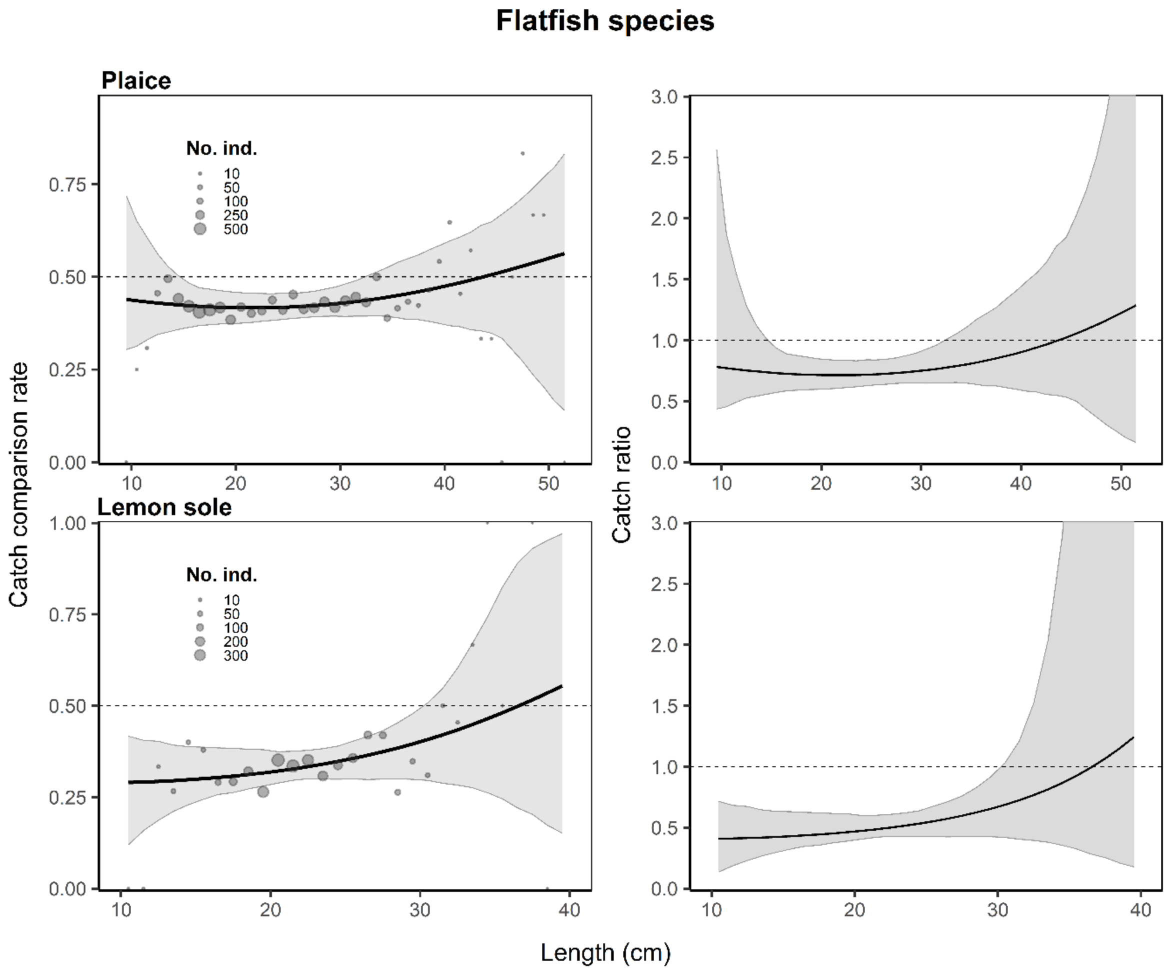

Figure 5. Catch comparison rates and catch ratios for the two flatfish species analysed. The curve (solid line) represents the combined model fitted to the experimental points (dots). The size of the dots is relative to the total number of individuals of that length class caught in either trawl. The grey ribbon represents 95% Efron Confidence Intervals. The dashed horizontal line describes equivalence in catch between the two trawls.

$\text{FLEXSELECT}_{raised}$ vs $\text{FLEXSELECT}_{sweep}$

When compared to the effect of $\text{FLEXSELECT}_{sweep}$, $\text{FLEXSELECT}_{raised}$ had a significantly different effect on four of the seven species analysed (Fig. 6). In particular, the ratio of catch ratios showed that significantly less *Nephrops* (32–41 mm CL) and cod (10–25 and 52–80 cm), and significantly more whiting (28–36 cm) and lemon sole (21–31 cm) were caught using floating scaring lines. Therefore, in terms of efficiency as a bycatch reduction device, $\text{FLEXSELECT}_{raised}$ was significantly more effective at reducing the capture of cod. However, it was less effective on whiting and lemon sole and caused a loss of commercial target catch of *Nephrops*. No significant effects were found for haddock, hake and plaice.

