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DTU Aqua
National Institute of Aquatic Resources

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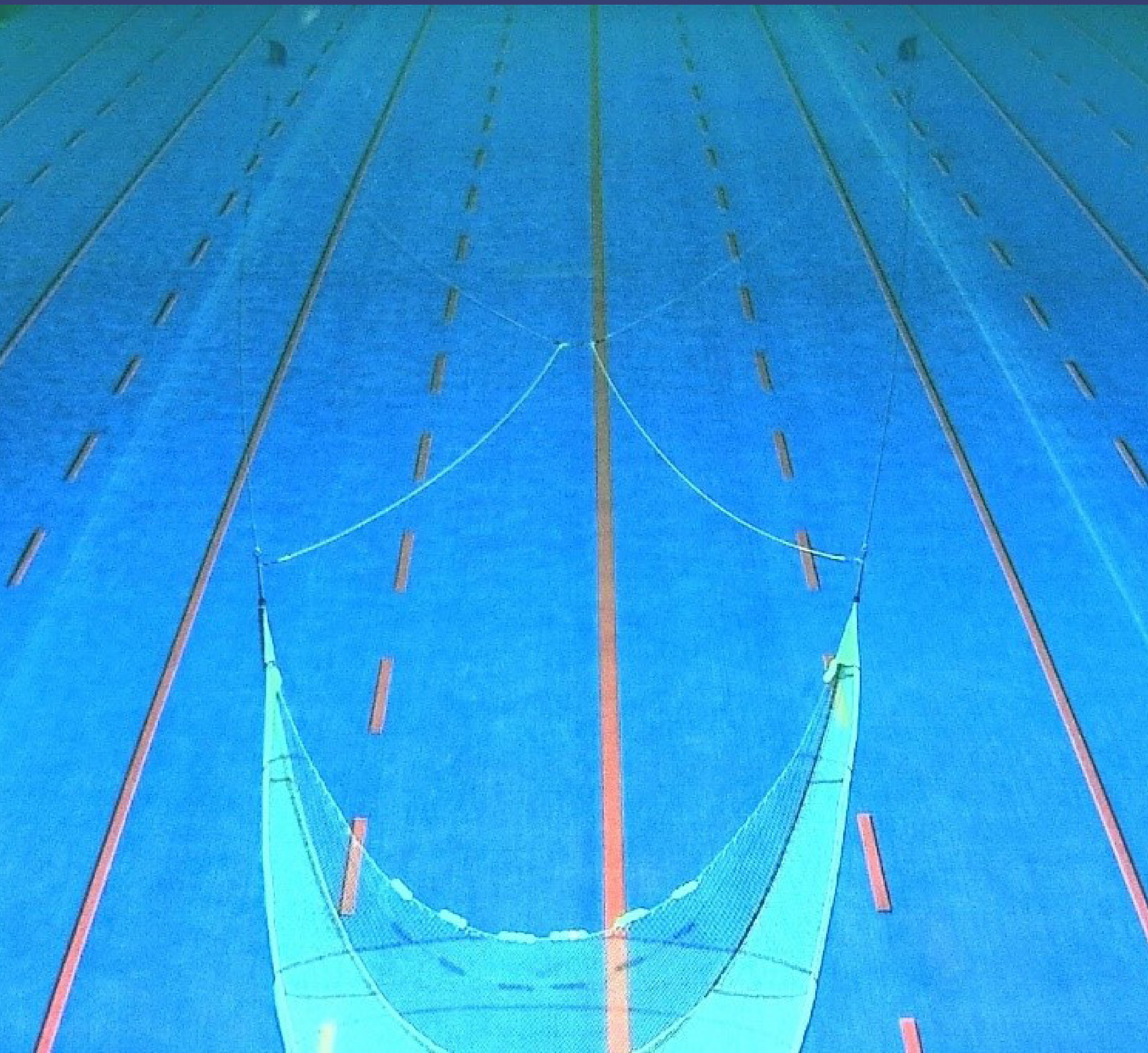
DTU Aqua Report no. 352-2019



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In collaboration with

DANMARKS FISKERIFORENING
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Title: Scaring lines—An innovative and flexible solution for the *Nephrops* fishery (FLEXSELECT)

Authors: Jordan P. Feekings[1], Valentina Melli[1], Rikke P. Frandsen[1], Henrik Lund[2], Tiago Veiga-Malta[1], Marco Nalon[1], and Ludvig Krag[1]

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Cover: Photo: Jordan Feekings: Scaled version of the FLEXSELECT scaring lines in SINTEF's trawl tank in Hirtshals.

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Foreword

This is the final report for the project "Scaring lines—An innovative and flexible solution for the Nephrops fishery (FLEXSELECT) (in Danish: "Skræmmeliner – innovativ og fleksibel løsning til jomfruhummerfiskeriet (FLEXSELECT))" under the scheme " Fiskeri, natur og miljø EHFF – 2016" and is a collaboration between DTU Aqua and The Danish Fishermen's Association.

The objective of the project has been to develop and demonstrate a simple and efficient system that can be quickly coupled to any existing demersal trawl to reduce the catch of fish. For example, to improve the species selection in the Danish mixed demersal trawl fishery targeting Norway lobster. While most of the work related to the improvement of species and size selection has previously been concentrated around different solutions in and around the codend itself, FLEXSELECT is located ahead of the trawl. FLEXSELECT reduces the catch of unwanted fish by scaring or directing unwanted fish away from the path of the trawl so that they do not enter the trawl itself. The project was completed during the period 07-09-2016 until 23-08-2019 by DTU Aqua with participation from The Danish Fishermen's Association.

The project was carried out with financial support from the EU, the European Maritime and Fisheries Fund, the Ministry of Foreign Affairs' fisheries development program.

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European Union
European Maritime and Fisheries Fund

HAV & FISK

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Executive Summary

The FLEXSELECT project set out to develop and demonstrate a simple and efficient system that could be quickly coupled to any existing demersal trawl to reduce the catch of fish. For example, to improve the species selection in the Danish mixed demersal trawl fishery targeting Norway lobster. The principle of FLEXSELECT is the same as what is currently used today to herd fish into the path of the trawl, however, the scaring lines are mounted in a way that instead of herding the fish into the path of the trawl, they direct unwanted fish away from the trawl's path so that they do not enter the trawl itself.

This approach is somewhat different to most of the work that has been carried out to improve species and size selection in demersal trawls. A majority of the work has concentrated around different solution in and around the codend itself, as opposed to the introduction of simple devices ahead of the trawl that are capable of altering the catch composition.

The development and testing of the FLEXSELECT scaring lines took place on board R/V Havfisken in 2016 and 2017 and aimed at establishing the design principle, testing different design parameters, and developing a coupling system that makes it easy to assemble and disassemble to ensure maximum flexibility. Based on the results from the first trials, commercial testing was carried out together with the commercial fishing vessel FN 436 Tove Kajgaard. As part of the commercial trials, further design parameters were tested, a final prototype was produced and tested under commercial conditions.

The results obtained show that FLEXSELECT is a simple, cheap and effective selective device that can reduce the catch of fish bycatch, especially roundfish, in the mixed demersal trawl fishery targeting Norway lobster. Moreover, the device has the advantage to be applicable only when required, at the haul-by-haul level (e.g. in response to the availability of quotas or bycatch hotspots), and it can be easily adjusted to fit any trawl size. Furthermore, its applicability extends to any demersal trawl fishery wanting to reduced unwanted catches of fish.

The project was completed during the period 07-09-2016 until 23-08-2019 by DTU Aqua with participation from The Danish Fishermen's Association.

This report provides and overview of the work undertaken during the project and presents the results from the individual trials. Furthermore, the report highlights some of the challenges which arose during the project and how these can be addressed in the future.

1. Introduction

The new EU Common Fishery Policy (CFP) introduced the obligation to land all catches, both wanted and unwanted, for important harvested stocks (EU, 2013; 2016). Consequently, under the landing obligation, also referred to as “discard ban”, unwanted catches are to be count against fishermen’s quotas. This can potentially lead to additional costs for the industry due to the processing of the unwanted fraction of the catch (Hall et al., 2000; Hall and Mainprize, 2005). Both sorting time and handling costs are expected to increase as a bigger part of the catch has to be separated and stored; on a limited storage space this could force fishermen to increase the number of journeys to the harbour. Moreover, in mixed fisheries, whenever the quota for one species is exhausted, and the catch of that species cannot be avoided, fishing activities have to stop. These “choke” species can potentially lead to the under-exploitation of more productive stocks, with consequences on the economy of the fishery (Ulrich et al., 2011; Baudron and Fernandes, 2015). Therefore, one of the main expected outcomes of a discard ban is to strongly incentivize fishermen to couple selectivity with economy (Hall and Mainprize, 2005; Graham et al., 2007). Indeed, in the frame of a landing obligation, it is in fishermen’s interest to avoid or reduce the amount of unwanted catches by improving the selectivity of the fishing gear, for example adopting BRDs.

To be implemented effectively, with less undesirable economic impacts on the industry, a landing obligation needs to be combined with flexible technical regulations to increase fishermen’s ability to adjust the selectivity of their gears (EU, 2016; Feekings et al., 2019; Eliasen et al., 2019). The legislation of BRDs is often too rigid and follows a “one-gear-fits-all” approach, where technical solutions are applied at the fishery or regional level. In contrast, since the amount of unwanted catches is mostly determined by the combination of gear, fishing practice and quota availability, and since these may differ among vessels, the economic consequences of the landing obligation are vessel specific. Therefore, each vessel should be able to choose from a “toolbox” of BRDs to better match the gear selectivity with specific catch goals. Moreover, in mixed fisheries, one BRD is rarely enough to cope with the spatial and temporal variability in catch composition, as well as inter-annual variation in quotas. More gear options need to be identified to support alternative harvest strategies (Feekings et al., 2019; Eliasen et al., 2019). A toolbox of flexible gear modifications, which can be temporarily applied to the gear without requiring major structural changes, could enable a more dynamic adjustment of the gear selectivity at the haul-by-haul level.

The mixed demersal trawl fishery targeting Norway lobster (*Nephrops norvegicus*), hereinafter referred to as *Nephrops*, which is economically the most important demersal fishery in Denmark, is expected to be one of the fisheries where the transition to a landing obligation in connection with the implementation of the new CFP will present the greatest challenges. To efficiently catch *Nephrops*, relatively small meshes (80-90 mm), in combination with selective panels, are used. These small mesh sizes typically result in the capture of unwanted species and sizes, above and below the Minimum Conservation Reference Size (MCRS). Consequently, this is one of the fisheries in Denmark where a larger “toolbox” of BRD’s could potentially result in the largest benefit to the fishery and the stocks that are exploited.

The FLEXSELECT project set out to develop a selective device that would help achieve this needed flexibility, whereby the selectivity of the gear can be modified on a haul-by-haul basis to avoid unwanted species and sizes and subsequently be more suited to the quotas that are available. The FLEXSELECT scaring lines are a simple and efficient system that can be quickly coupled to any existing demersal trawl to reduce the catch of fish. For example, to improve the species selection in the Danish mixed demersal trawl fishery targeting *Nephrops*. The principle of FLEXSELECT is the same as what is currently used today to herd fish into the path of the trawl, however, the scaring lines are mounted in a way that instead of herding the fish into the path of the trawl, they direct unwanted fish away from the trawl's path so that they do not enter the trawl itself.

2. Study Area and Description of Fishery

The project, while applicable to a multitude of trawl fisheries that target crustaceans and where fish catches are an issue, focused on the Danish mixed demersal trawl fishery targeting *Nephrops*. The mixed species demersal trawl fishery, where *Nephrops* is the most economically important species, is one of the most profitable fisheries in Denmark, with a total number of vessels targeting *Nephrops* for at least part of the year of approximately 184 (2017 data; Danish Fisheries Agency). The main fishing areas are in the North Sea (ICES Division IVa and IVb), Skagerrak and Kattegat (ICES Division IIIa; Fig. 1). Total landings of *Nephrops* in 2017 were above 4˙000 tons, and had a first sales value of approximately 250 million DKK (http://www.statistikbanken.dk). In addition, these vessels landed approximately 2˙000 tons of fish, including cod (*Gadus morhua*), saithe (*Pollachius virens*), hake (*Merluccius merluccius*), haddock (*Melanogrammus aeglefinus*), plaice (*Pleuronectes platessa*), witch flounder (*Glyptocephalus cynoglossus*), lemon sole (*Microstomus kitt*) and monkfish (*Lophius piscatorius*), among others. Therefore, because of its highly morphologically diverse bycatch and the recovering status of some gadoid stocks in the area, this fishery has been classified as "very high risk" in terms of incompliance to the landing obligation (Anon, 2015).

