Reducing cod bycatch in flatfish fisheries

Juan Santos[a], Daniel Stepputtis[a], Daniel Oesterwind[a], Bent Herrmann[bcd], Uwe Lichtenstein[a], Constanze Hammerl[a], Uwe Krumme[a]

[a] Thünen Institute for Baltic Sea Fisheries, Alter Hafen Süd 2, 18069 Rostock, Germany

[b] SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, 9850 Hirtshals, Denmark

[c] Norwegian College of Fishery and Aquatic Science, University of Tromsø, 9037 Breivika, Tromsø, Norway

[d]DTU Aqua, Technical University of Denmark, 9850 Hirtshals, Denmark

Abstract

Management measures to facilitate the recovery of fish stocks can lead to shifts in traditional fishing patterns and target species. In the Baltic Sea, drastic reductions in catch quota for cod (*Gadus morhua*) force mixed demersal trawl fisheries to avoid cod bycatch and focus on flatfish species. This study developed and tested a simple selection concept that aims to avoid cod bycatch in flatfish-directed trawl fisheries by removing a section of the top panel from the extension piece of the trawl (roofless concept). Sea trials testing the performance of a baseline roofless design, and two designs intended to enhance escape reactions of cod were conducted during two sea cruises. Analysis of the resulting catch data revealed that applying the baseline roofless design consistently reduced cod bycatch by ~75%. Catches of the target species plaice (*Pleuronectes platessa)* and flounder (*Platichthys flesus*) were reduced by less than 15%; however, we estimated that catch losses of the two flatfish species could be balanced by increasing fishing effort to ~8% and ~12%, respectively. None of the two roofless designs, intended to enhance escape reactions on cod improved the performance of the baseline design. Under the scenario of fishery choke caused by limited cod quotas, we estimated that the use of the baseline roofless concept could increase fishing possibilities for flatfish by more than 300%.

Keywords

Bycatch reduction, roofless device, landing obligation, catch comparison, fishing effort, dual-species indicators, fish behaviour

Introduction

The productivity of commercial fish stocks is affected by natural and anthropogenic pressure, caused most obviously by changes in marine ecosystems and fisheries (Eero et al., 2011; Cushing, 1995). The Baltic cod populations, especially the eastern stock, are examples of fish stocks affected by adverse fluctuations in environmental factors (e.g. increasing temperature, decreasing salinity, and lower levels of oxygen) and continued overfishing, which have driven the stocks to their current situation of distress (Köster et al., 2017; Eero et al., 2015). Current environmental conditions in the Baltic Sea and recent forecast stock scenarios (ICES, 2020a) render it unlikely that the Eastern Baltic cod stock will recover in the short term (ICES, 2019a). Based on the assessment of the International Council for the Exploration of the Sea (ICES), zero-catch quotas were advised for 2020 and 2021 for the management of the Eastern Baltic cod (ICES, 2020b, 2019b), also affecting the mixing zone of both stocks in the central Baltic Sea (ICES, 2019c). To allow the flatfish-directed fishery to continue, it was agreed to provide a small cod bycatch quota for the fishers.

Traditionally, cod has been the most important target species in the demersal trawl fisheries in the Baltic Sea (Madsen, 2007). In these fisheries, cod is usually caught beside flatfish species (ICES, 2019c), such as plaice (*Pleuronectes plattessa*), flounder (*Platichthys flesus*), and dab (*Limanda limanda*). To maintain sustainable and economically viable demersal fishing activities in the current situation, the mixed fishery has to switch to a flatfish fishery, while avoiding cod bycatch as much as possible (ICES, 2019a). Avoiding cod bycatch is especially relevant considering the European landing obligation (European Union, 2013) implemented for the Baltic Sea in 2015. Under this regulation, using fishing gears optimised for catching cod can result in an early exhaustion of the limited bycatch quota, therefore choking fishing possibilities on the flatfish stocks, which are largely in a good state (ICES, 2020a).

Applying species-selection technologies to demersal trawl fisheries has been identified as a potentially efficient strategy to reduce the bycatch of Baltic cod (ICES, 2019a). Research into trawl selectivity in the Baltic Sea has traditionally focused on adjusting codend size selection (Madsen et al., 2021; Wienbeck et al., 2011, 2014; Madsen, 2007). In turn, few technologies developed specifically to avoid cod bycatch of any size are available to Baltic fishers. To the best of our knowledge, Madsen et al. (2006) is the only reference available that addresses the question of how to avoid cod bycatch in flatfish fisheries in the Baltic Sea. The trawl tested in Madsen et al. (2006) involved several innovations at different sections of the gear, including large square-mesh panels in the net section behind the headline, intended to provide an escape possibility to those fish performing upwards escape reactions at the mouth of the trawl. Trawls with the footrope positioned forward to the headline (so-called topless trawls or cutaway trawls) have been applied in flatfish fisheries of the Northwest and Northeast Atlantic to reduce the by-catch of gadoid species (Chosid et al. 2008; Pol et al., 2003; Thomsen 1993). However, while topless trawls have demonstrated high efficiency in avoiding catches of active gadoid species such as haddock (Krag et al. 2015; Thomsem, 1993), the ability of this trawl concept to reduce the bycatch of cod has proven to be less consistent (Krag et al. 2015), probably due to the slow reactions of cod at the mouth of the trawl (Pol et al. 2003).

Applying the trawl concept proposed by Madsen et al. (2006) or the topless trawl concept (Krag et al. 2015; Chosid et al. 2008; Pol et al., 2003; Thomsen 1993) in the Baltic Sea would require a costly replacement of the trawls in use. A simpler solution could be to add a specific selection device to the commercial trawls already in use. Selection devices designed to exploit differences in fish behaviour during the catch process can be efficient solutions to reduce the bycatch of unwanted species (Lomeli et al., 2018; Beutel et al., 2008; Bayse et al., 2016). Behavioural observations at the non-tapered rear section of trawls (i.e. the extension piece) have revealed the preference of flatfish to swim close to the bottom of the net towards the codend, without significantly altering their behaviour even when interacting with selection devices placed in their way (Santos et al., 2020; Krag et al., 2009; He et al., 2008). In contrast, cod exhibit no clear preferences for a vertical zone in the water column (Karlsen et al., 2019), but exhibit behaviour more active than flatfish in response to the presence of selection devices (Santos et al., 2020). Such differences in behaviour between cod and flatfish have been used recently to reduce flatfish catches by establishing a simple escape opening in the bottom panel of the extension piece (the non-tapered section of the trawl ahead of the codend) of a trawl (Santos et al., 2020). Following the same principle, it is relevant to investigate if establishing an escape opening in the upper panel of the extension piece can be an efficient strategy to reduce cod bycatch without affecting the catches of the targeted flatfish.

In practice, the use of selection devices often leads to catch losses of the target species, compromising the devices' adoption in commercial fisheries (Macher et al., 2008; Suuronen et al., 2007). In this scenario, and especially in fisheries subjected to landing obligations, it is of interest to quantify the trade-off between catch losses of targeted species per unit of effort and the additional fishing opportunities derived from a reduction in the bycatch of a potential choke species. However, such trade-offs cannot be quantified using traditional analytical methods that assess the selectivity of fishing trawls from a single-species perspective (Wileman et al., 1996). Key questions to be answered are: (i) How much must the fishing effort be increased to compensate for potential catch losses of targeted species owing to the use of a given selection device? (ii) To what extent would the reduction in the bycatch of the most limiting (potential) choke species improve the fishing opportunities for the target species? Answering such questions would provide a wider picture of cost–benefit trade-offs related to the use of a given selection device, thus aiding in the identification of the best technical solution for individual fishing and management scenarios. This study will develop and test a selection device that provides an escape opening in the upper panel of the net, designed to reduce cod bycatch without affecting flatfish catch efficiency. The selection device can be applied directly to current commercial trawls without major gear modifications. We also investigate to what extent the escape rates of target and bycatch species could be affected by (i) the length of the escape opening, and (ii) active stimulation strategies to enhance the escape reaction in cod. To quantitatively assess the cost-benefit trade-offs associated to a potential adoption of the proposed selection device in the fishery, information from traditional analysis on single-species catch-data is supplemented in this study with fishery usability indicators based on simultaneous assessment of catches from targeted and bycatch species.