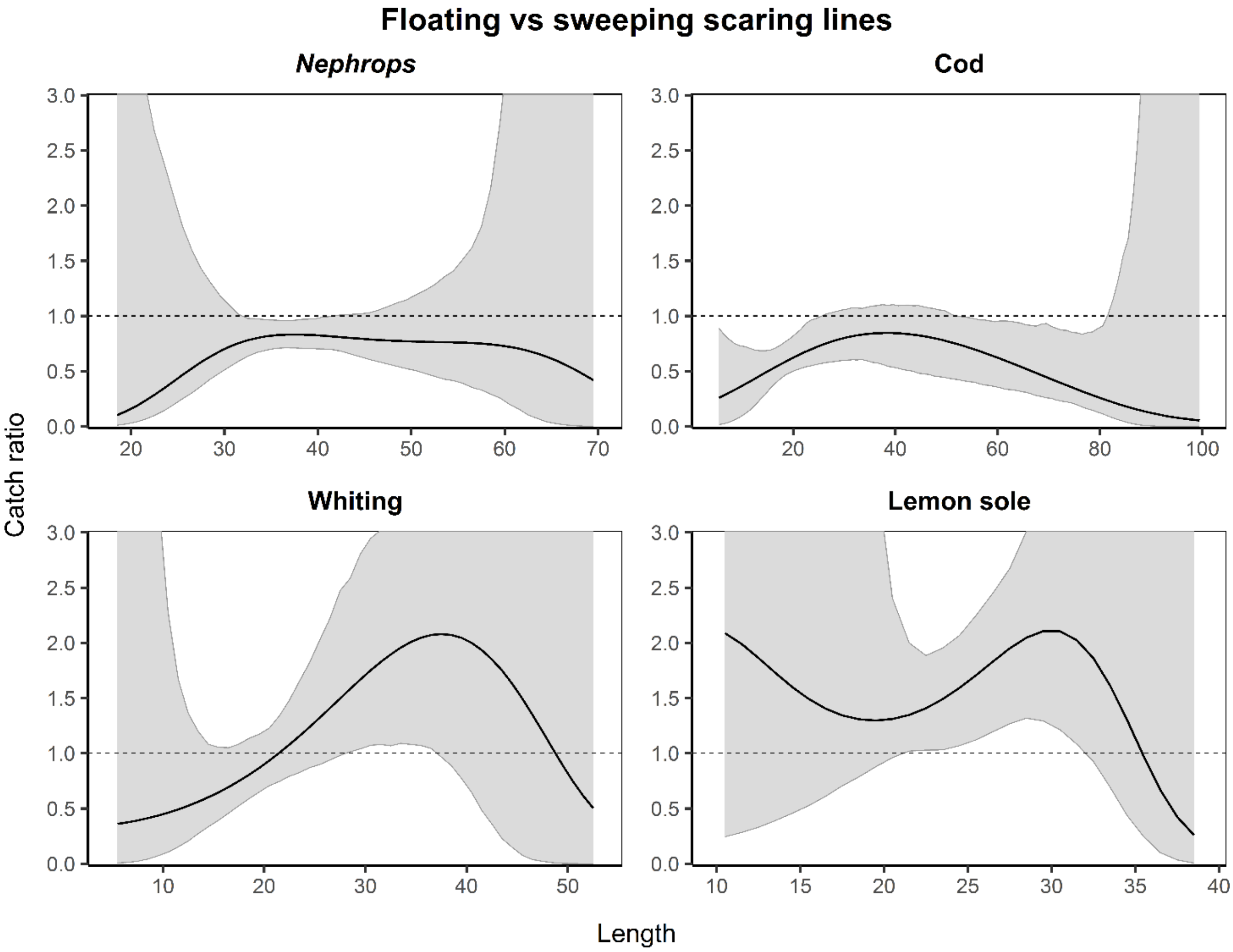

Figure 6. Comparison of $\text{FLEXSELECT}_{raised}$ and $\text{FLEXSELECT}_{sweep}$ (Melli et al., 2018). The curve (solid line) represents the modelled ratio of catch ratio curves from the two individual experiments. The grey ribbon represents 95% Efron Confidence Intervals estimated from the two bootstrap sets from each catch ratio model estimated for either FLEXSELECT design. The dashed horizontal line, located at 1.0, describes equivalence in efficiency between the FLEXSELECT designs.

Discussion

In this study, we verified that the effect of the counter-herding device FLEXSELECT could be maintained while reducing its interaction with the seabed. Even though from video observations it was impossible to confirm that the entire length of the scaring lines was suspended above the seabed, the catch comparison analyses showed significant changes in performance of $FLEXSELECT_{raised}$ with respect to $FLEXSELECT_{sweep}$ for four out of seven species considered, supporting the conclusion that most of the lines were successfully raisedThe scaring lines appeared to be stable at a height of approximately 20-30 cm, and no sediment cloud was observed generating from the lines. The results showed that, despite being raised off the seabed, the scaring lines were significantly effective in reducing the catch of fish bycatch with respect to the baseline trawl. Contrary to expectations, the raised scaring lines were still effective on both flatfish species and not only on the roundfish ones (Ryer 2008). However, species-specific differences in the strength of the effect were found for cod, whiting, lemon sole and *Nephrops*, with respect to the configuration with sweeping lines (Melli et al. 2018). Notably, in Melli et al. (2018) major differences in effect were identified between species that have been described to have similar responses to the approaching gear (e.g. cod and whiting; Winger et al., 2010); in contrast, the effect of $FLEXSELECT_{raised}$ in this study was found to be more consistent within fish group, as the modelled curves were remarkably similar among the four roundfish (Fig. 4) and between the two flatfish (Fig. 5) species. This may indicate that raising the lines off the seabed removes some of the factors leading to differential behavioural responses in species with similar anti-predator strategies.