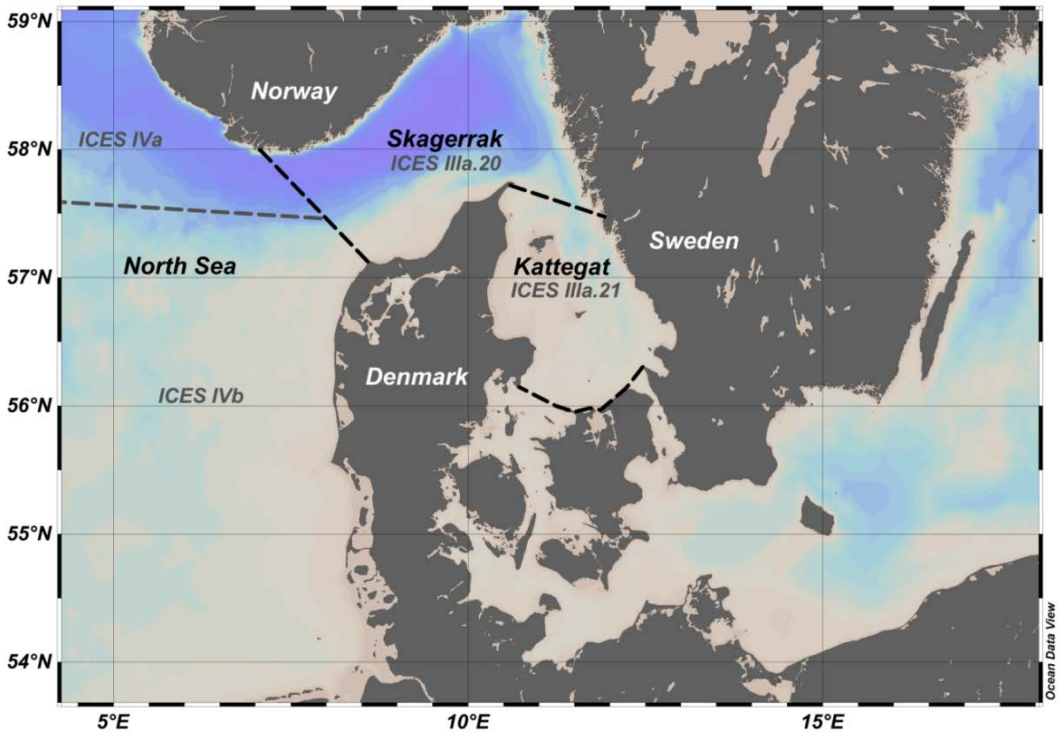

Figure 1. *Geographic position and ICES classification of the main fishing areas for Nephrops-directed trawl fishery.*

Most vessels operating in the Danish mixed species demersal trawl fishery have quota to land fish species, which can contribute up to 2/3 of the profit of the fishery (Danish Fisheries Agency). Consequently, the Danish fishery adopts the so-called Combi trawls, which are designed to maximize the retention of both *Nephrops* and fish species. The trawlers, which are typically between 15 and 30 m in length (http://www.statistikbanken.dk), tow in general two identical trawls in a twin-rig configuration (Fig. 2). The trawls have a minimum mesh size of 70 or 90 mm (depending on region). Due to the poor selective properties of these mesh sizes in relation to the MCRS of the fish species, since 2013 Danish trawlers targeting *Nephrops* have been required to use either of the following options: i) a species-selective grid with 35 mm-spaced vertical bars inserted in a 70 mm square mesh codend, at least 8 m from the codline, to exclude the fish bycatch, both undersized and commercial sized; or ii) a trawl codend (termed SELTRA trawl) consisting of a 90 mm diamond mesh codend with a 3 m long escape panel inserted in the upper netting of codend, starting at least 7 m before the codline. Depending on the fishing area, the panel can be of either square meshes (140 mm, 3 opening angle ratio in Skagerrak; 180 mm, 4 opening angle ratio in Kattegat) or diamond meshes (270 mm, both areas; Madsen et al., 2012; ICES, 2014). The escape panel is effective in reducing the catch of undersized individuals while retaining commercial sized individuals (Frandsen et al., 2009; Briggs et al., 2010). Therefore, it is the option adopted by most of the Danish mixed demersal trawl fishery targeting *Nephrops*. However, the release efficiency of an escape panel is variable because it relies on the fish actively contacting the panel to escape. Moreover, the escape panel was not designed to reduce commercial sized fish; however, such reduction may now become necessary if quota for one of the fish species is exhausted before that of the main target species, *Nephrops* (i.e. “choking effect”).

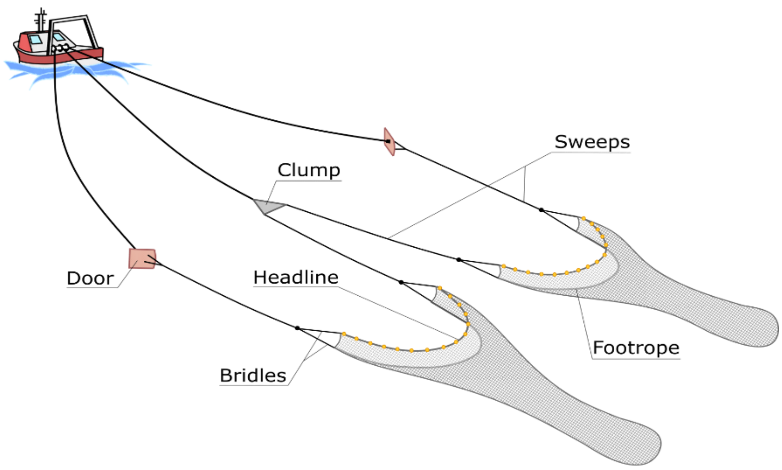

Figure 2. *Schematic illustration of the trawl design and twin-rig configuration used by the Danish Nephrops-directed mixed trawl fishery.*

3. Practical and scientific knowledge pertaining to scaring lines

Trawl gears are inherently behavioural devices, which harness the innate escape responses of fish to facilitate their capture. Indeed, to be caught by the trawl, species have to be in the path of the trawl (i.e. area swept by the footrope). Therefore, the forward, spreading components of the trawl have the function of concentrating them into the trawl's path, a result achieved by exploiting fish behavioural responses (Winger et al., 2010). This mechanism is generally referred to as "herding". Fish in the herding area (i.e. between the doors) are stimulated by the doors and sweeps, which interact with the seafloor producing vibrations and resuspending sediment (Glass and Wardle, 1989; Engås and Ona, 1990; Winger et al., 2010). Most species react to these stimuli as they would in case of an approaching predator (Fernö and Huse, 2003). Demersal roundfish such as cod, haddock, and whiting respond by moving closer to the seafloor and swimming directly away while keeping the predator at the edge of their visual field (Winger et al., 2010). With respect to trawl gears, the perceived threat is represented by the anterior gear components (i.e. doors and sweeps) and, thus, the escape response is directed towards the mouth of the trawl (Fig. 3a; Winger et al., 2010). As a consequence, these species can easily be herded into the path of the trawl by exploiting the visual and mechanical stimuli produced by the anterior trawl components (Wardle, 1993; Winger et al., 2010). In contrast, benthic species such as flatfish and monkfish (Lophius spp.), which use camouflage as an anti-predator strategy and have lower swimming capacity, tend to keep their position until after direct or near contact with the gear components (Main and Sangster, 1981; Ryer et al., 2010). Consequently, the escape response of these species is delayed and their herding is possible only if fish are given sufficient time to swim into the trawl path (Ryer et al., 2010). For both roundfish and flatfish, the herding process has been found to be size-dependent, and its efficiency known to vary according to the towing speed, because of differences in swimming capacity (Winger et al., 2010; He, 2011). In particular, those individuals that cannot maintain swimming speeds at least as fast as the towing speed would be overtaken by the sweeps before reaching the trawl path, and thus escape capture (Winger et al., 2010).

Among the technical factors influencing the efficiency of herding, two are known to play a fundamental role: the length and the angle of the sweeps with respect to the towing direction (Winger et al., 2010). For cod and haddock, sweep lengths between 20 and 120 m (Engås and Godø, 1989) and angles between 10 and 20 degrees (Strange, 1984) were found to significantly increase catches. In contrast, flatfish require longer sweeps (up to 400 m) and small sweep angles to leave enough time for the individuals to reach the trawl path (Ryer et al., 2010).

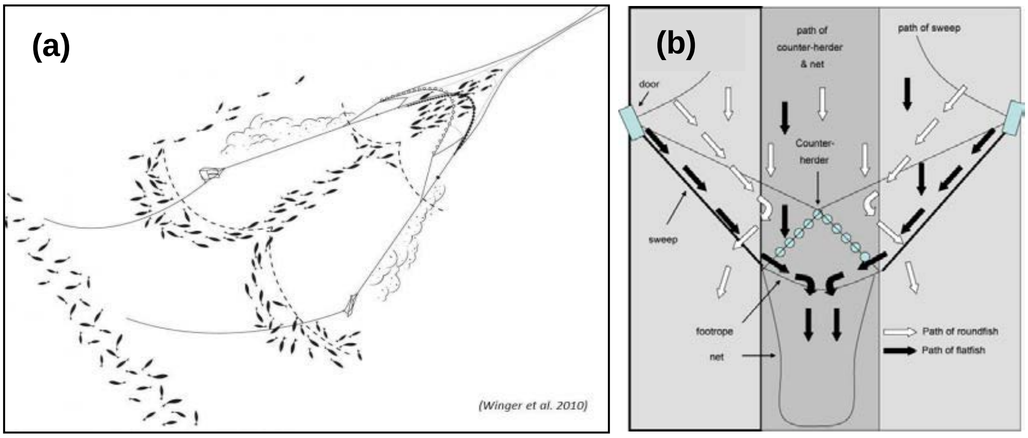

Figure 3. *(a) Schematic illustration of the herding process for roundfish species (Winger et al., 2010); (b) Hypothetical floating counter-herding device from Ryer (2008)*

The same stimuli that triggers the herding response can be used to re-direct fish away from the trawl path. Higher-order multi-net configurations such as quad-rig systems (i.e. four gears towed in parallel) have been shown to catch less fish due to the additional presence of wires to connect the different gears, which lead the fish to the outer extremities of the catching zone (Broadhurst et al., 2013a; b). Similarly, additional elements, such as diagonal wires, ropes and plastic banners can be added in the herding area to anticipate species perception of the trawl mouth and/or re-direct fish escape away from the trawl path (Ryer, 2008; McHugh et al., 2014, 2015; BIM, 2018; Melli et al., 2018; 2019). Ryer (2008) hypothesized that herding of roundfish could be re-directed with a counter-herding design, e.g. a second inverted stimulus, positioned between the sweeps (Fig. 3b). 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 were known to have been tested before this project.

Some Danish fishermen (e.g. FN109 Nordland), on their own initiative, have experimented with the use of scaring lines to reduce fish catches in the Danish demersal trawl fishery targeting *Nephrops.* Fisheries inspectors (Vestkysten) inspected FN109 Nordland on March 17, 2015 in the Skagerrak and noted the effect caused by such scaring lines on the vessel's catch composition compared to the catch composition from other vessels fishing in the same area. Various scaring lines have also been designed and theoretically assessed, for example, in relation to fishing for flatfish in the United States, and have indicated a significant potential for improving species selection in trawl gear. Such simple and effective solutions, which have the potential to modify the catch composition on a haul-by-haul basis to suit the quotas available, should be developed and documented in order to ensure success of the landing obligation.

4. Stakeholder involvement

To ensure optimal functionality of the scaring lines, and to facilitate the practical understanding of how the scaring lines should be constructed and mounted, fishermen and net makers were involved in all aspects of the project, from the beginning of the design and construction process to the final testing. Moreover, to ensure the work in the project was sufficiently disseminated, substantial effort was made to ensure the project and its results were disseminated in a number of different media with the purpose of targeting different stakeholder groups, namely fishermen, net makers, managers, and scientists. The fishing industry were informed about the project and its results through the Danish fisheries newspaper (Fiskeritidende), participation of project participants at fishing exhibitions (Danfish), and through several meetings with the industry (Table 1). Furthermore, the project and its results were also disseminated through social media via the DTU Aqua fisheries technology Facebook page (www.facebook.com/fiskeriteknologidtuaqua). The engagement of scientists in the project was primarily through the publication of scientific articles and presentations held at international meetings (Table 1).

Table 1. *Methods used to engage different stakeholder groups.*

News Articles	Meetings (Industry)	Electronic	Meetings (Management/ science)	Scientific publications
• Skræmmeliner giver renere jomfruhummerfangst, Fiskeritidende, 25th November 2017 • Liner skræmmer uønskede fisk væk, Fiskeritidende, 12th January 2019 • Smarte liner skræmmer uønsket fangst væk, Fiskeritidende, 5th October 2019 • Velfungerende selektive redskaber, Fiskeritidende, 19th October 2019 • Nye tekniske løsninger til fiskeriet, Fiskeritidende, 2nd November 2019	• 2 x Strandby Fiskeriforening (Strandby) • Danfish, Aalborg, 11th-13th October 2017 • Danfish, Aalborg, 9th-11th October 2019	• Social media (www.facebook.com/fiskeriteknologidtuaqua/)	• ICES Working Group on Fishing Technology and Fish Behaviour (WGFTFB) 2017, Nelson, New Zealand • ICES Annual Science Conference 2018, Hamburg, Germany • ICES Working Group on Fishing Technology and Fish Behaviour (WGFTFB) 2019, Shanghai, China	• Melli, V., Karlsen, J. D., Feekings, J. P., Herrmann, B., Krag, L. A., 2018. FLEXSELECT: counter-herding device to reduce bycatch in crustacean trawl fisheries. Canadian Journal of Fisheries and Aquatic Sciences, 75: 850–860. https://doi: 10.1139/cjfas-2017-0226 • Melli, V., Herrmann, B., Karlsen J.D., Feekings, J.P., Krag L.A. Predicting optimal combinations of bycatch reduction devices in fishing gears: a meta-analytical approach. In press, Fish and Fisheries. DOI: 10.1111/faf.12428 • Melli, V., Krag, L. A., Herrmann, B., Karlsen, J. D., Feekings, J. P. Two objectives, one device: refining the counter-herding device FLEXSELECT to observe fish behaviour while reducing unwanted catches. Manuscript

5. Scientific testing on board R/V Havfisken

Two scientific trials were conducted on board the research vessel "Havfisken" (17 m, 373 kW). The vessel was equipped for three-wire, twin-trawling, with two identical Combi trawls (40 m long footrope, 420 meshes circumference of the square, 80 mm mesh size) towed in parallel. The twin rig was spread with two Type 2 Thyborøn doors (1.78 m2, 197 kg) and a 400 kg triangular central clump. 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 identical non-selective codends (41.65±1.33 square mesh size, measured on dry netting). The only difference between the two trawls was represented by the counter-herding device, FLEXSELECT, mounted on one of them, while the other trawl worked as 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. To prevent any systematic effect of the trawl position (i.e. side of the vessel) on the catch, the FLEXSELECT device was shifted from one trawl to the other approximately every sixth haul.