Material and methods

2.1. The roofless device

The species selection concept investigated here was established by removing a net section from the upper panel of the extension piece of the trawl (Figure 1). This simple modification is hereafter referred to as the roofless device. It is assumed that establishing the roofless device will create a zone of increased sensorial stimuli that could trigger escape reactions in fish (Kim, 1997; Glass and Wardle, 1995; Briggs, 1992). Following the different behavioural patterns observed for flatfish and cod at the non-tapered section of the trawl (Santos et al., 2020; Karlsen et al., 2019; Krag et al., 2009; He et al., 2008), the intended species selection was made on the assumption that the local sensorial stimuli created by the roofless device will attract cod towards the escape opening, whereas flatfish will not react to the presence of the device, continuing their path towards the codend.

The extension piece was made of four panels of diamond-mesh netting, 4 mm double PE twine, and a mesh size of ~114 mm (mesh measurements according to Fonteyne et al., 2007). The panels were 39.5 meshes long and 25 meshes wide. The extension piece was connected to the trawl body by a 2-to-4 panel adapter and to the codend by a 4-to-2 panel adapter, made of the same material as the extension and having a total length of 22.5 meshes each. The approximate length of the whole gear, combining the extension piece with the front and rear adapters, was ~10.1 m (estimated length of fully stretched netting). Connected to the gear was a mandatory T90 codend (European Union, 2019), made of 4 mm double PE twine, and measured mesh size of ~120 mm, 50 meshes in circumference and ~8 m long.

The roofless device was formed by removing a 14.5-meshes-long rectangular net section of the top panel (~175 cm long) and as wide as the panel, excluding the meshes in the selvedge. The longitudinal cut of the panel was straight (N-cut) and ran backwards from the first quarter of the total length of the extension. The transversal cut was also straight (T-cut). The section of the top panel directly in front of the escape opening was raised by two floats of 2.5 kg buoyancy mounted in line, one after another. Hereafter, this design is referred to as RL175 (derived from RoofLess 175 cm) or baseline design (Figure 1). To keep the width of the escape opening stable, two plastic rods of 25 mm diameter and 90 cm long were attached crosswise to the extension, one to the bottom panel underneath the escape opening, and the other to the top panel at the rear end of the escape opening. In addition, lead weights and floats were attached respectively to the lower and upper selvedges to keep a stable vertical distance between the bottom panel of the extension and the escape opening. Further technical information on the test gear (extension piece, adapters, and RL175) can be found in the Supplemental Material (Figure S1).

In addition, two modifications of the baseline design thought to further stimulate cod escape behaviour were developed and tested (Figure 1). In the first modification, the length of the escape opening was increased to nearly double the length of the section removed from the top panel (27.5 meshes deep, ~330 cm long). In the second modification, float ropes were applied according to Herrmann et al. (2014). Each float rope consisted of six floats of 0.115 kg buoyancy attached to a PE rope. The lower tip of the rope was attached to the bottom net panel of the extension underneath the opening; the upper tip was attached to the rear edge of the escape opening. Four float ropes were mounted, one beside the other, across the tunnel, thus disturbing the free passage of fish swimming through the extension towards the codend. The ropes' upward inclination and their fluttering motion during towing were predicted to stimulate cod to swim upwards towards the escape opening. Hereafter, the stimulus-enhancing design with an elongated escape opening will be referred to as

RL330 (derived from RoofLess 330 cm), and the design mounting float ropes will be referred to as RL175+.

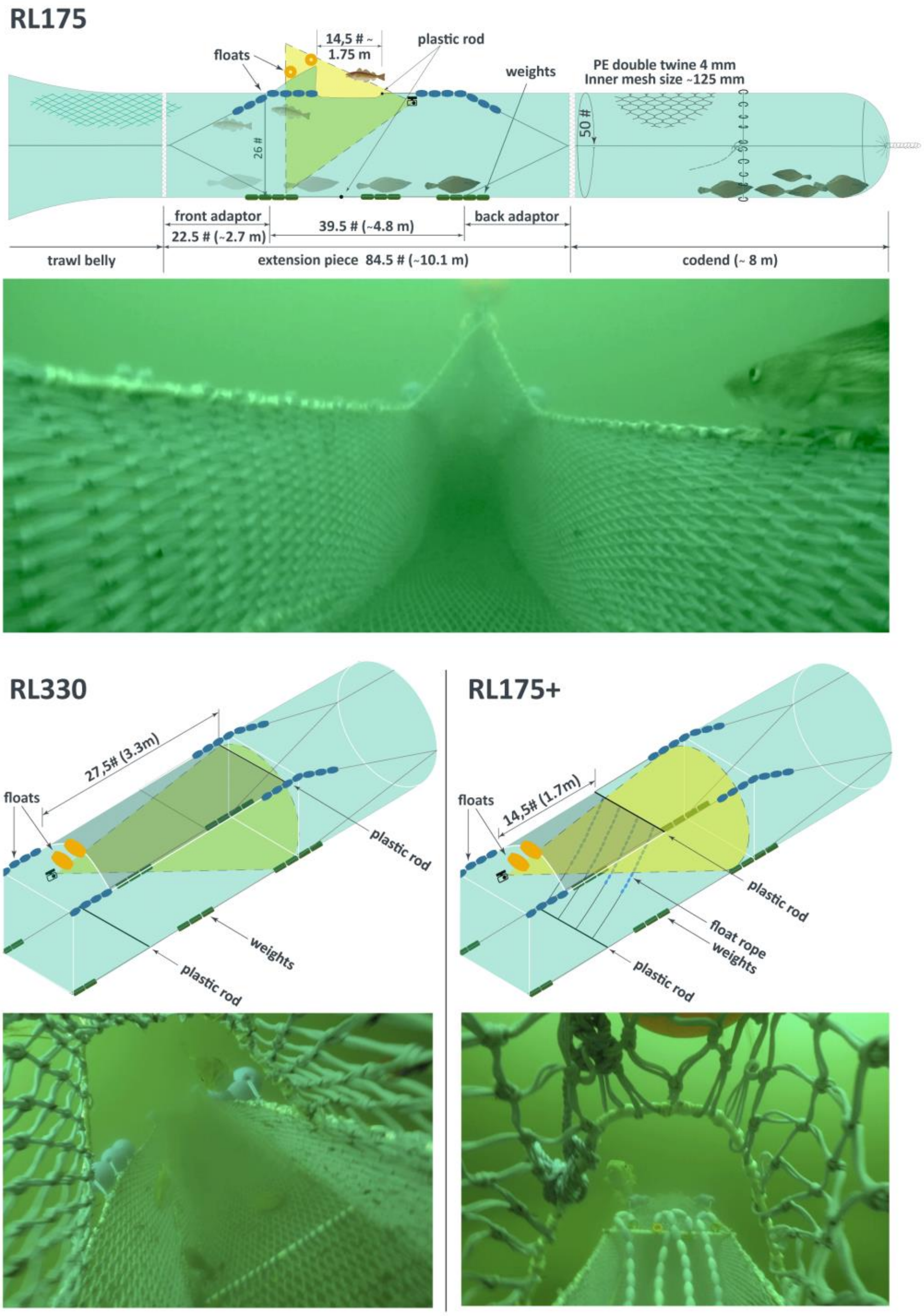

Figure 1. Design and underwater pictures of the baseline roofless device and its modifications. Top: technical characteristics and conceptual functioning of the baseline roofless device (RL175), mounted in the test gear together with the mandatory T90 codend. Bottom: technical characteristics of the two stimulus-enhancing designs, RL330 with enlarged escape opening (left) and RL175+,

which added four floating ropes to the baseline design to stimulate upwards escape reactions of cod (right). The drawings also show the camera positioning and perspective (yellow area) from which the related underwater pictures were taken.