The strongest difference in performance between FLEXSELECT configurations was observed for cod, whose reduction was substantially higher when using $FLEXSELECT_{raised}$. In Melli et al. (2018), the effect of $FLEXSELECT_{sweep}$ on cod was modest, in comparison to the other roundfish species, and strongly length-dependent, with a significant reduction of catches between 25 and 71 cm, but an increase in catches of individuals below 14 cm. In the present study, the reduction in cod catches was the highest among all the species analysed, and the effect was significant for most of the length range represented in the data (11–81 cm). Moreover, no significant increase in catches of small cod was observed, a result consistent with the hypothesis formulated by Melli et al. (2018) that small cod were mechanically raised off the seabed by the sweeping scaring lines, leaving them exposed to capture. By raising the lines off the seabed, this effect was avoided, and small cod appeared to be able to react to the scaring lines, although to a lower extent than larger individuals likely due to constraints in swimming capacity (Winger et al. 2000). The efficiency of $FLEXSELECT_{raised}$ in reducing cod catches is of substantial interest for the *Nephrops*-directed mixed trawl fishery in the Kattegat and Skagerrak, where cod can represent a choke species (North Sea Advisory Council 2018). Nonetheless, it is also pertinent for any other fishery where catches of cod need to be avoided due to stock recovery plans (Hutchings and Rangeley 2011; Kraak et al. 2013). In these fisheries, a device such as $FLEXSELECT_{raised}$ could be added to the trawl when encountering high abundances of cod, without requiring any major modification to the gear or changes in fishing area. The design tested in this study was not thought for commercial applications, as the observation platform introduced some logistical challenges, but its effectiveness on cod alone warrant further commercial development. In particular, a similar floating effect of the scaring lines could be achieved by applying floats or simply replacing the observation platform with a plastic bobbin.

The other fish species for which there was a significant difference in performance of $FLEXSELECT_{raised}$ (i.e. lemon sole and whiting) were characterized by a reduction in effect on larger individuals, meaning that more of these individuals reacted to sweeping scaring lines rather than floating ones. From a behavioural point of view, the reduced effect on lemon sole is consistent with the hypothesis that a loss of efficacy on benthic species occurs when raising the counter-herding device off the seabed (Ryer 2008). Nonetheless, the reduction of the effect was minimal and no difference was observed for plaice. Considering that both in this study and in Melli et al. (2018) lemon sole showed a strong response to FLEXSELECT (approximately 65% reduction of catches in Melli et al. 2018), we conclude that the species is highly sensitive to the stimuli created by the counter-herding device and reacts more promptly than plaice. In contrast, the reduction in effect on whiting was inconsistent with the expectations in Ryer (2008) and it is more difficult to interpret from a behavioural perspective. Perhaps more individuals passed below the scaring lines, failing to be re-directed outside the trawl path, as the species is known for having the tendency to move closer to the seabed in response to the approaching trawl (Handegard and Tjøstheim 2005; Winger et al. 2010). However, the same behaviour characterizes cod, which instead was more responsive to $FLEXSELECT_{raised}$. Finally, raising the scaring lines off the seabed had a significant effect on *Nephrops*

(24–45 mm CL), leading to significant loss of commercial target catch (32–41 mm CL) with respect to $FLEXSELECT_{sweep}$. This difference could not be explained by a reduction in trawl spread, and thus fishing area, because the difference in spread between the two trawls was minimal and not significant. A potential explanation that warrants further investigation is that the floating scaring lines were flapping during towing, thus stimulating *Nephrops* to enter their burrows (Bell et al. 2016). In the video observations collected, the scaring lines appeared to be quite stable, but due to their length, it is reasonable to expect some oscillation in proximity of the attachment to the bridles. Future studies should investigate the dynamics of the scaring lines under controlled conditions (e.g. flume tank). This would provide useful information to interpret the differences in performance observed, and to mitigate the negative outcomes (such as a loss of target catch) while keeping the positive ones (like the effect on cod).

Future attempts to observe fish responses to counter-herding devices should be conducted with means other than video cameras (e.g. acoustic observation technologies, tagged individuals), as the position and dimension of the device complicate the collection of usable footage. Indeed, even though it was possible to incorporate successfully an observation platform into the design of FLEXSELECT, the type of narrow and powerful beam of light required to illuminate the long scaring lines was too easily reflected by the illuminated objects or particles in the water, and resulted in frequent blinding of the cameras. Moreover, future studies should aim at quantifying the orientation of fish behavioural response in relation to the relative position within the geometry of the scaring lines. In the preliminary observations collected in this study, in the section of the scaring lines approximately parallel to the towing direction, when a response was observed it resulted in multiple swimming trajectories. Perhaps only few of these trajectories would ultimately lead to a successful escape from the trawl path. Since the relative proportion between trajectories may vary over the length of the lines due to the increase in angle with respect to the towing direction, and considering that the doors spread affects the overall geometry of the counter-herding device, the efficiency of FLEXSELECT needs to be investigated in relation to these factors.