5.1 1st scientific trial

AIMS

The first trial aimed at designing a functional FLEXSELECT and testing the efficiency of the scaring lines in reducing fish bycatch. We tested FLEXSELECT in the mixed species trawl fishery targeting *Nephrops*. As previously mentioned, the small mesh sizes used in this fishery lead to substantial quantities of undersized roundfish and flatfish being caught, thus leading to large portions of the catch being unwanted/ discarded (Kelleher 2005). The high levels of unwanted catch can potentially choke the fishery once fish quotas are exhausted. 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 chances of survival; 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 antipredator strategies.

EXPERIMENTAL SETUP

The FLEXSELECT design tested in this trial 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. 4). The two positioning lines (54 m) were made of mix wires (steel core and polypropylene cover, six strands, 14mmin diameter, 0.21 kg·m–1). 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, three strands, 26 mm in diameter, 0.31 kg·m–1), 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 (i.e. without reducing the spread of the gear). 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, relatively light materials were chosen.

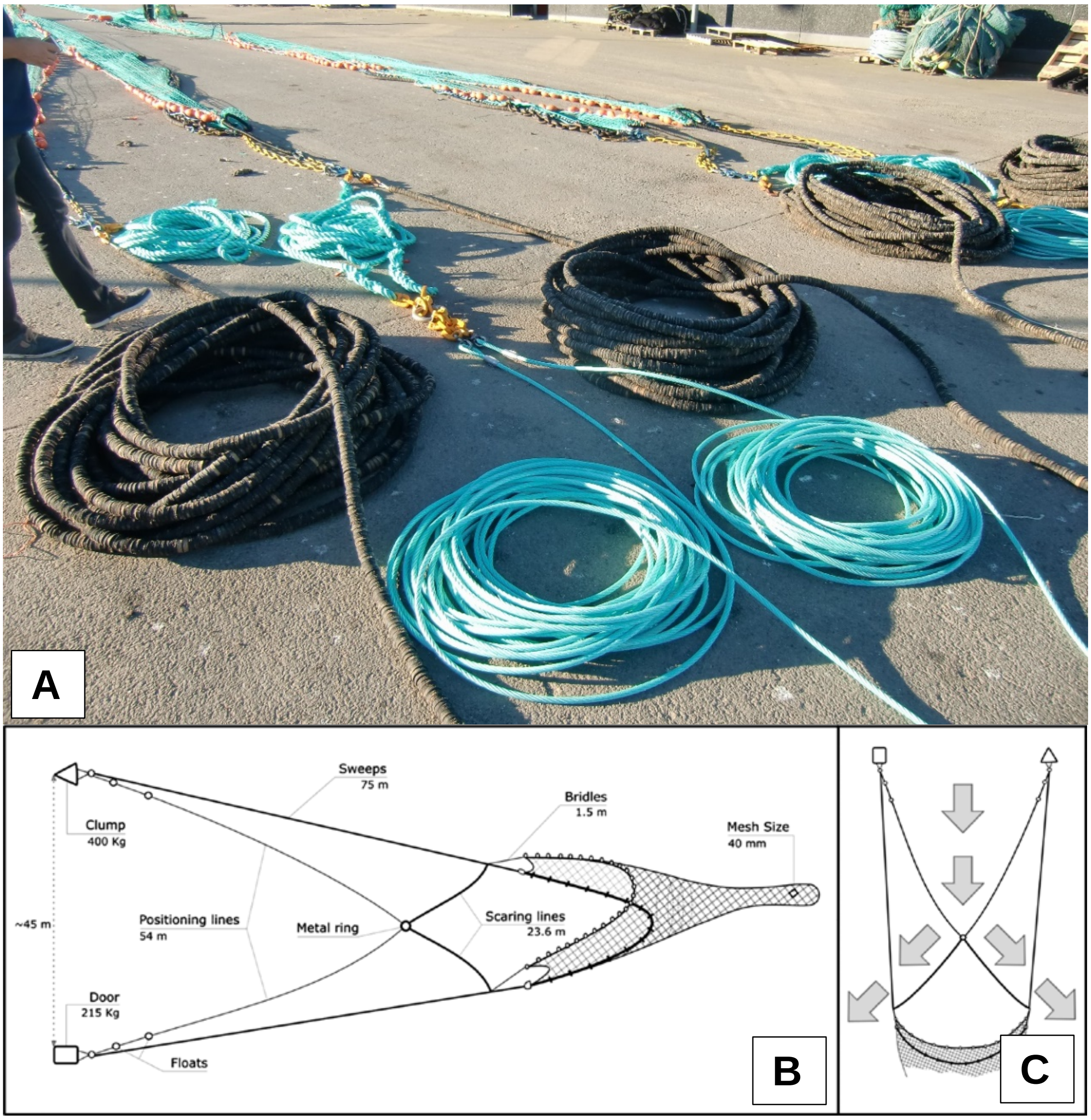

Figure 4. *FLEXSELECT design. (A & B) The port trawl in a twin rig with FLEXSELECT mounted. Proportions are not respected to facilitate the identification of all FLEXSELECT components. (B) Desired counter-herding effect. The grey arrows represent the direction of fish escape.*

Fishing was conducted during 5–20 September 2016 on commercial grounds in the Skagerrak, at depths between 33 and 87 m. 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.

To compare 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 rates 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. To understand the efficiency of FLEXSELECT in reducing fish catches, we estimated Catch Ratios with 95% Efron confidence intervals (Herrmann et al., 2017). Normally, 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. In contrast, a value of 0.5 indicates a 50% reduction in catch.

RESULTS

The FLEXSELECT counter-herding device became functional after a few adjustments of the design (e.g. addition of the floats to prevent twisting). A small reduction in door-to-clump spread (less than 4 m) in the trawl with FLEXSELECT was noticed. This was accounted for during the analyses by correcting the baseline values for equality (i.e. for catch ratio a value of 0.98 instead of 1.0).

Seven commercial species were included in the analysis: the target species, *Nephrops*; four roundfish species, cod, haddock, whiting, and hake; and two flatfish species, plaice and lemon sole. Because of 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. 5). 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 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. 5).

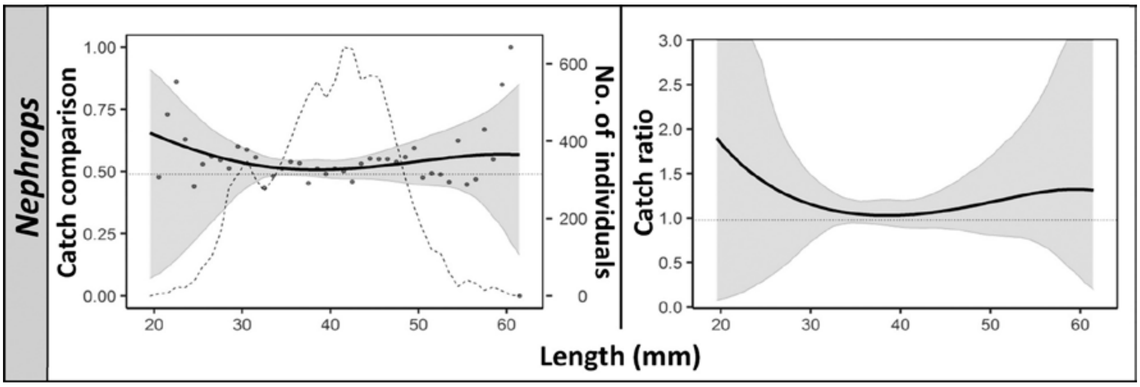

Figure 5. *Catch comparison rates and catch ratios for the target species Nephrops. Left panel: the curve (solid line) represents the modeled catch efficiency fitted to the experimental points (dots). The grey band represents 95% confidence intervals and the dashed line the length distribution observed in the catch. The dotted horizontal line, located at 0.49, describes equivalence in catch rates between the two trawls. Right panel: 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.*

Fish species

For the six fish species examined, FLEXSELECT reduced the catch in numbers by 39% (CI: 29%–46%). When considering the MCRS, catches of individuals above and below the limit were reduced by 49% (CI: 39%–57%) and 29% (CI: 19%–39%), respectively (Table 2). The catch ratio averaged over length showed significant effects for all fish species except for cod (Table 2). 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.

Table 2*. Catch ratios averaged over length classes.*

	Mean	CI low	CI high
Total 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	0.3	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

Note: 95% confidence intervals (CIs) are also shown. 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.

A significant catch reduction was detected for at least some of the length classes of all the four roundfish species analysed (Fig. 6). 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 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.

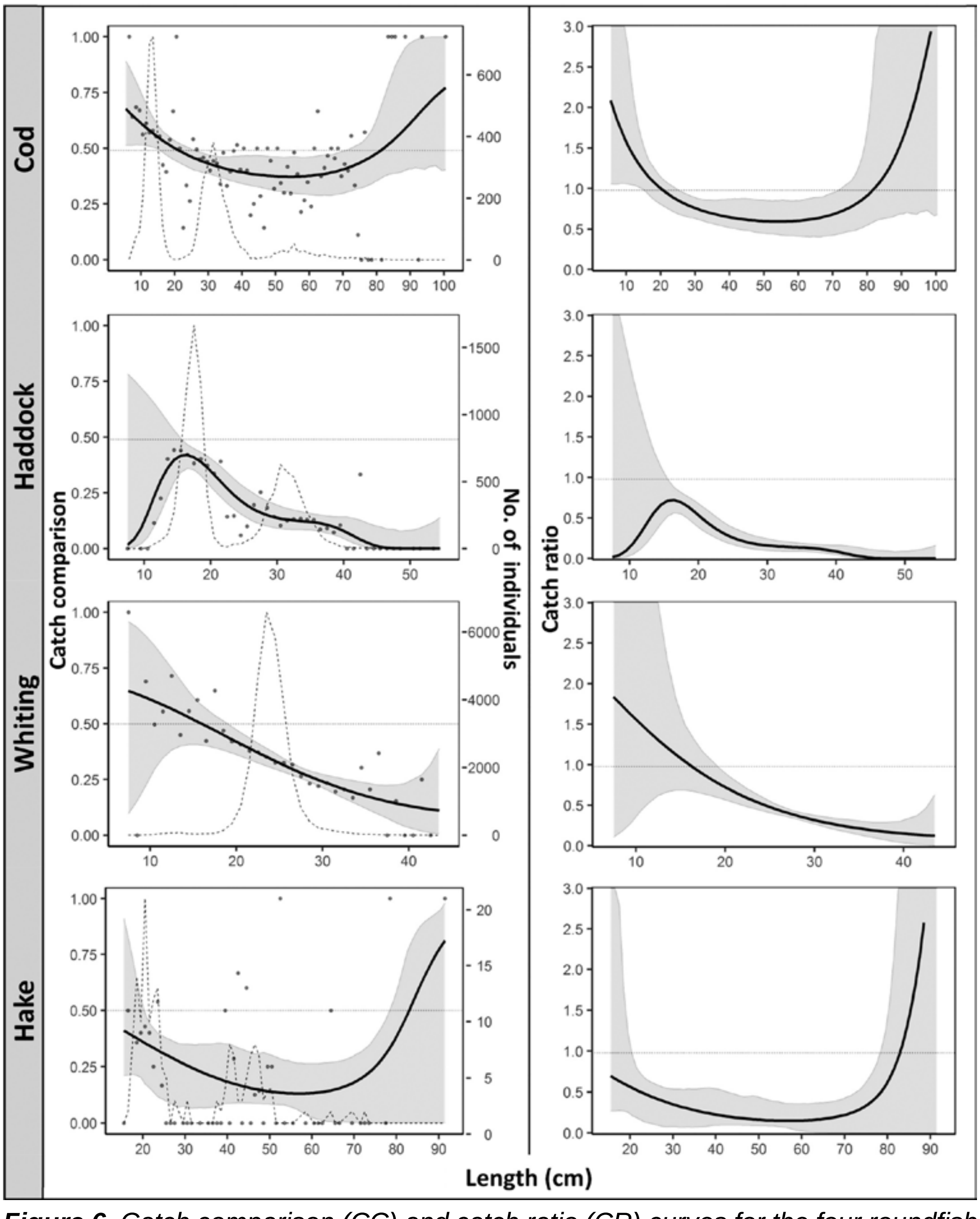

Figure 6. *Catch comparison (CC) and catch ratio (CR) curves for the four roundfish species. Left column: CC curves (solid lines) representing the modeled catch efficiencies fitted to the experimental points (dots). The grey bands show 95% CI's and the dashed lines the length distributions observed in the catch. The dotted horizontal lines, located at 0.49, represent the baseline for no effect. Right column: CR curves (solid line) with 95% CI's (grey bands). The dotted horizontal lines, located at 0.98, describe equivalence in catch between the two trawls.*

The catch ratio curves show that lemon sole catches were significantly reduced for length classes that were well represented in the data, whereas only small plaice (below 35 cm) were significantly affected by FLEXSELECT (Fig. 7).