2.2. Experimental fishing and data collection

The performance of the three roofless designs was tested during two cruises. Fishing trials during Cruise 1 were conducted on board the German research vessel FRV Clupea (28.80 m LOA, 478 kW), and took place between 11 and 19 December 2019, within the area of distribution of the western cod stock (Hemmer-Hansen et al., 2019; Weist et al., 2019), at the border zone between ICES Subdivisions 22 and 24 (Figure S2). The tows were conducted during daylight at fishing depths averaging 15.5 m (SD = 2.2), the towing speed was set at 3 knots, and the towing duration averaged 54 min (SD = 12). The roofless designs tested during Cruise 1 were the baseline (RL175) and the RL330 designs. The experimental design applied was a catch comparison (Herrmann et al., 2018; Krag et al., 2015) using twin-trawl type TV300/60 (Figure S3), similar in design to the commercial trawls used in demersal Baltic fisheries. One trawl mounted the extension piece with the roofless device (test gear); the other trawl mounted the same extension piece with the top panel unaltered (reference gear). The test trawl involved two selection processes, provided sequentially by the roofless device and the mandatory T90 codend. As selection device, the other trawl had only the same T90 codend as the test gear. Therefore, this trawl was considered the reference for the current selectivity in the commercial fishery.

Fishing trials during Cruise 2 took place between 4 and 8 February 2020, on board the German FRV Solea (42.40 m LOA, 1780 kW). Cruise 2, covering a wider spatial area than Cruise 2, included the same fishing grounds as Cruise 1, the overlapping zone between western and eastern cod stocks in ICES Subdivision 24 (Weist et al., 2019), and fishing grounds within the area of distribution of the eastern cod stock (ICES Subdivision 25; Figure S2). As in Cruise 1, hauls were conducted in daylight conditions. Average fishing depths was 22.9 m (SD = 15.5) in Subdivision 24, and 65.2m

(SD = 5.4) in Subdivision 25. The towing speed was set to 3 knots, whereas the towing duration was, on average, shorter than the average haul duration from Cruise 1 (40.3 min, SD = 11.7). Catch data from commercial trawl fisheries reveals the ratio of plaice to flounder catches to decrease from west to east across the fishing zones used in this study (ICES, 2020a). Consequently, it was expected to find a higher abundance of plaice at the border zone between ICES Subdivisions 22 and 24 (Cruise 1), while flounder would be expected to be the dominant flatfish species in catches at the zone between Subdivision 24 and Subdivision 25 (Cruise2).

Tests on the performance of the baseline roofless design were replicated during Cruise 2, using the same extension pieces and codends as were used during Cruise 1, but under different experimental and fishing conditions. Furthermore, during Cruise 2, we assessed the effect of adding float ropes (RL175+) to the baseline escape efficiency. Owing to the lack of twin-trawl facilities on board FRV Solea, the catch comparison was performed using the same double belly trawl (DBT) as described in Santos et al. (2020; Figure S4).

The experimental design was applied consistently during both cruises. Each roofless design was tested one at a time for a given number of hauls. When possible, consecutive hauls were done in opposite towing directions in order to neutralise any potential influence of uncontrolled operational conditions (e.g. sea state) on the probability that a fish will enter either trawl. Previous trials with the same vessels and trawls have demonstrated equal fishing efficiency, independent of the side on which the trawls were mounted (see Figure S5 as proof of the lack of side effect for the DBT). Consequently, it was not considered necessary to switch the trawls between sides during the experiment. Catches from the test and reference gears were kept separate and sampled one after another. The catch from each codend was sorted by species, and all individuals from each of the analysed species were length-measured to the half centimetre below (total length), using Scantrol electronic measuring boards.

2.3. Data analysis

2.3.1. Catch comparison analysis

Based on a group of valid hauls $i = 1,..,h$, the expected average length-dependent catch efficiency of the test gear relative to the reference gear for a species can be estimated as:

$$CC_l = \frac{\sum_{i=1}^{h} nt_{il}}{\sum_{i=1}^{h}(nt_{il} + nr_{il})} \quad (1)$$

where nt_{il} is the number of fish of length l caught in the test gear, nr_{il} is the number of fish of length l caught in the reference gear, and CC_l expresses the experimental catch comparison rate used here to assess the relative catch efficiency of the roofless device (test gear) in relation to the reference gear (Krag et al., 2014, 2015). A value of $CC_l = 0.5$ implies that the catches of a given species at length l would be shared equally among the test and the reference gears, which indicates no effect of the roofless device on the catch efficiency of the test trawl. Following the same interpretation, the lower the value below 0.5, the smaller the catch in the test gear compared with the reference gear, and so, the larger the catch reduction caused by the roofless device. The comparative assessment of the roofless effect across lengths is done by estimating the most likely catch comparison curve, which implies the modelling of the experimental CC_l data. In this study, the catch comparison curve is defined as:

$$CC(l, \mathbf{v}) = \frac{exp(f(l, \mathbf{v}))}{1.0 + exp(f(l, \mathbf{v}))} \quad (2)$$

where $f(l,\mathbf{v})$ is a smooth function of fish length, with a functional form controlled by a 4-order polynomial basis with parameters $\mathbf{v} = (v_0, v_1, v_2, v_3, v_4)$. The length-dependent catch comparison analysis is therefore reduced to an optimisation problem, in which the values of the parameters $\mathbf{v}$ associated with the curve most likely related to the experimental data are estimated. Thus, the maximum likelihood function involving Equation (2) and the catch data is defined as:

$$logLik = -\sum_{i=1}^{h}\sum_{l}\left(nt_{il} \times log(CC(l,\mathbf{v})) + nr_{il} \times log(1.0 - CC(l,\mathbf{v}))\right) \quad (3)$$

Equation (3) is minimised relative to ***v***, which is equivalent to maximising the probability for the observed data. Evaluation of a model's ability to describe the data sufficiently well using Equations (2 and 3) was based on the calculation of the corresponding *p*-value together with the visual inspection of residuals distribution. The *p*-value expresses the likelihood of obtaining at least as large a discrepancy between the fitted model and the observed experimental data by coincidence. This p-value is based on testing the null hypothesis, that the modelled length-dependent release efficiency and the observed experimental data belongs to the same length-dependent distribution. Therefore, since *p*-value <0.05 would indicate poor goodness-of-fit of the fitted model to the data, we are seeking for models with p-value ≥0.05. Wileman et al. (1996) provide details on how to apply and interpret these fit statistics.

Leaving out one or more of the parameters $v_0,...,v_4$ led to 31 additional models that were also considered as potential models for the catch comparison analysis. Among these models, estimations of the catch comparison curves were made using multimodel inference (Burnham and Anderson 2002; Herrmann et al. 2017). Specifically, the models were ranked and weighed in the estimation according to their AICc values (Burnham and Anderson 2002). The AICc is calculated as the AIC (Akaike 1974), but it includes a correction for finite sample sizes in the data. Models that resulted in AICc values within +10 of the value of the model with lowest AICc value ($AICc_{min}$) were considered for the estimation of $CC(l,\mathbf{v})$ following the procedure described in Katsanevakis (2006) and Herrmann et al. (2015).

If the catch comparison curve $CC(l,\mathbf{v})$ has been estimated by applying Equations (2) and (3) and multimodel inference, then the length-dependent curve describing the ratio of catches in the test trawl to the catches in the reference trawl can be obtained by:

$$CR(l,\mathbf{v}) = \frac{CC(l,\mathbf{v})}{1.0 - CC(l,\mathbf{v})} \quad (4)$$

The resulting $CR(l,\mathbf{v})$ curve directly relates the catch efficiency of the test trawl to the catch efficiency of the reference trawl, and so, it is better suited to quantitatively assess the escape efficiency of the roofless device than the $CC(l,\mathbf{v})$ curve. For example, values of $CR(l,\mathbf{v})$ close to 1.0 would imply similar catches in the test and reference gears. In the present study, such values would be desirable for marketable sizes of flatfish species, indicating low escape efficiency of the targeted flatfish. Conversely, low $CR(l,\mathbf{v})$ values for cod would express high escape efficiency for this bycatch species. For example, a value of $CR(l,\mathbf{v}) = 0.2$ would imply that catches at length l in the test gear are 20% of what the reference trawl would caught at length l, which can be interpreted as an escape efficiency of 80%.