In conclusion, the significant differences in performance of FLEXSELECT found in this study highlight the great potential for further development of counter-herding devices. Indeed, these devices can prevent unnecessary interaction between unwanted species and the trawl (McHugh et al. 2015, 2017; Melli et al. 2018), but their efficiency is sensitive to the behavioural mechanisms that they trigger. The results of this study show that the stimuli produced by the counter-herding device are still sufficient to reduce the catch of most of the fish species considered, even when raised off the seabed. By better understanding the underwater dynamic of the scaring lines, as well as species perception and response to them, counter-herding devices could be developed in commercial fisheries without adding to the seabed impact of the baseline gears. Moreover, the species-specific differences between configurations here identified suggest that, in the future, FLEXSELECT design could be adjusted to selectively reduce specific species or group of species (e.g. only roundfish). Because these anterior devices can be deployed at the haul-by-haul level and in any trawl fishery, the different FLEXSELECT designs could be used as a flexible solution to match the selectivity to the vessel-specific catch goals.

Acknowledgements

This study has received funding from the European Maritime and Fisheries Fund (https://ec.europa.eu/fisheries/cfp/emff_en) and the Ministry of Environment and Food of Denmark. Project: FlexSelect – Scaring lines, an innovative and flexible solution for the *Nephrops* fishery (Grant Agreement No 33113-I-16-068).

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List of Tables

Table 1. Overview of the valid hauls. Hauls were distinguished by treatment (L=with LED lights, NL=no LED lights). The position of the test trawl was switched every 4-6 hauls from port (P) to starboard (S) side of the twin-rig.

Haul	Treatment	Side of twin-rig	Fishing time (min)	Mean depth (m)	Towing speed (knt)	Total catch test trawl (Kg)	Total catch baseline trawl (Kg)	Spread test trawl (m)	Spread baseline trawl (m)
1	L	P	90	69	2.7	696	951	45.6	45.5
2	L	P	60	85	2.7	396	560	41.9	40.9
3	L	P	60	87	2.7	312	489	42.3	43.7
4	L	P	70	88	2.7	390	855	41.2	43.1
5	L	P	75	43	2.7	139	175	40.6	42.8
6	L	S	80	42	2.7	80	127	41.8	44.7
7	L	S	95	44	2.7	106	139	43.3	44.3
8	L	S	120	39	2.7	245	350	43.8	45.6
9	L	S	90	91	2.7	745	860	41.3	43.4
10	L	P	60	38	2.7	184	250	39.6	40.8
11	L	P	90	76	2.7	321	645	45.4	44.2
12	NL	P	60	39	2.7	138	200	43.7	44.3
13	NL	P	60	105	2.7	162	376	44.6	43.4
14	NL	P	60	115	2.6	226	440	43.5	40.2
15	NL	S	60	38	2.7	130	186	45.4	48.6
16	NL	S	60	94	2.7	440	460	42.9	44.8
17	NL	S	60	42	2.7	123	155	44.2	43.3
18	NL	S	60	98	2.7	159	362	48.1	50.4
19	NL	P	60	111	2.7	130	166	47.3	46.0
20	NL	P	60	42	2.7	165	184	39.1	40.3
21	NL	P	60	90	2.7	285	645	44.0	45.4

Table 2. Number of hauls and individuals per species included in the analyses. For species subsampled, the actual number of individuals length-measured is shown in parentheses.

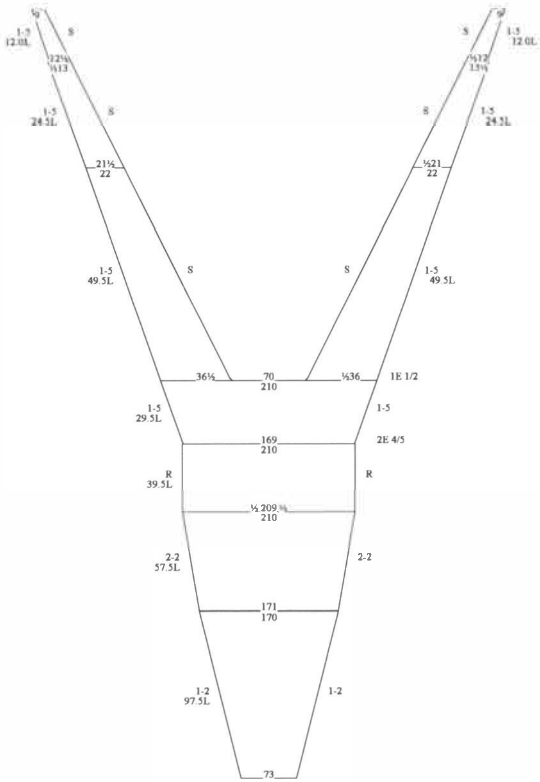
	Hauls	No. of individuals
Nephrops	12	30625 (25116)
Cod	20	14023
Haddock	12	1600
Whiting	21	30965 (29524)
Hake	10	464
Lemon sole	17	2839
Plaice	19	7033

Table 3. Fit statistics for the modelled catch rates. DoF denotes the degree of freedom.