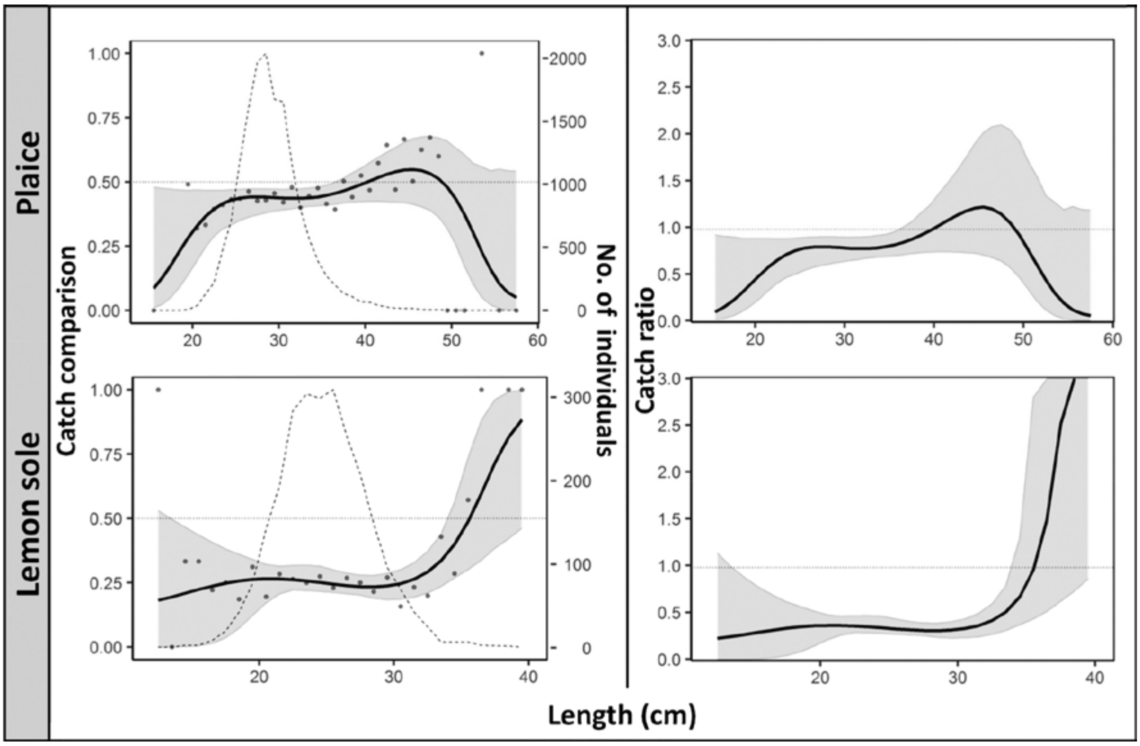

Figure 7. *Catch comparison (CC) and catch ratio (CR) curves for the two flatfish species. Left column: CC curves (solid lines) representing the modeled catch efficiencies fitted to the experimental points (dots). The grey bands show 95% CI's and the dashed lines the length distributions observed in the catch. The dotted horizontal lines, located at 0.49, represent the baseline for no effect. Right column: CR curves (solid line) with 95% CI's (grey bands). The dotted horizontal lines, located at 0.98, describe equivalence in catch between the two trawls.*

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 mixed trawl fishery, in which a reduction of fish bycatch is desirable after exhaustion of fish quotas. In such periods, fish in general represent 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 cod end (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.

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 basis 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 whether FLEXSELECT’s scaring lines stimulate fish to rise vertically in the water column and escape over the headline or whether 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 the same also applies 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 that are commercially less relevant but may still be important in an ecosystem context.

5.2 2nd scientific trial

AIMS

In this study, we modified the FLEXSELECT counter-herding device that was developed in the first scientific trial to reduce fish catches in a mixed species trawl fishery targeting *Nephrops*, to include an observation platform. The observation platform, consisting of a sledge, was used to observe species behavioural responses to FLEXSELECT. Furthermore, the observation platform raised FLEXSELECT’s scaring lines out of the seabed, a modification that was expected to reduce the efficiency of the device for flatfish species. Therefore, this study had the dual objective of understanding the behavioural mechanism underlying FLEXSELECT’s effect while quantifying the impact of the modification introduced in its design.

EXPERIMENTAL SETUP

The same components as of the original FLEXSELECT device (Melli et al., 2018) were used in this study: 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 from 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). The only difference introduced was the substitution of the central metal ring (25 mm thick, 17 cm diameter, 3 kg) with a metal sledge, hereafter referred to as observation platform (85L x 50W x 40H cm, 37 Kg, stainless steel; Fig. 8). The UTOFIA camera developed in an ongoing Horizon 2020 project was supposed to be used on the observation platform to collect footage of fish and *Nephrops* behaviour. Unfortunately, the UTOFIA camera requires to be cable-connected to the vessel and the lengths of the cable available at the time of the experiments where not compatible with the depths on the fishing grounds. As an alternative, the observation platform was equipped with three GoPro cameras (Hero 3), one directed forward, in the towing direction (Fig. 8b), and two directed backwards, each towards one of the scaring lines (Fig. 8c). Due to the fishing depth and optical characteristics of the fishing area (Aarup et al., 1996), artificial illumination was required for video recording. However, artificial lights could alter the behavioural responses in response to the FLEXSELECT components (Nguyen and Winger, 2019). Therefore, hauls were conducted with and without two Big Blue TL4500P LED Lights (4500 lumen), placed below the GoPro cameras, and the effect of the LED lights was determined statistically. These narrowed-beam powerful LED lights were chosen in the attempt of illuminating several meters of the 26 m long scaring lines.

To facilitate the deployment of the observation platform and prevent it from digging into the muddy bottoms, 10 floats (8 x 850 gr lift, 2 x 8610 gr lift) were attached on top of the sledge. 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.

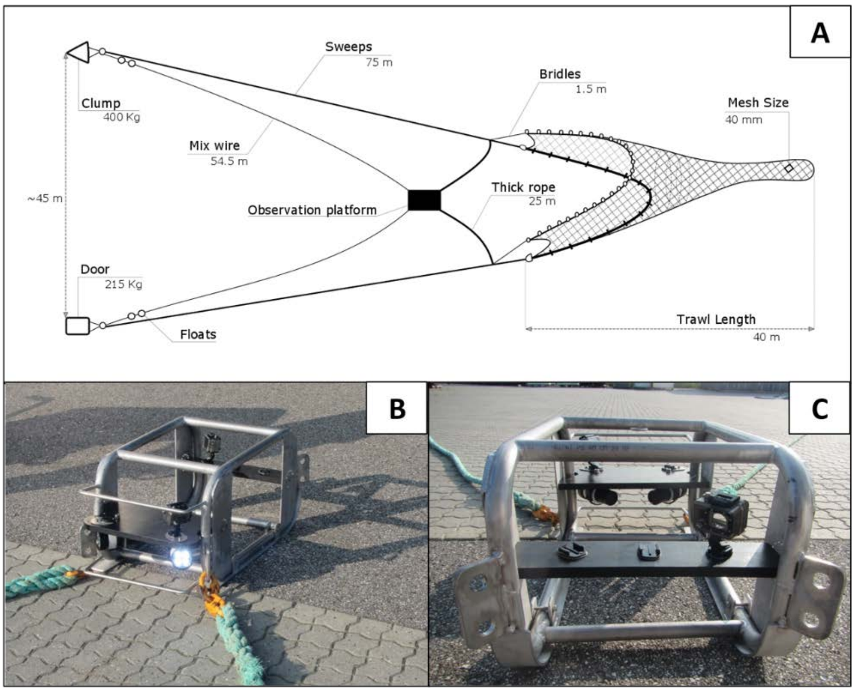

Figure 8. *A) FLEXSELECT and position of observation platform. B) Observation platform with scaring lines (back view). C) Observation platform, front view.*

Fishing was conducted in September 2017 in commercial grounds in the Skagerrak Sea, at depths between 33 m and 87 m. Hauls were performed only during day-time, i.e. one hour after sunrise and before 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. Video footage was collected during the hauls where the observation platform was equipped with LED lights.

The video footage collected showed that the introduction of the observation platform raised the scaring lines out of the seabed, just enough for them not to sweep the bottom. Therefore, we were interested in determining if and how this modification would alter the effect of the previous FLEXSELECT design, with sweeping scaring lines (Melli et al., 2018). Because the gear used as baseline in Melli et al. (2018) was the same used in this study, it is possible to indirectly assess eventual differences in efficiency between the two FLEXSELECT designs. Therefore, the analyses were conducted in two steps: first, we estimated the length dependent relative catch efficiency of the trawl equipped with the current FLEXSELECT design, i.e. floating scaring lines, in relation to the baseline gear; second, we determined the difference with respect to the previous FLEXSELECT design, i.e. sweeping scaring lines, by calculating the ratio between the catch ratio curves obtained from the two trials (Veiga-Malta et al., 2019). All the analyses were performed using the software SELNET (Herrmann et al., 2012).

The effect of FLEXSELECT was assessed for each species separately, comparing the catches of the test trawl (T) equipped with the counter-herding device, and the baseline trawl (B). Hauls with and without LED lights were first analysed separately to determine any significant change in efficiency deriving from the presence of artificial illumination. If no difference was detected, the analysis was conducted on the totality of the hauls.

RESULTS

The 11 hauls with LED lights were used to collect video observations of fishes behavioural responses to the scaring lines. The quality of the footage was insufficient to attempt any quantitative analyses, as species identification was often not possible. Nonetheless, the footage collected allowed assessing qualitatively the main type of behavioural response and its direction with respect to the scaring lines, at least for roundfish species. Most individuals were observed swimming individually or staying in proximity of the seafloor. Once approached by the scaring lines, they reacted by a quick burst in swimming speed, to rapidly gain distance from the lines (Fig. 9). After this first burst, most individuals stabilized their swimming speed and swam away. The direction of the escape was extremely variable: some individuals rose vertically (Fig. 9a), some moved away while staying close to the seabed (Fig. 9b) and some crossed the scaring lines, either below or above them, and swam in the opposite direction then when first encountering the lines (Fig. 2c-e). No species-specific pattern in the direction of the response was evident in the footage, as individuals of the same species were observed escaping in different directions.

The effect of the novel FLEXSELECT design, with floating scaring lines, was quantified for seven commercial species: the target species, *Nephrops*; four roundfish species, cod, haddock, whiting and hake; and two flatfish species, lemon sole and plaice. All species were sampled in hauls with and without LED lights on the observation platform; no significant difference in the effect of FLEXSELECT was detected for any of the species. Therefore, for all seven species, the effect of FLEXSELECT was estimated on the totality of the valid hauls for that species.

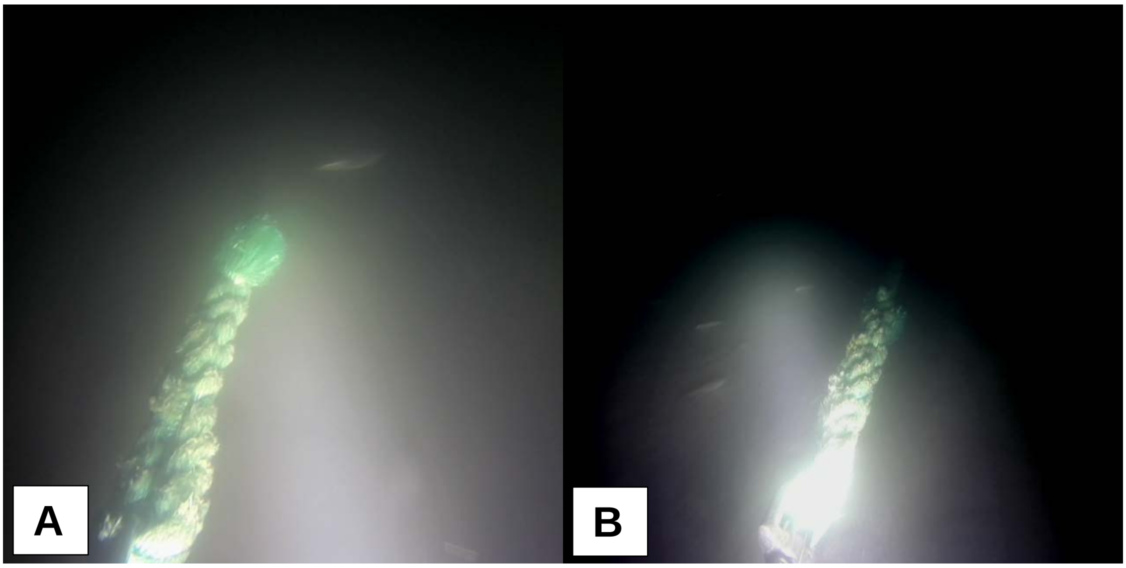

Figure 9. *Screenshots from underwater video observations. A) A gadoid rising over the scaring lines. B) Fish staying close to the seabed.*

Target species: *Nephrops*

In terms of effect of the FLEXSELECT device, the catch ratio between the test and the baseline trawls detected a significant loss of *Nephrops*, as the confidence intervals did not overlap the baseline for equal catch for length classes between 24 and 45 mm CL (Fig. 10).