Efron confidence intervals (95% CI) of the curves predicted by Equations (3) and (4) were obtained using the double bootstrap procedure (1000 iterations) traditionally applied in selectivity studies (Krag et al., 2014; Millar, 1993). This includes accounting for between-haul variation in the catch comparison curve and the uncertainty in individual hauls resulting from the capture of a finite number of fish. In addition, the bootstrap method accounts for the uncertainty related to the model-averaging procedure used to predict $CC(l,\mathbf{v})$. The catch comparison analysis described above was carried out using the software tool SELNET (Herrmann et al., 2018; Krag et al., 2014).

2.3.2 Quantifying the effect of stimulus-enhancing designs on the baseline escape efficiency

Similar to the method described in Melli et al. (2019), the effect of each of the two stimulus-enhancing modifications tested was assessed by quantifying the differences between the baseline catch ratio curve $CR_b(l,\mathbf{v})$ obtained with the RL175 design, and the catch ratio curves obtained from either the RL330 or the RL175+ designs ($CR^*(l,\mathbf{v})$):

$$\Delta CR(l,\mathbf{v}) = CR_b(l,\mathbf{v}) - CR^*(l,\mathbf{v}) \quad (5)$$

Confidence intervals associated with $\Delta CR(l,\mathbf{v})$ were obtained by synchronising the outer bootstrap resampling scheme from both the baseline and the stimulus-enhancing design being assessed.

2.3.3 Fishery usability indicators

Contrary to the curves estimated by Equations (3) and (4), the indicators defined in this section are point estimates that consider the size structure of the catches obtained during the experiments. The estimated indicators are used to answer relevant questions related to the usability of the roofless device in the fishery:

What is the relative performance of the test gear on catch fractions defined by management reference sizes?

The first three indicators are used to assess the catch efficiency of the test gear relative to the reference gear. Point estimates are obtained by pooling the catch data over hauls (due to the paired-gear experimental method applied, each haul contains catch data from both the test and the reference gear) and grouping the numbers at fish length into fractions defined by a given reference size of the species being analysed:

$$
\begin{aligned}
nS &= 100 \times \left(\frac{\sum_{i=1}^{h} \left\{ \sum_{l} nt_{il} \right\}}{\sum_{i=1}^{h} \left\{ \sum_{l} nr_{il} \right\}} \right) \\
nS_{-} &= 100 \times \left(\frac{\sum_{i=1}^{h} \left\{ \sum_{l<mrs} nt_{il} \right\}}{\sum_{i=1}^{h} \left\{ \sum_{l<mrs} nr_{il} \right\}} \right) \\
nS_{+} &= 100 \times \left(\frac{\sum_{i=1}^{h} \left\{ \sum_{l\geq mrs} nt_{il} \right\}}{\sum_{i=1}^{h} \left\{ \sum_{l\geq mrs} nr_{il} \right\}} \right)
\end{aligned}
\qquad (6)
$$

Indicators in Equation (6) are calculated as the ratio of catches (in numbers) of species *S* in the test gear to catches in the reference gear. The catch ratios are estimated based on the total catch (nS), and catch fractions below ($nS-$) and equal to or greater ($nS+$) than a species-specific management reference size (mrs). The reference size used here for cod and plaice are the species minimum conservation reference sizes (MCRS) in the Baltic Sea (35 cm and 25 cm, respectively). The minimum conservation reference size used for flounder in the area where the sea trials were conducted is 23 cm. However, according to the current preferences in German markets, there is no commercial interest in flounder smaller than 25 cm. Therefore, we used the same reference size as for plaice.

How much should fishing effort be increased to compensate for potential catch losses of targeted flatfish?

Applying the roofless device to the test gear can lead to catch losses of targeted flatfish (*f*), expressed as $nS_f+ < 1.0$. In such a scenario, the indicator *ΔEffort* quantifies how much additional fishing effort would be required to balance the catch losses in the test gear relative to catches in the reference gear, after *h* hauls:

$$\Delta Effort = 100 \times \left(\frac{h}{h \times nS_f+} - 1.0 \right) \tag{7}$$

What are the cost–benefit trade-offs related to potential reductions in cod bycatch and catch losses of target flatfish species?

In fisheries subjected to landing obligations, the costs associated with a loss in catchability of the target species derived from the use of the selection device need to be assessed considering the benefits associated with a potential reduction in bycatch from species with limited quota. Considering cod (*c*) as the bycatch (choke) species and flatfish (*f*, either plaice or flounder) ≥ 25 cm as the target, the following dual-species indicators are calculated:

$$nR_t = \frac{\sum_{i=1}^{h}\{\sum_l ntc_{il}\}}{\sum_{i=1}^{h}\left\{\sum_{l\geq mrs} ntf_{il}\right\}}$$

$$nR_r = \frac{\sum_{i=1}^{h}\{\sum_l nrc_{il}\}}{\sum_{i=1}^{h}\left\{\sum_{l\geq mrs} nrf_{il}\right\}}$$

$$nRR_t = \frac{nR_t}{nR_r} \qquad (8)$$

where nR_t and nR_r are bycatch ratios in test and reference gears, and nRR_t is the relative bycatch ratio of the test gear.

In a simulated scenario where the maximum allowable catches of the choke species would be achieved after conducting *h* hauls with the reference gear,

$$\sum_{i=1}^{h}\sum_{l} nrc_{il} = nc_{choke} \qquad (9)$$

the indicator nRR_t can be used to project how many additional fishing possibilities for the targeted flatfish species could be expected by using the test trawl once the nc_{choke} *is* reached:

$$nf^* = \frac{\sum_{i=1}^{h}\sum_{l\geq mrs} nrf_{il}}{nRR_t}$$

$$nRf^* = \frac{nf^*}{\sum_{i=1}^{h}\sum_{l\geq mrs} nrf_{il}} \qquad (10)$$

where nf^* is the projected catches estimated for the test gear once the total catch of cod reached the threshold defined by nc_{choke}; nRf^* is the ratio between the flatfish catches projected for the test gear to the empirical catches obtained in the reference trawl after *h* hauls. Values of $nRf^* > 1.0$ would indicate gains in fishing possibilities for the targeted species derived from the use of the roofless device.

Indicators described in Equations (6–10) were calculated for each roofless design by cruise and after combining the information from both cruises. The resulting values are presented in percentages. Efron confidence intervals (95%) associated with the fishery usability indicators were obtained using the same bootstrap scheme described in the previous section. The indicators analysis was conducted using R (R Core Team, 2020).

3. Results

3.1. Description of fishing operations and catches

A total of 16 valid hauls were successfully conducted during Cruise 1 (Table 1). The first eight hauls (11–16 December) tested the escape efficiency of the RL330 design. Catches were made of cod (n = 1821), plaice (n = 1394), and flounder (n = 428). The remaining eight hauls were used to test the baseline roofless design RL175 (17–19 December). Although the catch profile was very similar to the previous experiments, catch volumes decreased to nearly half. Cod and plaice were again the most abundant species (n = 925 and n = 723, respectively), whereas catches of flounder were relatively small (n = 291).

In all, 22 valid hauls were conducted during Cruise 2. The baseline roofless (RL175) and RL175+ designs were alternated across hauls, totalling 12 and 10 hauls, respectively. The total cod catches obtained in each trial were comparable with those obtained in Cruise 1 (n = 1254 and n = 1098 for RL175 and RL175+ trials, respectively). Conversely, flounder was the most abundant flatfish species in Cruise 2 (n = 3267 and n = 2132 for RL175 and RL175+, respectively), whereas catches of plaice were small (n = 329 and n = 252 for RL175 and RL175+, respectively).

3.2 Catch comparison analysis

Data from all experimental hauls were used to analyse the performance of the three roofless designs, except for the plaice data from Cruise 2, haul 14, owing to problems in the collection of catch data from this specific species. The models described in Equations (3–5) were successfully fitted to the data (Table 2). The inspection of models residuals did not reveal any concerning systematic trends. Most of the fitted models present high goodness-of-fit to the experimental data (p-values > 0.05). However, four models presented poor fit statistics (p-values < 0.05), likely caused by a combined effect of model overdispersion and weak length dependence of the observed catch comparison data. The distribution of the residuals produced by the fitted models are showed in Figures S6-S8 in Supporting Material.