	***p*-value**	**Deviance**	**DoF**
Nephrops	0.01	70.52	46
Cod	0.03	93.63	70
Haddock	0.26	38.95	34
Whiting	0.01	62.28	40
Hake	0.06	33.05	22
Lemon sole	0.21	28.19	23
Plaice	0.62	33.79	37

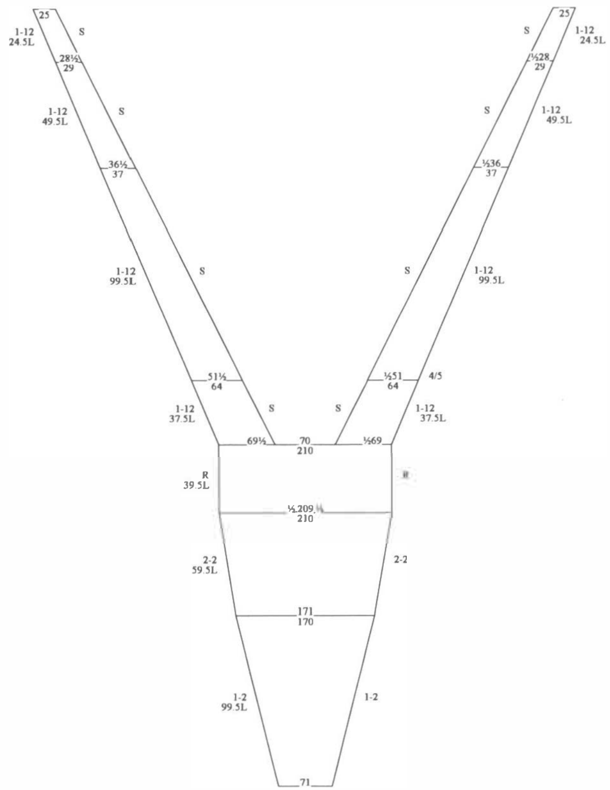
Top panel

Mesh mm	Twine	Stretch længde	Knots i mm
100 0	100 3,0	2.50	4
100 0	100-2,5	5 00	4
100 0	100-2,5	10 00	4
50 0	50-2,5	3 00	4
40 0	40-1,8	3.20	4
40 0	40-1, 8	4 64	4
40 0	40-2,5	7 84	4



Bottom panel

Mesh mm	Twine	Stretch length	knuder i mm
50 0	50-3,0	2.50	4
50.0	50-2,5	5 00	4
50 0	50 2,5	10 00	4
40 0	40 2,5	3 04	4
40 0	40-1,8	3 20	4
40 0	40-1,8	4 80	4
40 0	40 2,5	8 00	4



Trawl 130FODS 420 MA COMBITRAWL MED GUMMIRUB
Type . COMBITRAWL MED GUMMIRUB
Firma . STRANDBY NET A/S
Skib HAVFISKEN
Fil . trawl001 ctf
Dato . 01 08.16 Design . LP

Appendix B

Estimation of the catch comparison curve for each set of hauls

Hauls with and without LED lights were first analysed separately to determine whether there was any significant change in the catch efficiency deriving from the presence of artificial illumination. For each species, and each set of hauls (with and without LED lights, respectively) count data for the different length classes *l* were used to estimate the proportion of the total catch of that species caught by the test gear, using the catch comparison equation (*cc*; Krag et al. 2014):

(A.1) $$cc_l = \frac{\sum_{j=1}^{h}\left(\frac{nT_{lj}}{qT_j}\right)}{\sum_{j=1}^{h}\left(\frac{nT_{lj}}{qT_j}+\frac{nB_{lj}}{qB_j}\right)}$$

where nT_{lj} and nB_{lj} are the number of individuals length-measured per length class *l* and haul j in the test and baseline gears, respectively, and qT_{lj} and qB_{lj} are the associated sampling factors. These sampling factors were generally equal to 1.0, with the exception of a few hauls where catches of *Nephrops* (*Nephrops norvegicus*) and whiting (*Merlangius merlangus*) were subsampled. The summation in equation 1 is over the number of hauls *h*, with and without LED lights, respectively. For each species, only hauls with 10 or more individuals were included in the analysis following Krag et al. (2014).

To model the size-dependent catch comparison rate *cc*(*l*) averaged over hauls we used maximum likelihood estimation by minimizing the following equation:

(A.2) $$g(\boldsymbol{v}) = -\sum_l \sum_{j=1}^{h}\left\{\left(\frac{nT_{lj}}{qT_j}\right) \times \ln\big(cc(l,\boldsymbol{v})\big) + \left(\frac{nB_{lj}}{qB_j}\right) \times \ln(1 - cc(l,\boldsymbol{v}))\right\}$$

where ***v*** represents the parameters describing the catch comparison curve *cc(l,**v**)*.