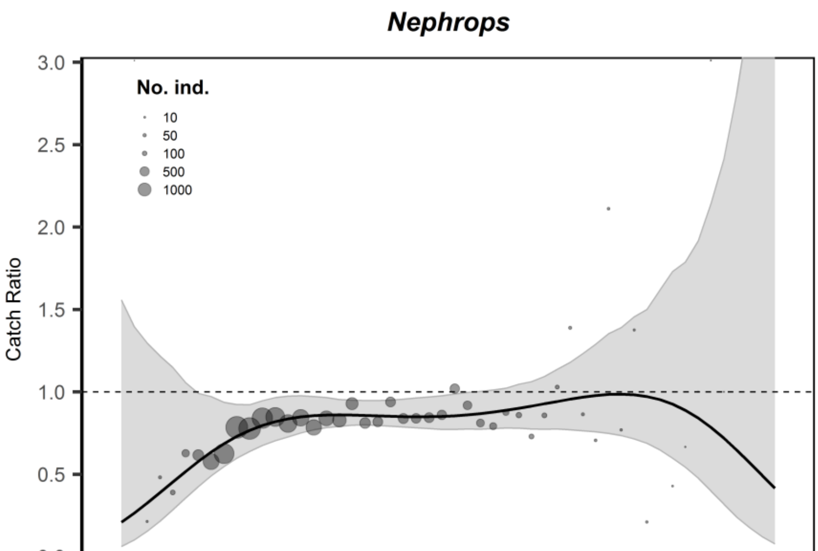

Figure 10. *Catch ratio for the target species Nephrops. The curve (solid line) represents the modelled catch ratio fitted to the experimental points (dots). The size of the dots is relative to the total number of individuals of that length class caught in either trawl. Experimental points above 3.0 in Catch Ratio were placed at the upper margin of the plot. The grey ribbon represents 95% Efron Confidence Intervals. The dashed horizontal line, located at 1.0, describes equivalence in catch between the two trawls.*

Fish species

The catch ratio curves showed a significant reduction in the catches of the test trawl with FLEXSELECT for all the commercial fish species analysed (Fig. 11). 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 represented by the wider CIs (Fig. 4); nonetheless, a significant reduction was detected for lengths between 18–24 and 41–99 cm. All roundfish species showed a length-dependent effect of FLEXSELECT, with a stronger reduction of larger individuals rather than smaller individuals. In contrast, for the two flatfish species, the significant reduction in catch was limited to smaller individuals, between 10–29 and 15–31 cm for lemon sole and plaice, respectively (Fig. 11). However, as shown by the size of the experimental points in Figure 11, very few large individuals (i.e. above the MCRS, for the species) were encountered during the trial.

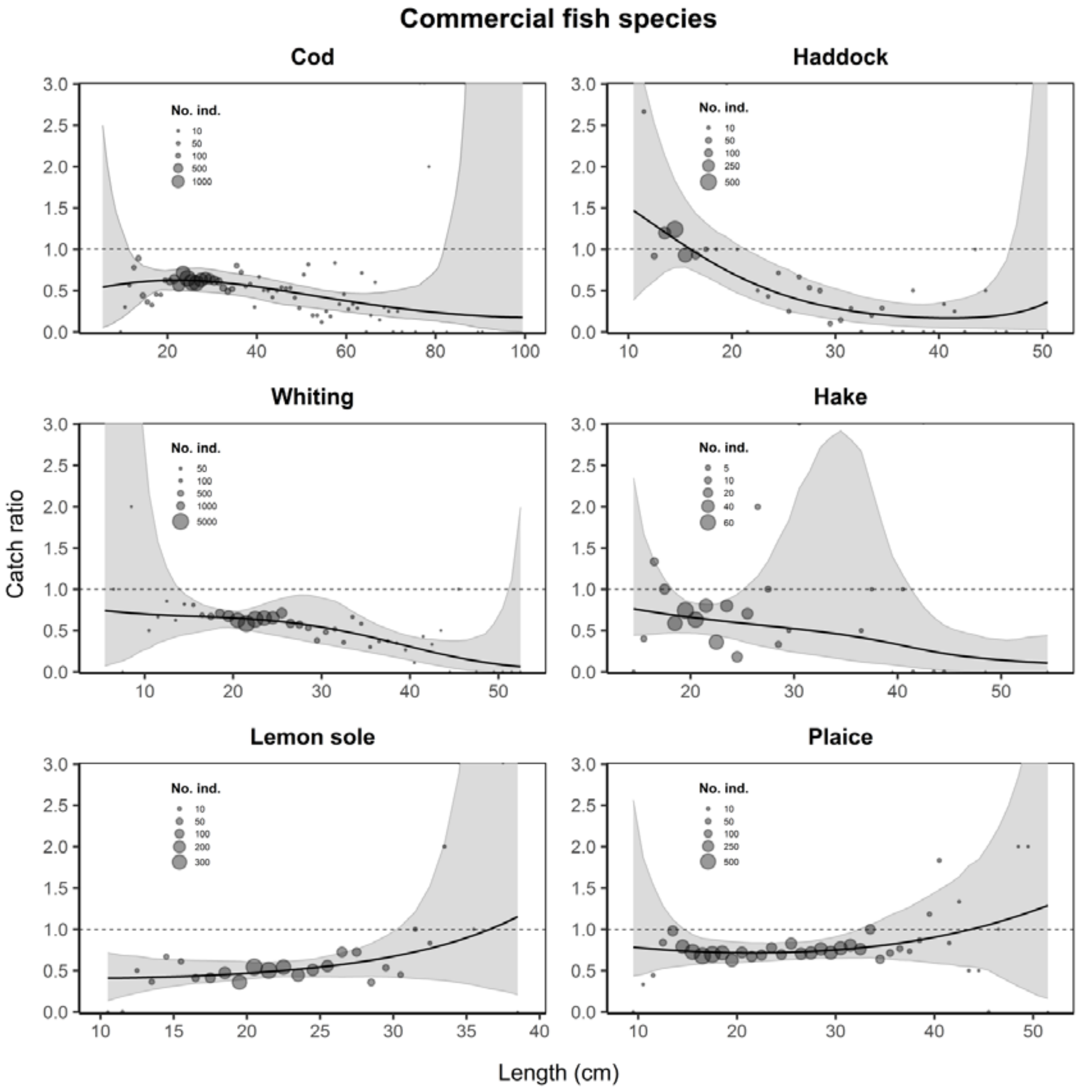

Figure 11. *Catch ratio for the six commercial fish species. The curve (solid line) represents the modelled CR fitted to the experimental points (dots). The size of the dots is relative to the total number of individuals of that length class caught in either trawl. Experimental points above 3.0 in Catch Ratio were placed at the upper margin of the plot. The grey ribbon represents 95% CI's. The dashed horizontal line, located at 1.0, describes equivalence in catch between the two trawls.*

Original design vs floating scaring lines

When compared to the effect of the previous FLEXSELECT device, with sweeping scaring lines, the new design had a significantly different effect on four of the species analysed (Fig. 12). In particular, the ratio of catch ratios showed that significantly less *Nephrops* (32–41 mm CL) and cod (10–25 and 52–80 cm) were caught using floating scaring lines with respect to sweeping ones. In contrast, the new FLEXSELECT design retained significantly more whiting (28–36 cm) and lemon sole (21–31 cm). Therefore, in terms of efficiency as a bycatch reduction device, the FLEXSELECT with floating scaring lines was significantly and substantially more effective on cod. However, it was less effective on whiting and lemon sole and caused a loss of commercial target catch of *Nephrops* (MCRS in the Skagerrak and Kattegat = 32 mm).

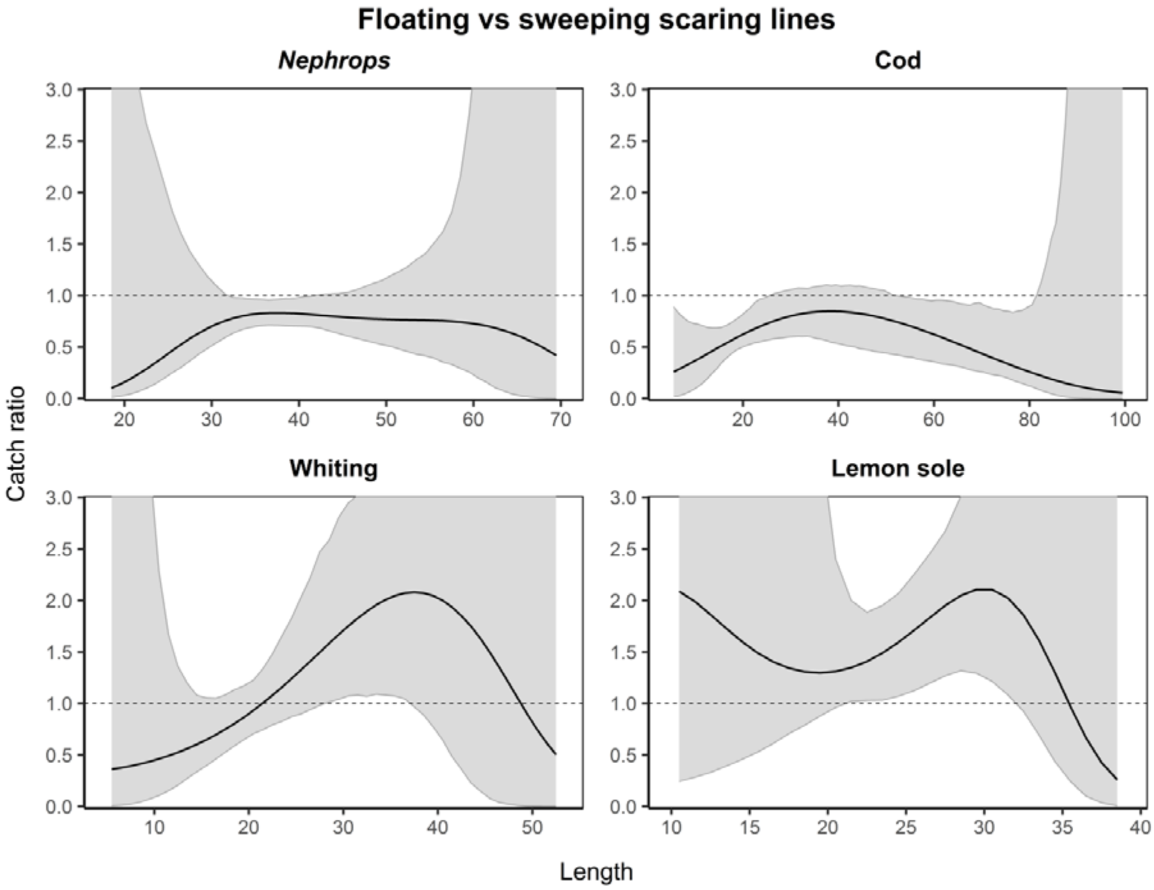

Figure 12. *Comparison of FLEXSELECT designs: floating scaring lines (current design) vs sweeping ones (Melli et al., 2018). The curve (solid line) represents the modelled ratio of catch ratio curves from the two individual experiments. The grey ribbon represents 95% CI's estimated from the two bootstrap 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 successfully incorporated an observation platform into the design of FLEXSELECT, collecting useful footage of species behavioural responses in a critical phase of the capture process. By incorporating the observation platform into FLEXSELECT we were able to collect footage throughout the experiment. Unfortunately, the usability of the video collected was limited by the image quality. Although quantitative behavioural analyses were precluded due to the limits mentioned above, the footage collected was sufficient to understand the main behavioural response behind FLEXSELECT efficiency. Indeed, the responses observed are consistent with the avoidance behaviours described towards other anterior gear components, with multiple studies having reported an increase in swimming speed of the individuals (e.g. Handegard and Tjøstheim, 2005; McQuinn and Winger, 2003; Winger et al., 2010).