The experimental catch comparison data revealed that cod was caught mostly in the reference codend, irrespective of the roofless design used (Figure 2). Consequently, the estimated catch comparison curves $CC(l, \mathbf{v})$ are significantly lower than the value of $CC = 0.5$. This result is linked to significant escape efficiency for cod. Assessment of the resulting $CC(l,\mathbf{v})$ curves reveals no clear length dependence on escape efficiency for cod in the case of the tested roofless designs. However, three of the curves predicted a slight negative trend throughout the most abundant lengths, which suggests a slight increase in escape efficiency for larger cod.

Table 1. Operational information of the hauls conducted during Cruise 1 and Cruise 2, and catches by species, haul, and gear (test and reference).

			Haul	Duration	Latitude	Longitude	Course	Depth	Cod (n fish)		Plaice (n fish)		Flounder (n fish)	
Cruise	Date	Tested design		(min)	(°)	(DD)	(°)	(m)	Test	Reference	Test	Reference	Test	Reference
1	2019/12/11	RL330	1	60	54°11.8	11°53.7	101	16	55	294	94	101	36	52
	2019/12/12	RL330	2	60	54°12.2	12°00.5	265	13	4	95	60	85	13	15
	2019/12/12	RL330	3	60	54°11.7	11°53.9	94	18	10	56	43	57	23	35
	2019/12/12	RL330	4	60	54°12.0	11°59.5	258	14	12	5	51	45	9	15
	2019/12/13	RL330	5	60	54°12.2	12°00.2	261	13	30	88	90	148	10	16
	2019/12/16	RL330	6	60	54°12.1	11°59.8	259	13	57	253	78	116	20	21
	2019/12/16	RL330	7	60	54°11.8	11°52.5	97	18	125	595	114	167	38	52
	2019/12/16	RL330	8	30	54°11.9	11°52.1	96	18	17	125	63	82	40	33
	2019/12/17	RL175	9	30	54°11.9	11°52.3	98	17	22	84	47	57	16	26
	2019/12/17	RL175	10	30	54°11.7	11°52.3	277	17	7	13	107	114	43	60
	2019/12/17	RL175	11	60	54°11.7	11°53.9	96	17	17	256	35	36	9	9
	2019/12/18	RL175	12	60	54°12.1	11°59.9	258	13	14	31	25	16	7	3
	2019/12/18	RL175	13	60	54°11.8	11°52.4	98	17	21	82	28	46	19	42
	2019/12/19	RL175	14	60	54°11.8	11°53.4	95	17	12	28	47	35	10	19
	2019/12/19	RL175	15	60	54°12.2	12°00.2	243	13	17	161	27	47	4	13
	2019/12/19	RL175	16	60	54°12.1	11°59.9	253	13	78	82	29	27	4	7
2	2020/02/04	RL175	1	15	54°12.2	12°00.2	270	12	9	27	12	21	2	0
	2020/02/04	RL175+	2	60	54°12.2	11°58.5	268	13	26	126	34	42	2	5
	2020/02/04	RL175+	3	60	54°11.8	11°52.4	286	17	33	88	16	21	2	0
	2020/02/04	RL175	4	60	54°12.0	11°49.1	115	19	47	319	20	38	0	1
	2020/02/05	RL175+	5	30	54°12.2	12°00.1	264	12	19	47	2	1	0	1
	2020/02/05	RL175	6	45	54°12.0	11°56.5	61	15	61	364	9	17	1	1

2020/02/05	RL175	7	45	54°11.5	11°55.1	237	16	96	167	32	22	4	3
2020/02/05	RL175+	8	45	54°11.6	11°50.9	114	17	45	397	0	12	0	0
2020/02/05	RL175	9	45	54°11.8	11°53.2	94	17	33	126	1	3	0	0
2020/02/06	RL175	10	45	54°32.3	13°47.9	22	21	0	0	1	1	0	3
2020/02/06	RL175	11	45	54°40.3	13°46.8	28	32	0	12	1	6	8	32
2020/02/06	RL175+	12	47	54°44.4	14°45.9	206	54	7	30	3	16	70	199
2020/02/06	RL175	13	45	54°42.5	14°44.0	32	53	5	30	6	6	92	103
2020/02/07	RL175	14	45	54°53.1	15°17.4	202	76	23	45	NA	NA	740	768
2020/02/07	RL175+	15	30	54°52.0	15°17.0	197	69	5	27	21	29	395	364
2020/02/07	RL175+	16	30	54°52.0	15°10.2	269	64	26	46	12	18	381	348
2020/02/07	RL175	17	30	54°51.9	15°09.0	271	63	6	12	15	24	279	314
2020/02/07	RL175	18	30	54°52.1	15°06.6	102	62	5	16	3	5	137	88
2020/02/08	RL175	19	30	54°53.1	15°10.8	272	62	0	8	0	0	168	222
2020/02/08	RL175+	20	30	54°53.0	15°10.3	275	61	1	11	6	12	88	131
2020/02/08	RL175+	21	30	54°47.8	14°42.9	211	45	0	5	1	2	71	75
2020/02/08	RL175	22	45	54°47.9	14°42.8	211	45	2	0	9	3	140	161

Table 2. Fit statistics obtained from the catch comparison models for Baltic cod, plaice, and flounder, based on the catch comparison data obtained during the trials with the three roofless designs tested. Fitted models with *p*-values>0.05 in bold.

Species	Test design	Cruise	Number of hauls	Deviance	*p*-value
Cod	RL175	1	8	37.0	**0.954**
		2	12	99.5	0.014
	RL330	1	12	56.1	**0.905**
	RL175+	2	9	82.3	**0.148**
Plaice	RL175	1	8	43.2	**0.162**
		2	11	35.8	0.007
	RL330	1	12	50.5	**0.386**
	RL175+	2	9	55.0	**0.104**
Flounder	RL175	1	8	52.5	0.047
		2	12	34.4	**0.875**
	RL330	1	12	36.9	**0.696**
	RL175+	2	8	73.5	0.001