We adapted a flexible model for *cc*(*l,* ***v***) often applied for catch comparison studies (Krag et al. 2014, 2015):

(A.3) $$cc(l,\boldsymbol{v}) = \frac{\exp(\,f(l,v_0,\ldots,v_k)\,)}{1.0+\exp(f(l,v_0,\ldots,v_k))}$$

where *f* is a polynomial of order *k* with coefficients v_0 to v_k so $\boldsymbol{v} = (v_0,\ldots,v_k)$. To enable sufficient flexibility in the model, *f* was considered up to an order of 4. Leaving out one or more of the parameters $v_0 \ldots v_4$ provided 31 additional models that were considered as potential models to describe $cc(l,\boldsymbol{v})$. The selection of the final models was based on multimodel inference (Burnham and Anderson 2002). In this approach, an average of the best models (combined model), weighted by their respective Akaike's Information Criterion (AIC) values (Akaike 1974), is used rather than selecting the single model with the lowest AIC value. Models with AIC values within +10 the value of the model with the lowest AIC, were considered to contribute to the combined $cc(l,\boldsymbol{v})$ (Katsanevakis 2006; Herrmann et al. 2017). The ability of the combined model to describe the experimental data was assessed through the p-value, residuals deviance and how it relates to the degrees of freedom, and the visual inspection of the residuals distribution (Wileman et al. 1996). The *p*-value expresses the likelihood for obtaining by coincidence a discrepancy between the fitted model and the experimental data at least as large as that experimentally observed. Therefore, for the combined model to be a candidate model, the *p*-value should not be < 0.05 (Wileman et al. 1996). Moreover, residual deviances and the degrees of freedom should show values within the same order of magnitude (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 over-dispersion in the experimental data.

To quantify the effect of $\text{FLEXSELECT}_{\text{raised}}$, with and without LED lights, with respect to the baseline trawl, we calculated the catch ratio $cr(l,\boldsymbol{v})$, which gives a direct relative value of the catch efficiency between the test and baseline trawl. The catch ratios were derived from $cc(l,\boldsymbol{v})$ using the general relationship (Herrmann et al. 2017):

$$(\text{A.4}) \quad cr(l,\boldsymbol{v}) = \frac{cc(l,\boldsymbol{v})}{1-cc(l,\boldsymbol{v})}$$

The advantage of using the catch ratio is that if the catch efficiency of both trawls is equal, i.e. no effect of the FLEXSELECT device, the $cr(l,\boldsymbol{v})$ would be 1.0. A $cr(l,\boldsymbol{v}) = 1.25$ would mean that the test trawl catches on average 25% more individuals of length *l* than the baseline trawl. In contrast, a

$cr(l,\boldsymbol{v})$ = 0.75 would mean that the test trawl catches 25% less individuals of length l than the baseline trawl.

Confidence intervals (CI) for the size-dependent effect of FLEXSELECT were estimated using a double bootstrap method, accounting for uncertainty due to within- and between-haul variation in the catching process (Millar 1993). A total of 1000 bootstrap iterations were performed to estimate the Efron percentile 95% confidence limits (Efron 1982) for $cc(l,\boldsymbol{v})$ and $cr(l,\boldsymbol{v})$ for all relevant length classes.

Investigating the effect of LED lights

Because both experiments (with and without LED lights) were conducted with the same baseline gear, we could estimate the ratio between the catch ratio curves for $\text{FLEXSELECT}_{\text{raisedLED}}$ and $\text{FLEXSELECT}_{\text{raisedNoLED}}$ to identify any significant difference in effect relative to the LED lights:

(A.5) $$cr(l,\boldsymbol{v})_{raisedLED/raisedNoLED} = \frac{cr(l,\boldsymbol{v})_{raisedLED}}{cr(l,\boldsymbol{v})_{raisedNoLED}}$$

where $cr(l,\boldsymbol{v})_{raisedLED}$ indicates the effect on the catch of $\text{FLEXSELECT}_{\text{raised}}$ with LED lights on the observation platform and $cr(l,\boldsymbol{v})_{raisedNoLED}$ that of $\text{FLEXSELECT}_{\text{raised}}$ with no LED lights. The 95% Efron CIs for $cr(l,\boldsymbol{v})_{raisedLED/raisedNoLED}$ were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) from each catch ratio model estimated for either FLEXSELECT design. Since both bootstrap populations were obtained independently, a new population of results with 1000 bootstrap iterations was created for $cr(l,\boldsymbol{v})_{raised/sweep}$ following (Herrmann et al. 2018):

(A.6) $$cr(l,\boldsymbol{v})_{raised/sweep} = \frac{cr(l,\boldsymbol{v})_{raised\ i}}{cr(l,\boldsymbol{v})_{sweep\ i}} \quad i \in \ [1 \dots 1000]$$

where i represents the bootstrap repetition index.

If the 95% Efron CIs for $cr(l,\boldsymbol{v})_{raisedLED/raisedNoLED}$ overlapped the baseline for equality 1.0, there was no significant effect in efficiency of $\text{FLEXSELECT}_{\text{raised}}$ related to the LED lights. Since this was the case for all the species analysed (see Supplementary material for species-specific

$cr(l, \boldsymbol{v})_{raisedLED/raisedNoLED}$) the analyses were repeated on the totality of hauls available for that species, regardless of the presence of LED lights.