In terms of FLEXSELECT design, the introduction of the observation platform produced significant changes in the dynamics of the scaring lines, raising them out of the seafloor. This difference in the design significantly altered their effectiveness on four of the species analysed. The most affected species were cod and lemon sole, with an increase and decrease in the effect, respectively, with floating scaring lines. In Melli et al. (2018), the effect of FLEXSELECT with sweeping lines on cod was strongly length-dependent, with a significant reduction of catches between 25 and 71 cm, but an increase in catches of juveniles (below 14 cm). Here, the reduction in cod catches was significant for most of the length classes encountered (11–81 cm) and no significant increase in juvenile catches was observed. This result is consistent with the hypothesis formulated by Melli et al. (2018) of cod being over-taken by the sweeping scaring lines due to their closer proximity to the seafloor. In contrast, the novel FLEXSELECT device was less efficient in reducing the catch of lemon sole, suggesting that more individuals escape below the scaring lines or simply do not respond to them. These two species seem to react as predicted by Ryer (2008); however, contrary to expectations, a significant reduction of effect was found for whiting and no change in efficiency was identified for plaice. These results suggest that the degree of variation in behaviour between species, populations, and individuals remains poorly understood, likely due to the difficulty of observing and quantifying fish behaviour in this region of the gear (Bayse et al., 2016). Finally, raising the scaring lines out of the seafloor had a significant, although limited, effect on *Nephrops*, leading to a partial loss of commercial target catch. The 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. A potential explanation, warranting further investigation, is that the floating scaring lines had a flapping dynamic during towing, which stimulated *Nephrops* to enter their burrows (Bell et al., 2016).

Overall, the efficiency of the FLEXSELECT design with floating scaring lines is of substantial interest for the *Nephrops*-directed mix trawl fishery in Kattegat and Skagerrak. Indeed, cod represents a potential choke species in this area under the EU landing obligation (North Sea Advisory Council, 2018), thus the increased efficiency found in this study could prevent fishermen from running out of cod quota before they can fulfil the *Nephrops* quota. Moreover, the reduction in effect on lemon sole, which is not a quota-regulated species, and whiting, whose catches can be further reduced by the mandatory escape panel in the codend (Frandsen et al., 2009) should not represent a concern for the industry. Therefore, the single negative outcome of the modification introduced in FLEXSELECT design was the partial loss of commercial-sized *Nephrops*. Although the causes of such loss should be further investigated, it is unlikely to limit the usability of the device, which thanks to its fast and flexible attachment system can be applied to the trawl only when approaching quota exhaustion for the choke species (Melli et al., 2018).

6. Commercial testing on board FN 436 Tove Kajgaard

Two experimental trials were conducted on board the commercial vessel “Tove Kajgaard” (FN436; 29 m, 299 kW), during September 2018 and March 2019. The vessel was equipped for three-wire, twin-trawling, with two standard commercial trawls with SELTRA codends made of 90 mm diamond mesh and a 140 mm square mesh panel (4 m long; starting at 7 m from the codline). The trawls were rigged with 85 m long single wire sweeps with 4.3 cm (diameter) rubber cookies.

6.1 1st commercial test

AIMS

During the first commercial trial, FLEXSELECT’s performance under commercial fishing conditions was determined in comparison to the standard commercial gear. Moreover, two different length of scaring lines were tested to determine if and how the species-specific performance of FLEXSELECT varies depending on its geometry (e.g. angle of the scaring lines with respect to towing direction; Fig. 13). The hypothesis was that longer scaring lines could be more efficient in reducing catches of flatfish species, which require more time to swim out of the trawl path.

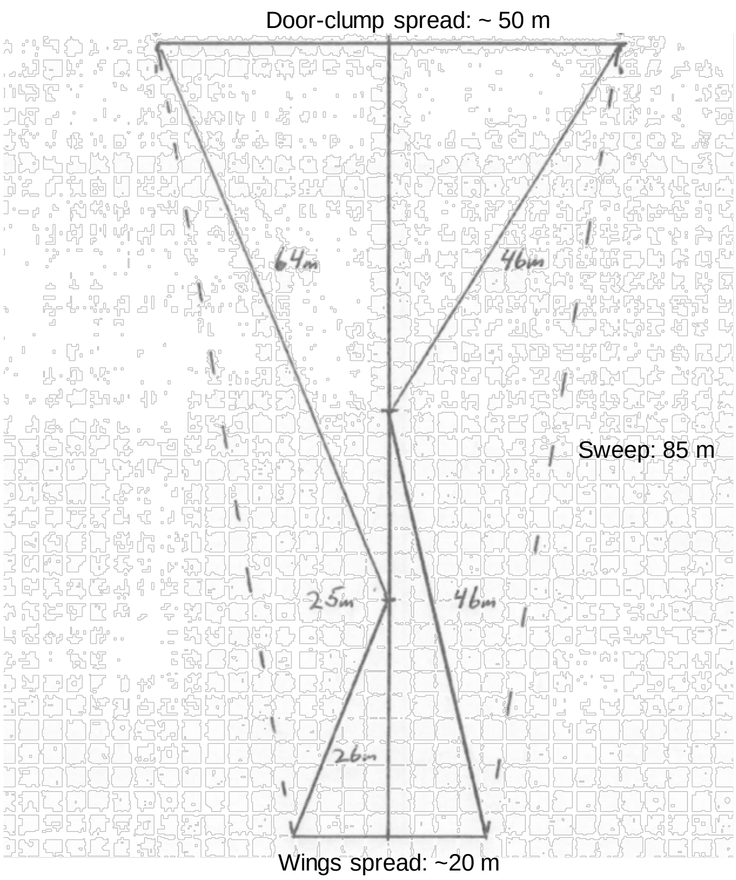

Figure 13. *Schematic illustration of the two geometries of FLEXSELECT tested. The left part of the scheme illustrates the configuration with short scaring lines (26 m), while the right part represents the configuration with long scaring lines (46 m).*

EXPERIMENTAL SETUP

FLEXSELECT’s design was scaled up to match the dimensions of the commercial gear and the materials used were adjusted in accordance to the fishermen’s suggestions, to facilitate even more the handling and deployment of the device. In particular, the two positioning lines, previously made of mix wires (steel core and polypropylene cover, 6 strands, 14 mm in diameter, 0.21 kg/m), were replaced by Dyneema ropes (10 mm diameter), a much stronger and durable Polyethylene fiber. The central link, previously represented by a metal ring, was replaced by a 1.5 m long braided rope (PE, 26 mm diameter) with links for the attachment of the positioning and scaring lines (Fig. 14); this solution enabled a higher flexibility in the geometry and, thus, a lower risk of constriction of the trawl spread.

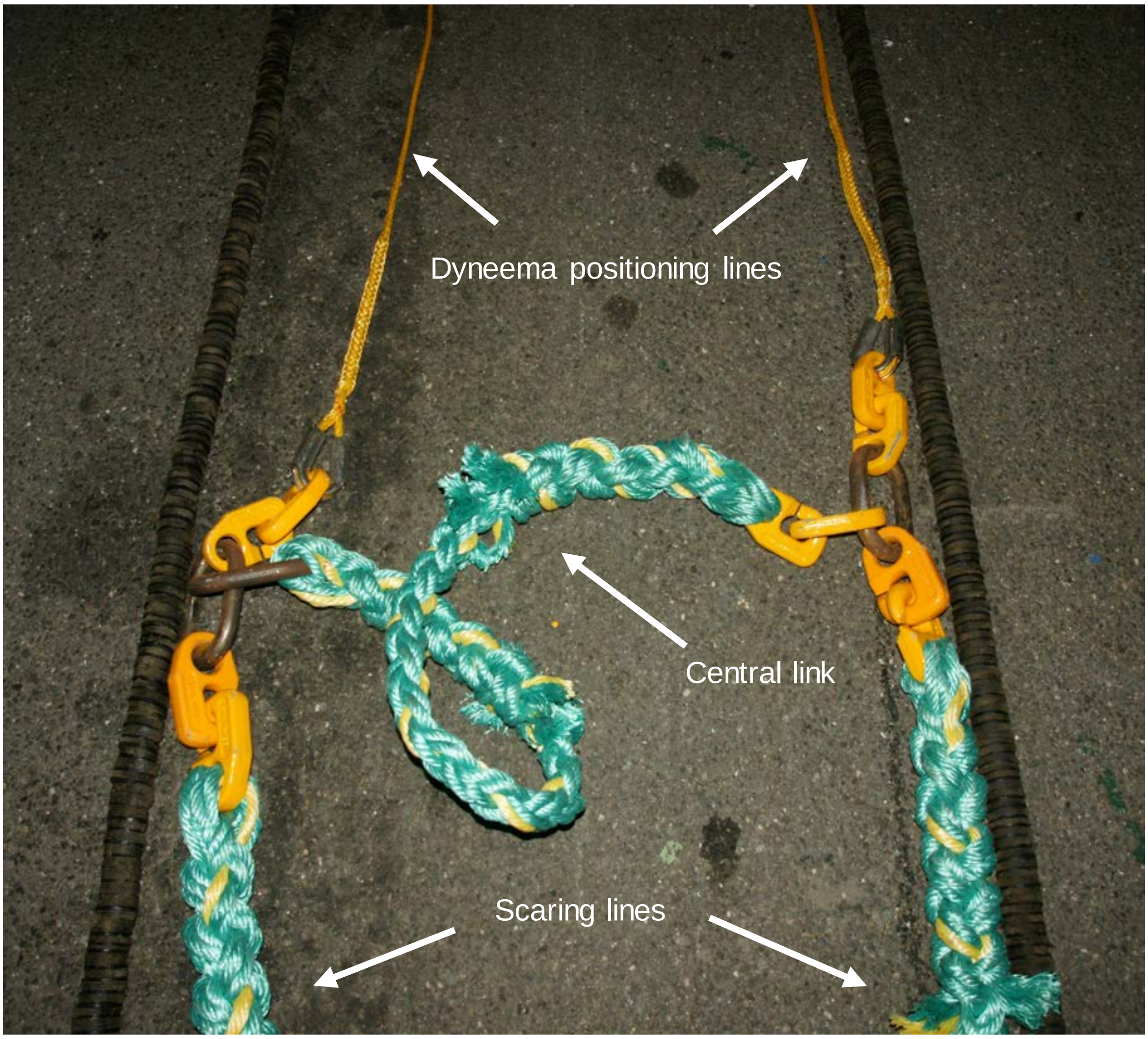

Figure 14. *Different components of the commercial version of FLEXSELECT used on FN 436 Tove Kajgaard.*

The two following FLEXSELECT configuration were tested:

1) Short (26 m) scaring lines made of 32 mm PE braided ropes;
2) Long (46 m) scaring lines made of 32 mm PE braided ropes.

The positioning lines were scaled accordingly to the length of the scaring lines used, to 64 and 46 m, respectively (Fig. 13).

For each of the FLEXSELECT configurations, one trawl was equipped with the device and one worked as control. Because the same control trawl was used between experiments, we could subsequently compare the performance of the two FLEXSELECT configurations. Fishing was conducted in September 2018 on commercial grounds in the Skagerrak and Kattegat, at depths between 40 and 110 m. Hauls were performed during both day- and night-time, as the previous data suggest no diel-effect on the efficiency of FLEXSELECT. After each haul, the total catch was weighed and 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.

To compare 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 rates 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. To understand the efficiency of FLEXSELECT in reducing fish catches, we estimated Catch Ratios with 95% Efron confidence intervals (Herrmann et al., 2017). 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. In contrast, a value of 0.5 indicates a 50% reduction in catch. The analyses were performed using the software SELNET (Herrmann et al., 2012).

RESULTS

Sufficient data for analyses were collected for *Nephrops*, three roundfish species (cod, hake, and saithe) and three flatfish species (plaice, lemon sole, and witch flounder).

The results confirmed the efficiency of FLEXSELECT, even in its commercial adaptation, in reducing the catch of fish without losing *Nephrops*. With the short scaring lines configuration (equivalent to the one tested during the scientific trials), significant reductions in catch in the test trawl with FLEXSELECT were detected for all roundfish, in particular cod (26-50 cm) and saithe (48-59; 97-106 cm; Fig. 15). In contrast, out of the three flatfish species analyzed, only plaice (27-35 cm) showed a significant reduction (Fig. 15). In regards to the target species, *Nephrops*, catches of individuals between 30 and 39 mm (carapace length) were significantly higher in the trawl with FLEXSELECT with respect to the control one (SELTRA).