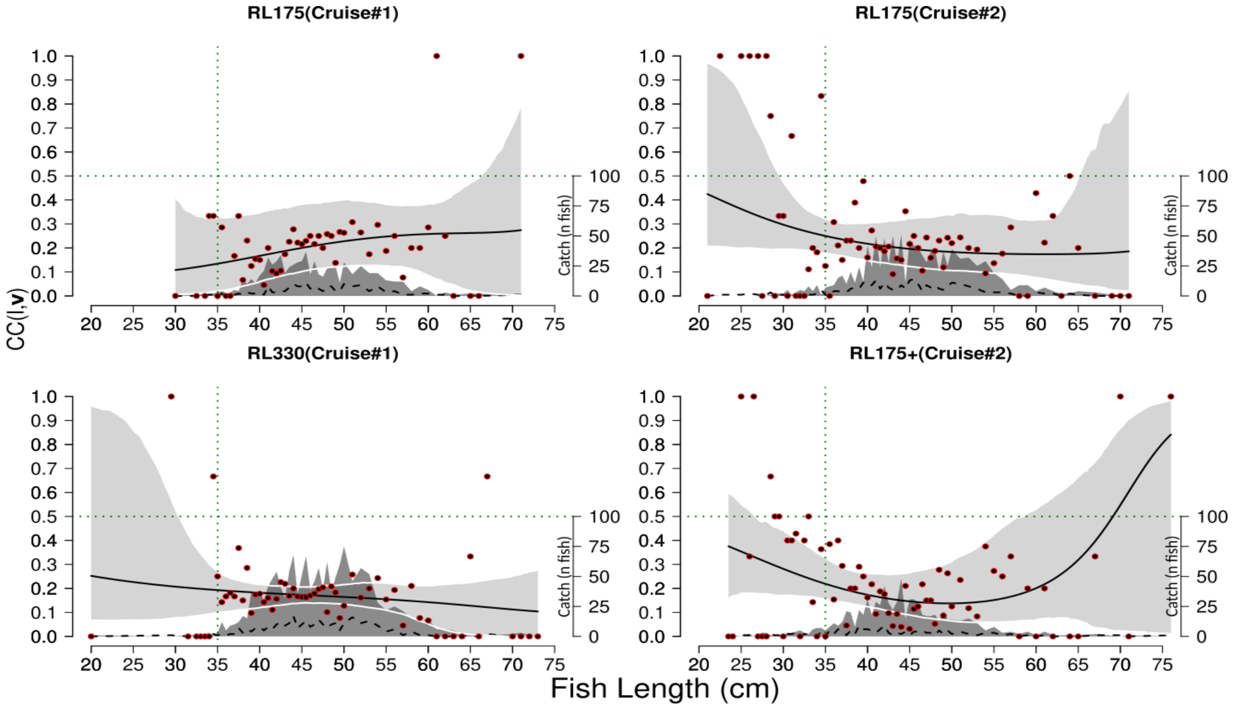

Figure 2. Average catch comparison curves (*CC(l,**v**)*, solid line) estimated for cod, by roofless design and by cruise (Cruise 1: left column, Cruise 2: right column). Grey shadowed areas: 95% confidence intervals of the estimation. Circles: catch comparison data *(CC_l)*. Horizontal dotted line: value indicating equal catch share among test and reference gears. Vertical dotted line: species MCRS (35 cm). Pooled catches represented at the bottom of the plots by a black dashed line (test gear) and a dark grey polygon (reference gear).

The *CR(l,**v**)* curves estimated for cod reveal a decrease in cod catch efficiency to values clearly lower than 50% of the reference catch efficiency, at least within the range of most abundant lengths (Figure 3). Neither the increment in the length of the escape opening (RL330, Cruise 1) nor the addition of float ropes (RL175+, Cruise 2) significantly improved the escape efficiency obtained with the baseline RL75 design. It is worth noting, however, the negative trend of the average Δ*CR(l,**v**)* curve derived from the comparison RL330 vs. RL175, which indicates that the enlarged escape opening had a positive marginal effect on the escape efficiency of larger cod (Figure 3).

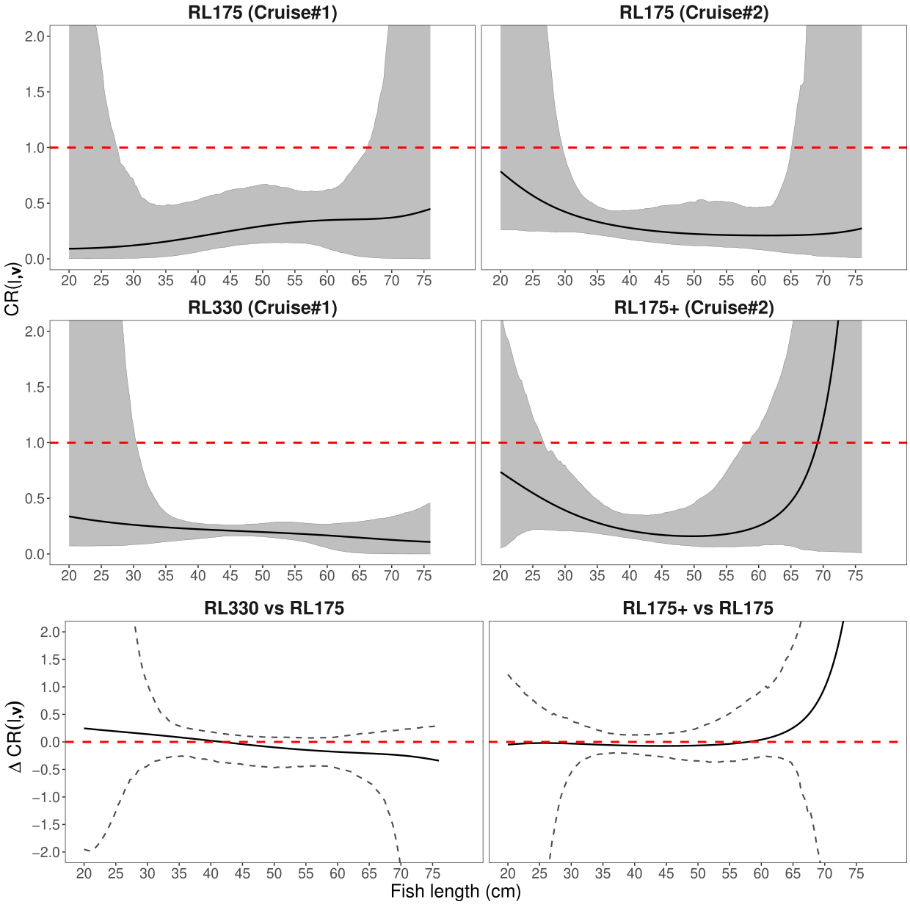

Figure 3. Left to right: Catch ratio curves for cod obtained in Cruise 1 (left column) and Cruise 2 (right column) by the baseline roofless design RL175 (first row), and the two other designs tested in each cruise, respectively (second row). Grey shadows: 95% confidence intervals of the estimation. Red dashed line: value indicating equal catch efficiency of test and reference gears (*CR* = 1.0). The third row shows the Δ*CR(l,**v**)* curves used to assess differences in performance of the baseline design vs. RL330 (Cruise 1) and RL175+ (Cruise 2). Red dashed line: value indicating no differences in performance between the baseline and the alternative designs (Δ*CR* = 0.0).

The *CC(l,**v**)* curves for plaice estimate a similar distribution of catches in the test and reference trawls and, as with cod, indicate no strong length dependence (Figure 4). The analysis related to the baseline roofless RL175 trial in Cruise 1, characterised by greater abundance of plaice catches, resulted in negligible deviation of the estimated *CC(l,**v**)* curve from the *CC* = 0.5 value. The replication of the baseline trial in Cruise 2, characterised by smaller catches of plaice, led to lower values of the *CC(l,**v**)* curve. However, there was no statistical evidence that the resulting curve differed from *CC* = 0.5 throughout the assessed lengths. Both increasing the length of the roofless section (RL330) and applying float ropes (RL175+) significantly reduced the catches of plaice in the test gear relative to catches in the reference gear. In the case of RL330, the significant reduction was detected between the lengths 26 and 37.5 cm, while the reduction in the case of RL175+ was significant all over the length range available until length 37.5 cm.