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Appendix C

Behavioural responses of fish species to the scaring lines of $FLEXSELECT_{raised}$

The following series of screenshots obtained from the video footage collected with the observation platform equipped with GoPro cameras (Hero 3) LED lights (Big Blue TL4500P 4500 lumen) illustrate the observed responses to the scaring lines.

Roundfish species

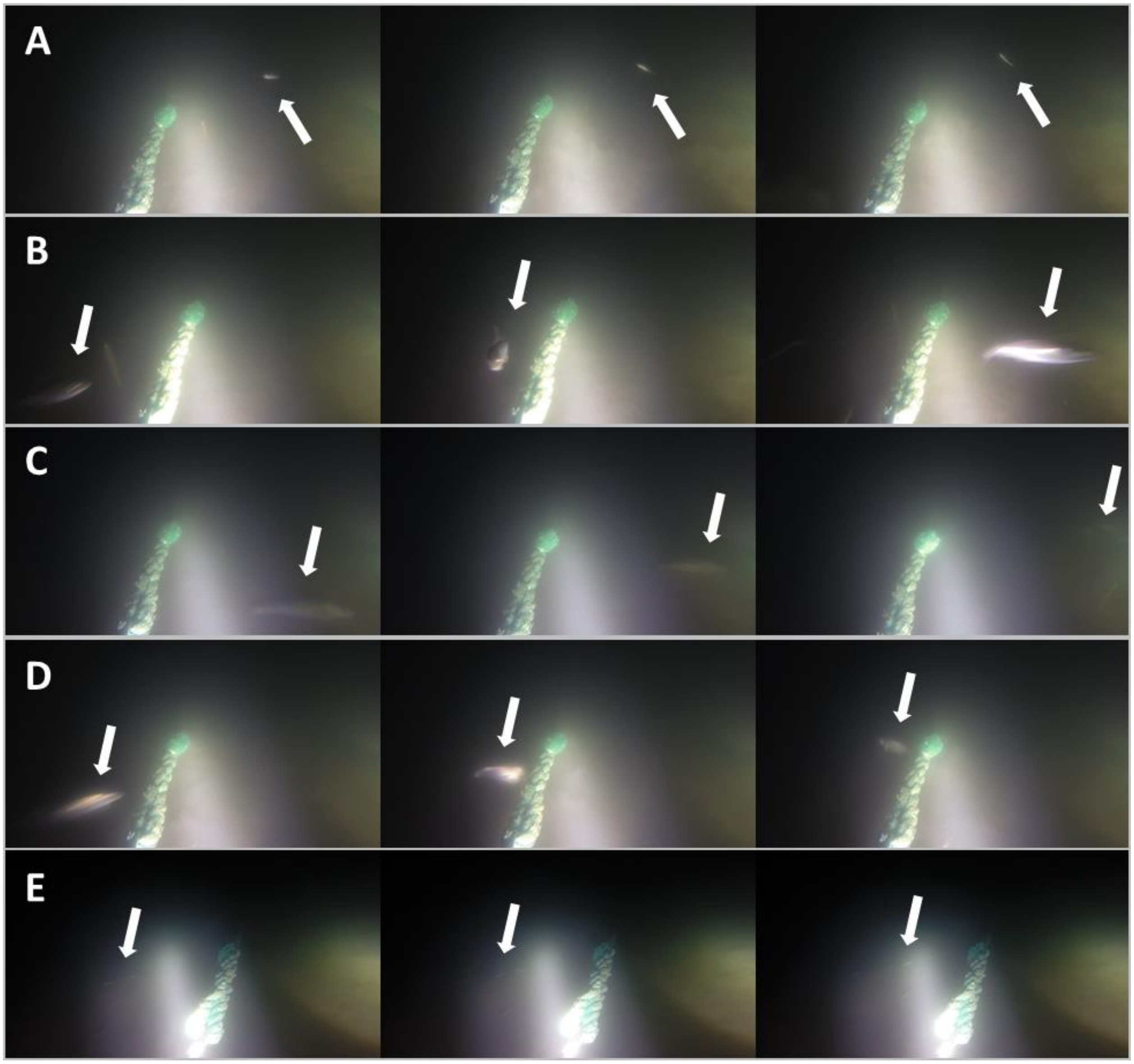

Figure C1. View of the scaring lines from the observation platform. In each image, the starboard-side scaring line is central, while the port-side scaring line is visible at the right end of the picture. Roundish escape trajectories are illustrated through series of three pictures: A) Upwards escape; B) Escape above and across the scaring lines; C) Escape below and across the scaring lines; D) Roundfish contacting the scaring line and moving away from it; E) Roundfish on the seafloor, away from the scaring line, not showing any reaction.