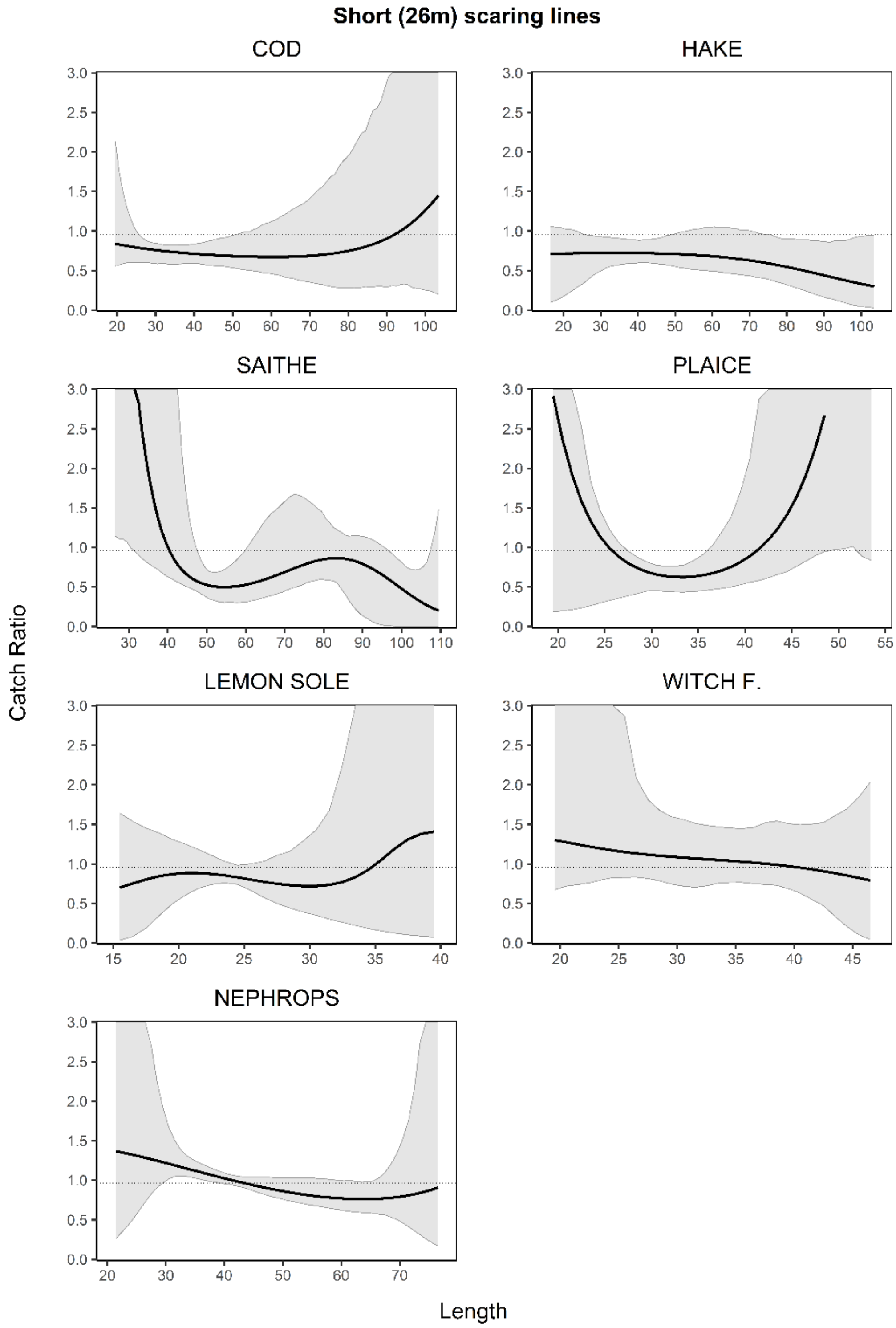

Figure 15. *Catch ratios showing the effect of the short scaring lines configuration for the seven species analysed. Catch ratio curves (solid line) with 95% confidence intervals (grey bands). The dotted horizontal lines describe equivalence in catch between the two trawls (i.e. no effect of FLEXSELECT). Lengths are in cm for fish species, and mm for Nephrops.*

When comparing the efficiency of the short (26 m) and long (46 m) scaring lines configurations, the short scaring lines were overall more effective in reducing the catch of fish. Indeed, with longer scaring lines the effect on the roundfish species (cod, saithe, and hake), as well as that on plaice, was lost, with no difference in catch detected between the test and control trawls (Fig. 16). Only the effect on *Nephrops* was maintained and even a stronger increase in catches was achieved with the longer scaring lines configuration (up to 15% increase of commercial sized *Nephrops*; Fig. 16).

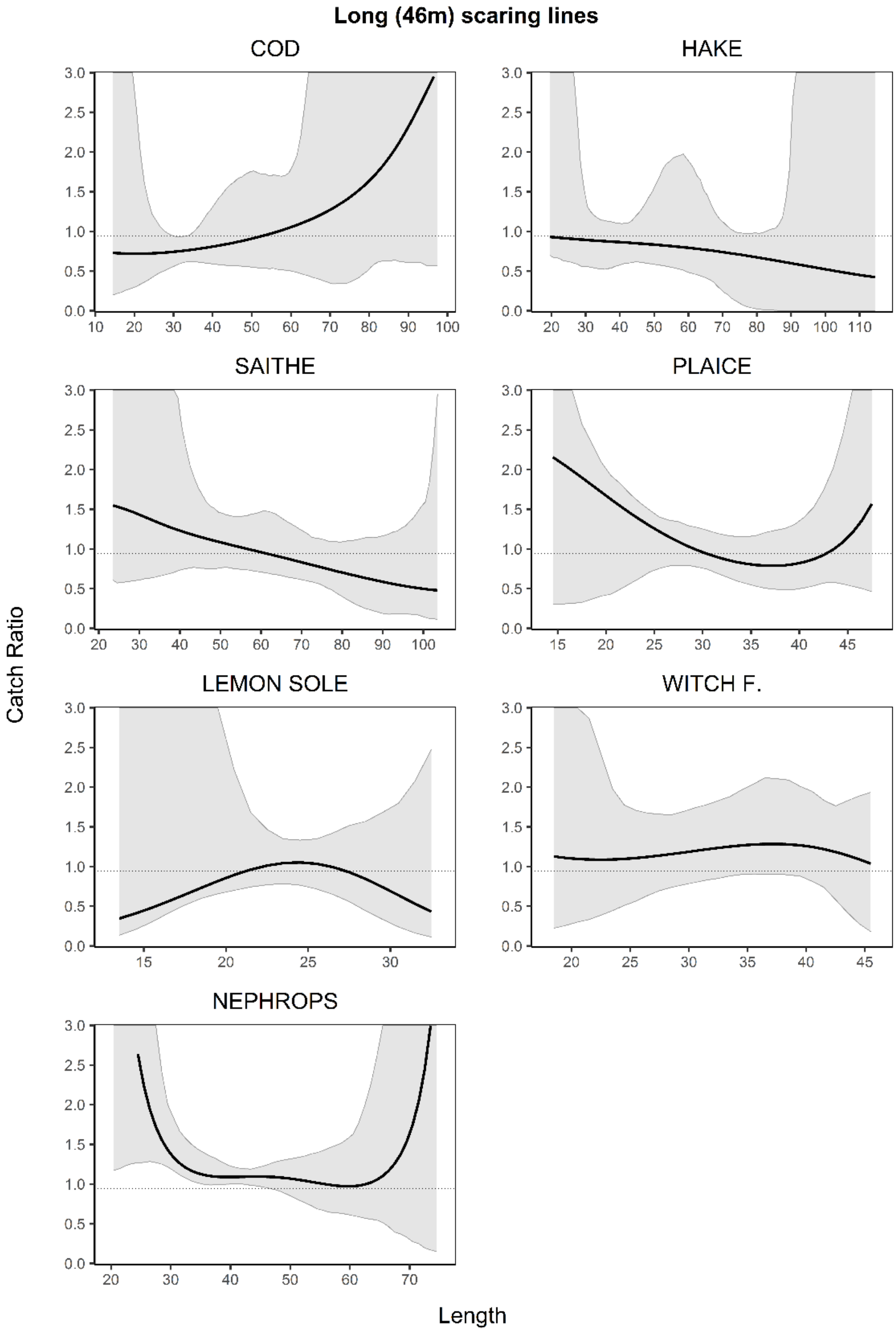

Figure 16. *Catch ratios showing the effect of the long scaring lines configuration for the seven species analysed. Catch ratio curves (solid line) with 95% confidence intervals (grey bands). The dotted horizontal lines describe equivalence in catch between the two trawls (i.e. no effect of FLEXSELECT). Lengths are in cm for fish species, and mm for Nephrops.*

DISCUSSION

This first commercial test of FLEXSELECT reiterated the potential of the configuration with short scaring lines as a flexible bycatch reduction device, to be applied in addition to the SELTRA codend when bycatch levels, especially those of roundfish, are high. The experiment also confirmed the increase in catch of *Nephrops*, previously identified as only a tendency during the scientific trials. Such increase, which extend to both undersized and commercial size individuals, can be considered a positive outcome, as long as the undersized individuals are discarded alive (Méhault et al., 2016).

Contrary to expectations, the configuration with longer scaring lines was not more effective in leading flatfish out of the trawl path. Even worse, this configuration was ineffective on all the species analysed with the exception of the main target species, *Nephrops*. This increased effect on *Nephrops* suggests that the individuals are perhaps overtaken by the scaring lines and instead of re-entering the burrows, they end up exposed to capture by the trawl.

Finally, the short scaring lines configuration was easier to operate and store on-board the vessel, as it is lighter and less cumbersome. Therefore, this configuration was identified as the best one for commercial use of the FLEXSELECT device.

6.2 2nd commercial test

AIMS

During the second commercial trial, we investigated the effect of varying the material used for FLEXSELECT's scaring lines and their construction. In particular, instead of using one thick rope, four thin ropes were tied together, resulting in a lighter and theoretically more dynamic (i.e. subject to oscillations) configuration. The performance of this new configuration was determined under commercial fishing conditions, with respect to the same control gear used in the previous trial. Because the same control gear was used, we could compare the efficiency of such configuration with respect to the previously tested ones. The aim was to determine if the change in materials and dynamics of the scaring lines would significantly affect the species-specific performance of FLEXSELECT.

EXPERIMENTAL SETUP

The same exact design of FLEXSELECT described in section 6.1 was used in this trial, with the exception of the scaring lines. These were made of four 8 mm thick ropes (PE, braided) tied together every 2 m (Fig. 17). According to the previous results, the length of the scaring lines was of 26 m (the configuration proved more efficient from the previous trial; section 6.1).

Fishing was conducted in March on commercial fishing grounds in the Skagerrak and Kattegat, at depths between 40 and 110 m. Similarly, to the previous trial, hauls were performed during both day- and night-time, the total catch of each trawl was weighed and sorted by species, and the length (TL and CL, respectively) of all commercial fish species and *Nephrops* were measured. Analyses were conducted as previously described in section 6.1, using the software SELNET (Herrmann et al., 2012).

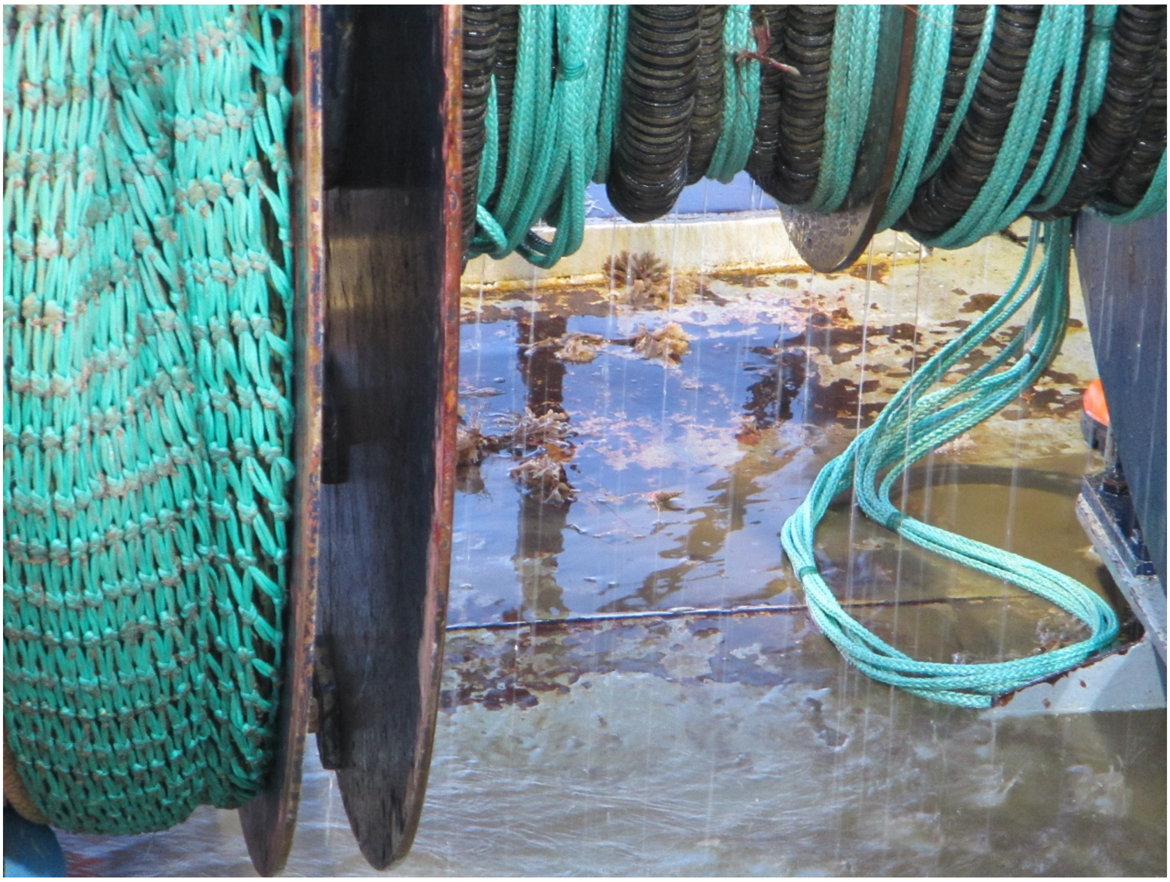

Figure 17. *Picture of the modified scaring lines used in the second trial on board FN 436 Tove Kajgaard.*

RESULTS

Sufficient data for analyses were collected for *Nephrops*, three roundfish species (cod, haddock and whiting) and two flatfish species (plaice and witch flounder). Unfortunately, fish catches were low during the trial period, resulting in high uncertainty in the modelled Catch Ratios (as represented by the wide confidence intervals in Fig. 18).