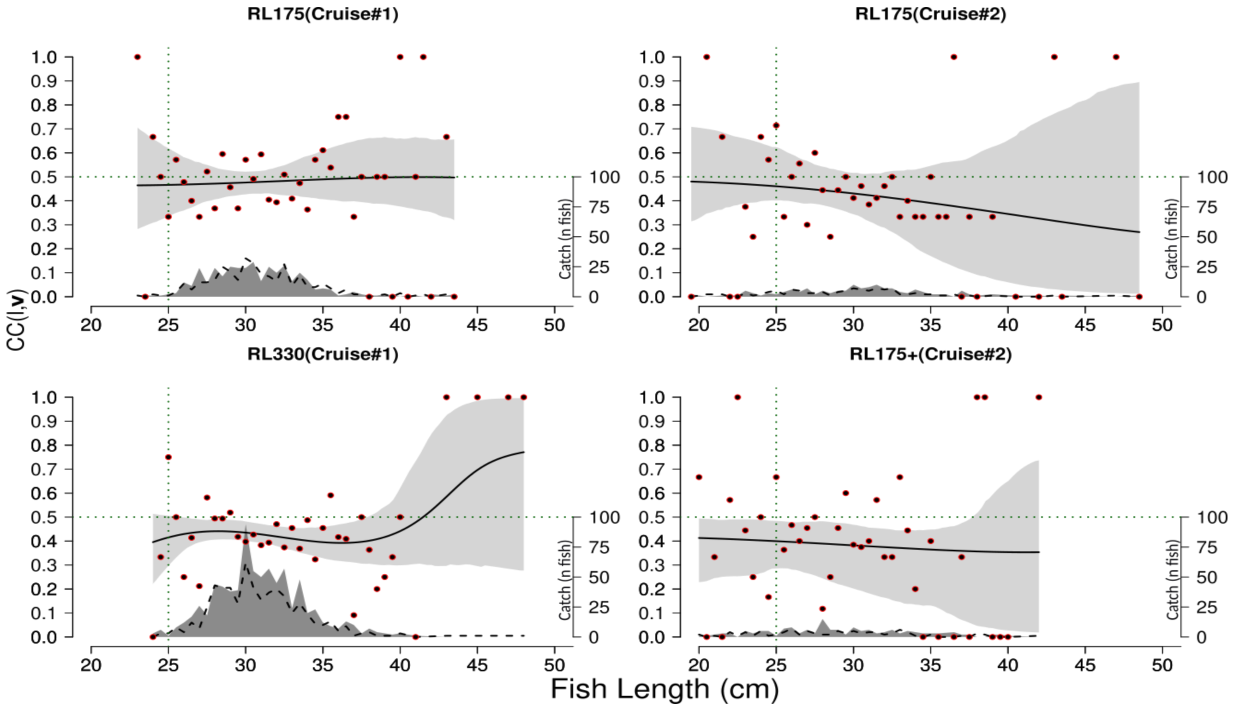

Figure 4. Average catch comparison curves (*CC(l,**v**)*, solid line) estimated for plaice, by roofless design and and by cruise (Cruise 1: left column, Cruise 2: right column). Grey shadowed areas: 95% confidence intervals of the estimation. Circles: catch comparison data (CC_l). Horizontal dotted line: value indicating equal catch share among test and reference gears. Vertical dotted line: species MCRS (25 cm). Pooled catches represented at the bottom of the plots by a black dashed line (test gear) and a dark grey polygon (reference gear).

The *CR(l,**v**)* curve estimated for the baseline RL175 design in Cruise 1 shows minimal reductions in catch efficiency lower than 10% (Figure 5). The *CR(l,**v**)* curves associated with the RL330 design reveal a larger and significant reduction in catch efficiency for plaice lengths between ~25 cm and

~37 cm. A similar decrease in catch efficiency was found for the RL175+, but extended to the whole range of lengths smaller than 37 cm. Although the significant losses in relative catch efficiency observed for the stimulus-enhancing designs, the respective $\Delta CR(l,\mathbf{v})$ curves detected no statistical differences compared with the relative catch efficiency of the baseline design. This was probably the result of the low inferential power resulting from the limited number of hauls, combined with a relative high between-haul variation in roofless performance (Figure 5).

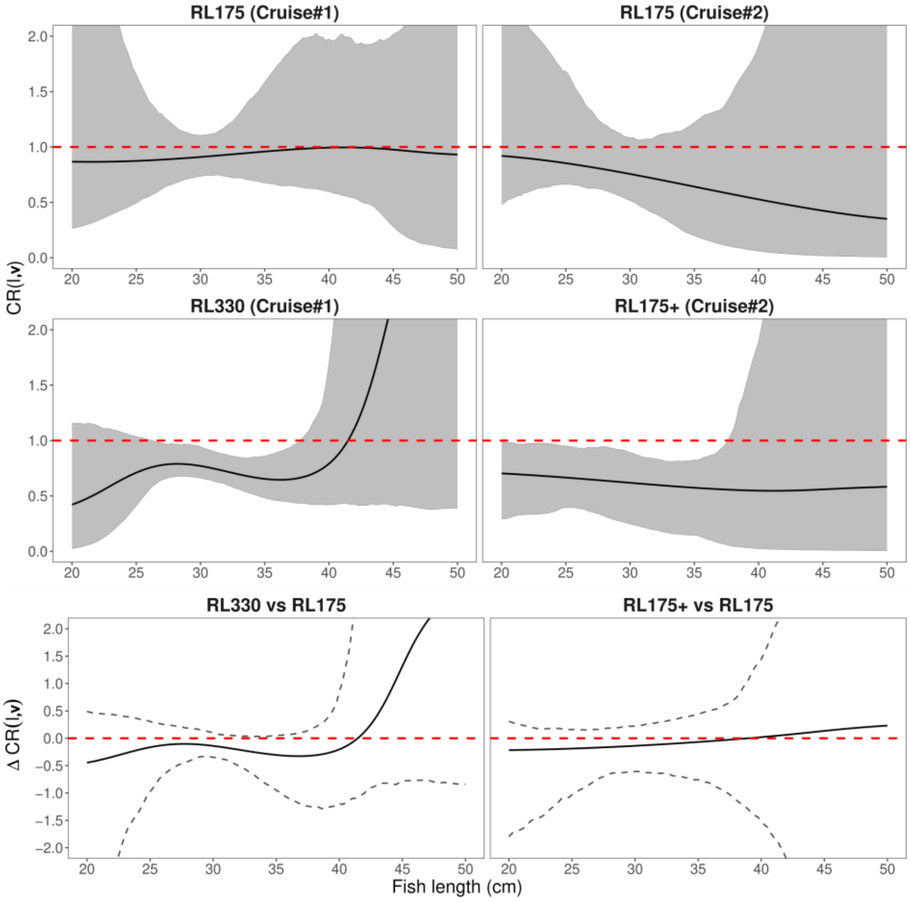

Figure 5. Left to right: catch ratio curves for plaice obtained in Cruise 1 (left column) and Cruise 2 (right column) by the baseline roofless design RL175 (first row), and the two other designs tested in each cruise, respectively (second row). Grey shadowed areas: 95% confidence intervals of the estimation. Red dashed line: value indicating equal catch efficiency of test and reference gears (CR = 1.0). The third row shows the $\Delta CR(l,\mathbf{v})$ curves used to assess differences in performance of the baseline design vs. RL330 (Cruise 1) and RL175+ (Cruise 2). Red dashed line: value indicating no differences in performance between the baseline and the alternative designs (ΔCR = 0.0).

The *CC(l,***v***)* curves for flounder were estimated close to *CC* = 0.5 in three out of the four experiments (Figure 6). As for plaice, a larger and significant deviation from *CC* = 0.5 occurred only when the species was caught in low abundance during Cruise 1.