Flatfish species

Figure C2. View of the scaring lines from the observation platform. In each image, the starboard-side scaring line is central in each image, while the port-side scaring line is visible at the right end of the picture. Flatfish responses are illustrated through series of three pictures: A) *Sole* spp. reacting to proximity of the scaring line by initiating swimming; B) Flatfish (perhaps plaice, *Pleuronectes platessa*) approached by the floating scaring line, but not showing any reaction.

Supplementary Materials

Effect of LED lights on the performance of FLEXSELECT$_{raised}$

Ratio between the catch ratio curves for FLEXSELECT$_{raised}$, with and without LED lights, for each of the species analysed. For all species, the 95% Efron Confidence Intervals overlapped the baseline for equality (1.0) implying that there was not a significant difference in the effect of FLEXSELECT$_{raised}$, which could be related to the presence of LED lights

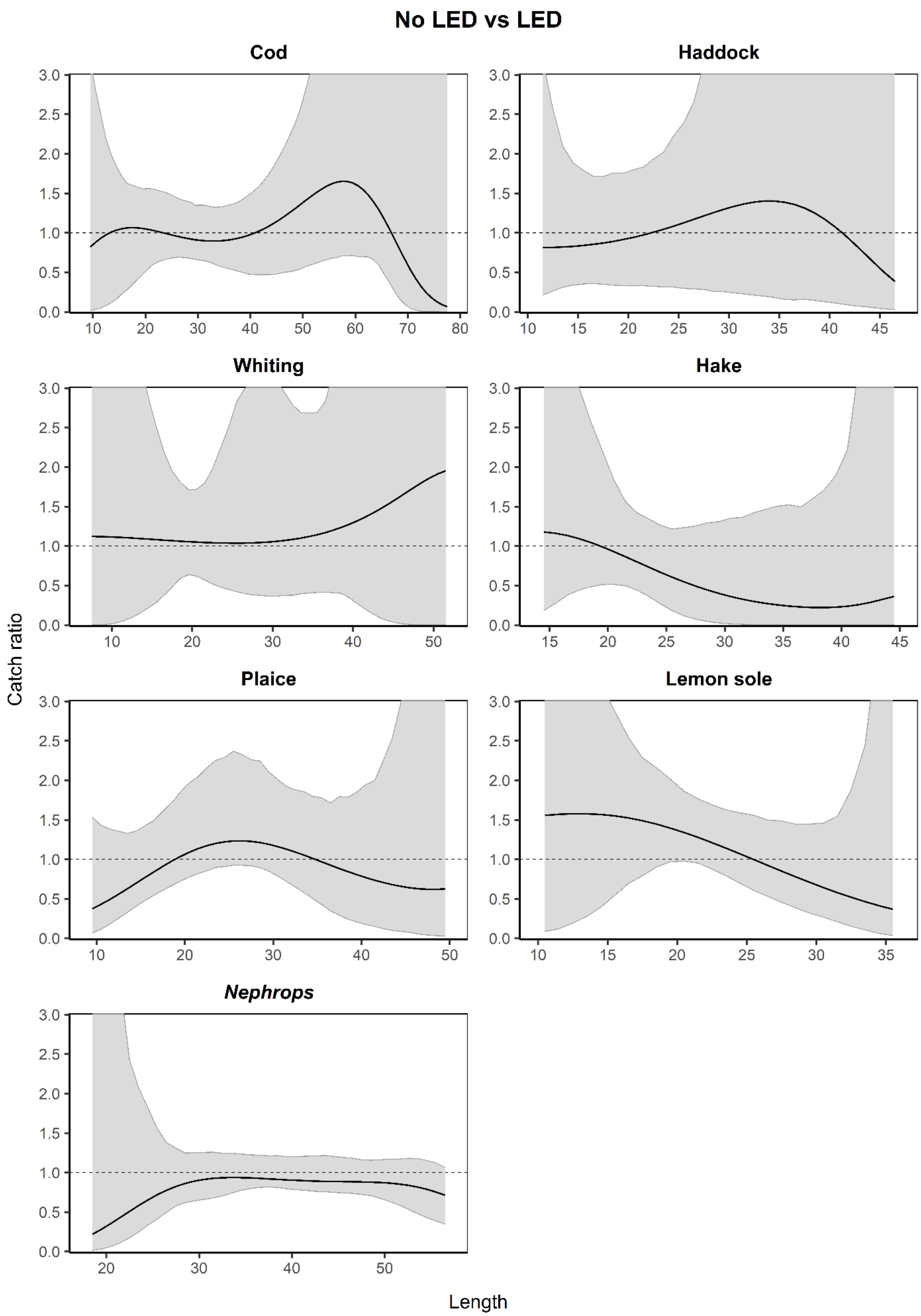
No LED vs LED
Cod
Haddock
Whiting
Hake
Plaice
Lemon sole
Nephrops
Catch ratio
Length

Figure S1. Comparison of the species-specific, size-dependent effect of $FLEXSELECT_{raised}$ without LED lights and with LED lights. The curve (solid line) represents the modelled ratio of catch ratio curves from the two individual experiments. The grey ribbon represents 95% Efron Confidence Intervals estimated from the two bootstrap sets from each catch ratio model estimated for either set of hauls (with and without LED lights). The dashed horizontal line, located at 1.0, describes equivalence in efficiency.