The configuration of FLEXSELECT tested was highly effective in reducing the catch of haddock and whiting, but no significant effect was detected for cod and plaice, and an increase in the catch of undersized witch flounder was identified. There are some indications that the lack of effect on cod was caused by the low number of individuals caught during the experiment and by the high variability across hauls that is typical of this species. It is likely that additional data for this species would prove a significant reduction.

Surprisingly, a relatively strong, and extended in terms of length range (32 to 57 mm CL), reduction in commercial catch of *Nephrops* was found for the test trawl with FLEXSELECT (Fig. 18). Such reduction was unprecedented in all experimental trials of FLEXSELECT, with only a minor reduction previously observed with the floating scaring lines in the second scientific trial (section 5.2).

Overall, there was no significant difference for the fish bycatch species in the performance of this configuration with respect to the one with 26 m long scaring lines made of single thick ropes. In contrast, the effect on *Nephrops* was significant, as that configuration led to an increase in catches while the currently described one caused a substantial loss.

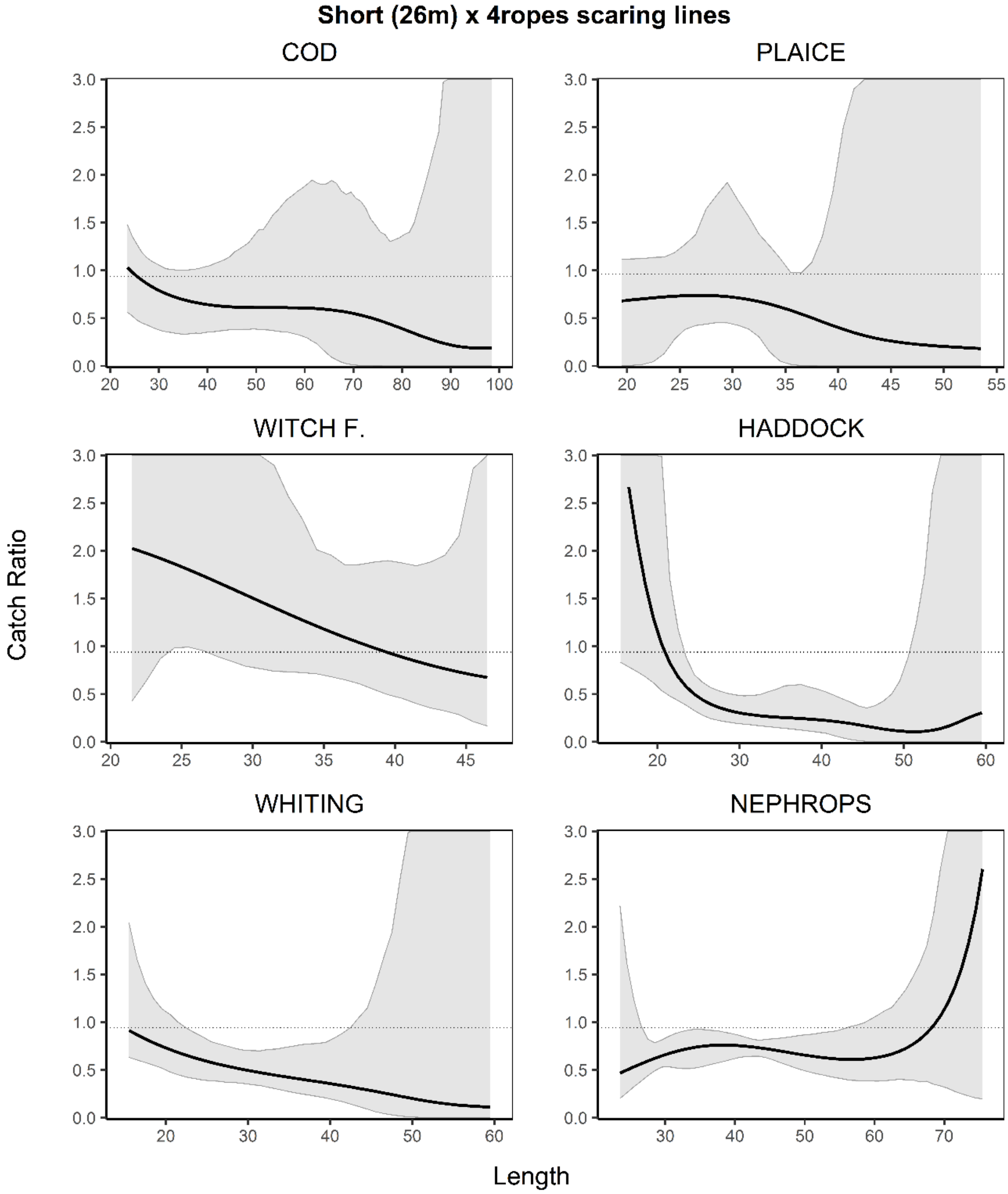

Figure 18. *Catch ratios showing the effect of the flapping scaring lines configuration for the six species analysed. Catch ratio curves (solid line) with 95% confidence intervals (grey bands). The dotted horizontal lines describe equivalence in catch between the two trawls (i.e. no effect of FLEXSELECT). Lengths are in cm for fish species, and mm for Nephrops.*

DISCUSSION

The results of this second trial provides interesting insights regarding *Nephrops* behaviour and catchability. We suspect that the loss of *Nephrops* was caused by the scaring lines flapping on the seafloor or producing vibrations that alerted the individuals in advance of the trawl approaching, allowing them to enter the burrows. The mechanism should, however, be clarified through video collection or laboratory experiments.

The increase in catch of undersized witch flounder is also intriguing, as it is difficult to explain from a behavioural point of view. This increase, although undesirable because of the individuals being undersized, has little relevance for the fishery, as this species is not subjected to quota. Finally, the results of this trial, together with the previous trials, showed that there is a great potential for further refinements of the FLEXSELECT counter herding device, as both changes in its geometry (length of scaring lines) and materials had significant consequences on its efficiency.

7. Technical specifications of FlexSelect

Among all the configurations of FLEXSELECT tested during the project, the commercial adaptation with short (26 m) scaring lines was the most successful and should be used as model for future commercial applications.
In particular, such configuration achieved the following goals:

- It was easy to handle, both on board the vessel and during deployment/recollection of the gear, and store when not used. This latter feature is highly desirable as the FLEXSELECT device is meant to be used at the haul-by-haul level, when fishermen encounter high abundances of unwanted bycatch species.
- It resolved the issue of reducing significantly the spread of the trawl by allowing more flexibility in the central link of the device. As a result, instead of being reduced the spread of the trawl with FLEXSELECT resulted more stable throughout the haul; this effect was appreciated by the fishermen because it may ensure also a more stable contact of the fishing rope with the seafloor, thus enhancing *Nephrops* catches.
- It was effective in reducing catches of low value commercial cod sizes (category IV and V) while allowing the retention of larger and more valuable cod individuals. This effect is of substantial interest, in particular for the Kattegat mixed fisheries, as quota for cod is strongly limited and it is likely to have a chocking effect on the fishery.

It is our recommendation that future commercial application of FLEXSELECT adopt the same materials and geometry as tested on board FN 436 Tove Kajgaard in September 2018, and described herein:

- Positioning lines: made of thin (8 mm) Dyneema. When scaling of the FLEXSELECT device is required, due to different trawl and/or sweeps lengths with respect to the used by FN 436 Tove Kajgaard, it is the length of the positioning lines, not of the scaring lines, that should be adjusted. The positioning lines, indeed, are meant to have little to no interaction with the seafloor and, thus, their elongation/shortening should not have strong consequences on the expected efficiency of the counter-herding device.
- Central link: the central link should be positioned approximately 20-25 m ahead of the fishing line, to enable sufficient time for the individuals to escape from the trawl path. It should also ensure some flexibility in the geometry of FLEXSELECT to prevent effects on the spread. Finally, the materials used should be strong enough to handle the drag produced by the interaction between the scaring lines and the seafloor. We found that the materials used during the trial on FN 436 Tove Kajgaard (26 mm PE rope, 1.5 m long, attached to the lines *via* Viking hooks) were efficient and easily accessible to the industry.
- Scaring lines: approximately 26 m long, thick ropes. We used 32 mm thick ropes in this study, and although it could be possible to adopt even heavier ropes, we concluded, in agreement with the crew of the FN 436 Tove Kajgaard, that thicker scaring lines wuld be more difficult to handle and store.

Finally, it is important to point out that the geometry of the FLEXSELECT device will vary depending on the door-to-clump spread. Because the spread varies typically according to the fishing depth, and because *Nephrops*-directed fisheries operate on a wide range of fishing depths, it is important to have on-board extension pieces for the Dyneema positioning lines so that these can be elongated when required to prevent tension in the lines (Fig. 19).

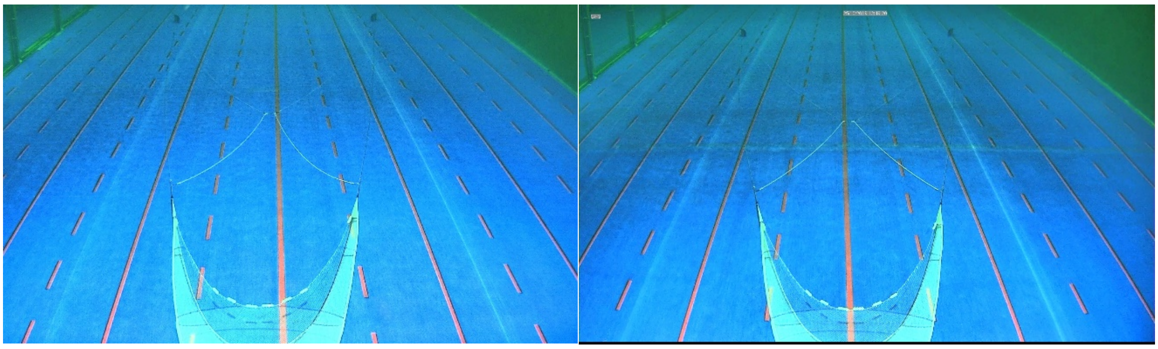

Figure 19. *Pictures from the scaled model of FLEXSELECT in SINTEF's trawl tank in Hirtshals, showing the device at two different spread openings. On the left, with smaller doors spread the scaring lines are not in tension and can sweep the seafloor. On the right, at a greater spread the scaring lines are in tension and may rise above the seafloor; some oscillation in the lines in proximity of the wings tip was also observed (not shown in figure).*

8. Discussion

8.1 Practicality of FLEXSELECT

FLEXSELECT is a very practical selective device in that it is constructed in such a way that it contains no large rigid parts that can compromise safety when handling and requires very little space on board the vessel. Furthermore, the different components of FLEXSELECT are standard materials that net makers typically have available. Moreover, it is easy to mount and demount, which provides the added benefit of being able to be used on a haul-by-haul basis depending on the catch goals of the vessel.

8.2 Applicability to different fisheries

The use of FLEXSELECT could be relevant for all crustacean fisheries where the bycatch of fish is an issue. 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 the interaction of fish 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.

8.3 Management implications

FLEXSELECT can help facilitate the successful implementation of the landing obligation by allowing fishermen to avoid catching species that may otherwise choke the fishery. For example, in many mixed demersal trawl fisheries targeting *Nephrops*, the quotas for several fish species (e.g. cod) may choke the fisheries, and the use of FLEXSELECT may permit these fisheries to remain open longer by reducing the capture of these species throughout the fishing season.

The technical specifications of trawls, as described in the EU regulation, pertain to the rear end of the gear, namely the codend and extension piece. Therefore, a flexible solution like FLEXSELECT, which is located ahead of the trawl, is something that the fishery can already legally use to help avoid unwanted catches.

Contrary to most other selective devices, FLEXSELECT can be used on a haul-by-haul basis, where its use is determined based on the desired 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.

9. Conclusions and Recommendations for Future Work

The FLEXSELECT project produced a simple, cheap and effective counter-herding device that can reduce the catch of fish bycatch, especially roundfish, improving the selectivity of the currently used commercial gear (SELTRA) in the Danish *Nephrops* trawl fishery. Moreover, the device has the advantage to be applicable only when required, at the haul-by-haul level (e.g. in response to the availability of quotas or bycatch hotspots), and it can be easily adjusted to fit any size trawl. Furthermore, its applicability extends to any demersal trawl fishery, whether there is a need for a temporary reduction of fish catch to prevent choking risks or a more permanent solution to eliminate as much unwanted catches as possible.

FLEXSELECT has been found to be suitable by the industry for commercial fishing activities, and several fishermen have shown interest in using it. Furthermore, it has attracted international interest and is currently being tested in other areas (e.g. Irish *Nephrops* fishery; BIM, 2019) and fisheries (e.g. Australian penaeid fishery; Melli et al., 2019). Finally, its efficiency in combination with other commonly used gear modifications is under investigation (Melli et al., *in press*).

In terms of research and development of counter-herding devices, future efforts should focus on enhancing the visual stimulus produced by the scaring lines to achieve an even stronger response. Indeed, on the basis of the results and observations collected we conclude that currently the mechanism underlying FLEXSELECT's efficiency is mainly mechanical (i.e. vibrations produced and direct contact with the lines). Nonetheless, many species rely on visual perception when escaping, thus the combination of FLEXSELECT with different forms of artificial illumination may strengthen its effect.

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