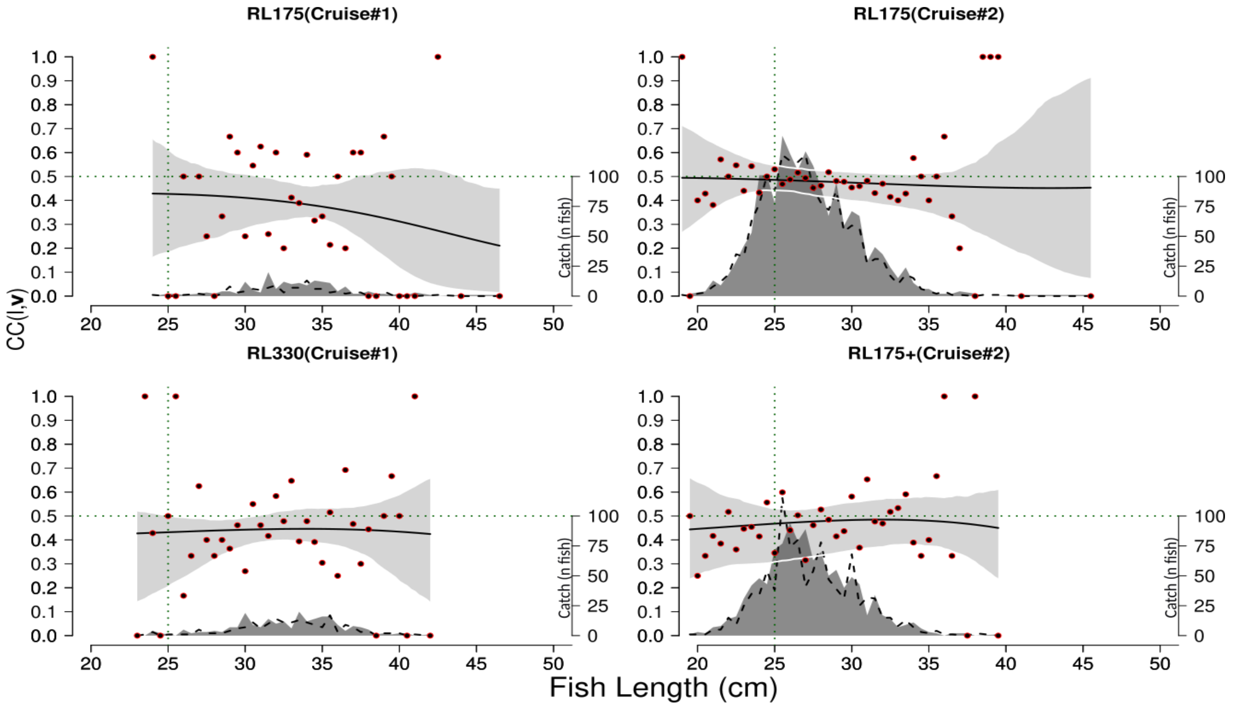

Figure 6. Average catch comparison curves (*CC(l,***v***)*, solid line) estimated for flounder, by roofless design and and by cruise (Cruise 1: left column, Cruise 2: right column). Grey shadowed areas: 95% confidence intervals of the estimation. Circles: species catch comparison data (CC_l). Horizontal dotted line: value indicating equal catch share among test and reference gears. Vertical dotted line: species reference size (25 cm). Pooled catches represented at the bottom of the plots by a black dashed line (test gear) and a dark grey polygon (reference gear).

The estimated *CR(l,***v***)* curves for the RL175 and RL175+ in Cruise 2 attained higher values than those obtained from Cruise 1, with decreases in catch efficiency lower than 10% (Figure 7). However, the Δ*CR(l,***v***)* curves detected no statistical catch efficiency differences between the baseline and the alternative roofless design (Figure 7).

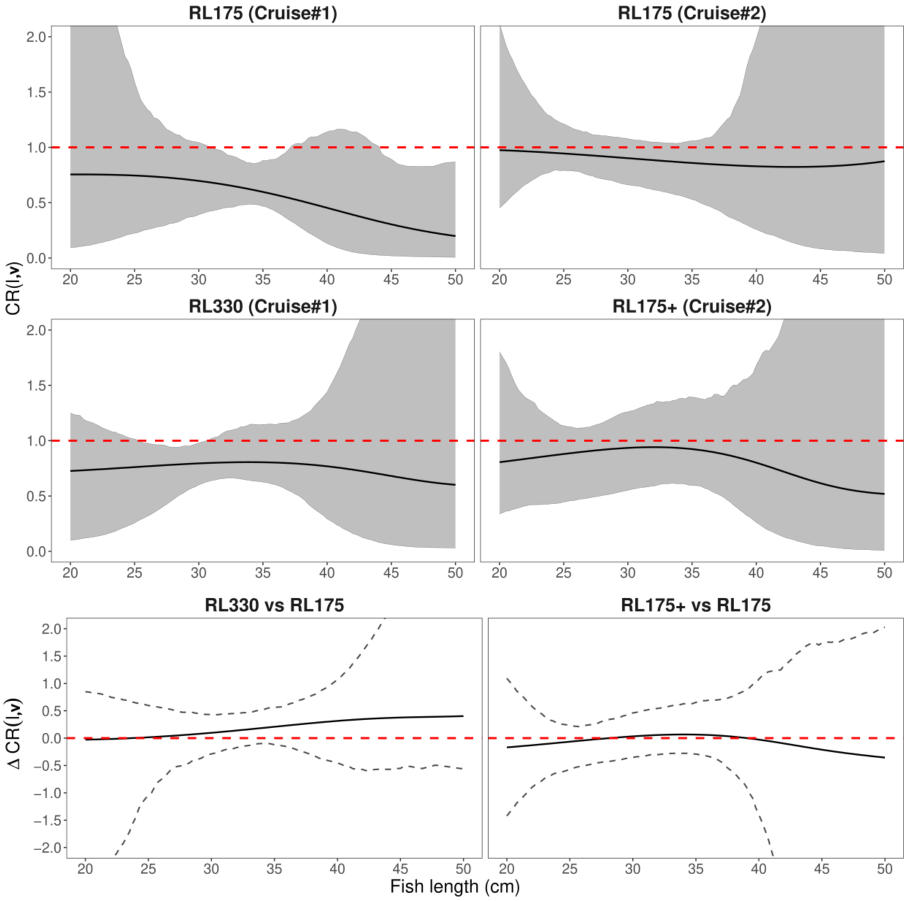

Figure 7. Left to right: catch ratio curves for flounder obtained in Cruise 1 (left column) and Cruise 2 (right column) by the baseline roofless design RL175 (first row), and the two other designs tested in each cruise, respectively (second row). Grey shadowed areas: 95% confidence intervals of the estimation. Red dashed line: value indicating equal catch efficiency of test and reference gears (*CR* = 1.0). The third row shows the $\Delta CR(l,\mathbf{v})$ curves used to assess differences in performance of the baseline design vs. RL330 (Cruise 1) and RL175+ (Cruise 2). Red dashed line: value indicating no differences in performance between the baseline and the alternative designs ($\Delta CR = 0.0$).

3.3 Fishery usability indicators

In line with the results obtained in the modelling section, the catch ratio indicator for marketable cod (*nS+*; Equation (6)) yielded values ≤ 25%, irrespective of the roofless design used (Figure 8). Hence, a consistent average reduction in catches ≥ 75% was achieved, although it also needs to be noted the large uncertainty in the estimation of the *nS+* indicator, associated to cod data collected during Cruise 1 with the baseline design (*nS+*= 25.5% [11.9%-56.8%]). Increasing the length of the escape opening (RL330), or adding float ropes (RL175+), reduced the relative catchability of cod further, by at least four percentage points. However, the overlap between confidence intervals around the mentioned *nS+* values for cod indicated no statistical differences across roofless designs (Figure 8). The smaller catches of cod in sizes less than the species minimum reference size obtained during both cruises (in average, < 5% of the total cod catches obtained in the reference and test gears) probably explain the very strong uncertainty estimated for *nS−* (length classes < mrs), and also explains the minor differences between values from the species *nS* (accounting for all length classes) and *nS+* (accounting for length classes ≥ mrs).

The use of the baseline roofless design (RL175) yielded average values of *nS+* > 90% for the most abundant flatfish species in catches (plaice in Cruise 1 (*nS+*= 90% [76.0%-108%]), flounder in Cruise 2 (*nS+*= 92.2% [74.3%-105%]). The upper confidence limits associated with these *nS+* > 90% values expanded beyond 100%, indicating no significant differences in the catch efficiency of sized flatfish between the test gear using the RL175 design and the reference gear. Unexpectedly, average values of *nS+* dropped significantly when catches of flatfish species were scarce. This was the case for flounder in Cruise 1 (*nS+*= 49% [62.0%-77%]) and plaice in Cruise 2 (*nS+*= 73% [49.0%-108%]). Combining the catch data from Cruises 1 and 2 led to average values of *nS+* > 85% (*nS+*= 88.6% [70.7%-100.2%]) for plaice and *nS+*= 86.5% [71.3%-101.6%] for flounder), revealing the little impact of hauls with low catches on the nS+ indicator. Increasing the length of the escape opening (RL330) reduced the average value of *nS+* for plaice obtained with the baseline design RL175 (Cruise 1 trials) by ~15 percentage points. On the contrary, the average *nS+* for flounder was higher for the RL330 design than for the baseline design. However, the later result needs to be treated with caution owing to the small catches of flounder during Cruise 1. The average *nS+* values obtained for plaice and flounder with the RL175+ design (Cruise 2 trials) revealed no clear effect of the stimulus-enhancing design on the catchability of flatfish. Similar to cod, catches of undersized flatfish were also small (representing ~10% of the total catches of plaice, and ~5% of total catches of flounder obtained in the reference and test gears; Figure 8).

Combining the catches from both cruises, the estimated *ΔEffort* indicator (Equation (7)) revealed that a trawl equipped with the baseline roofless design (RL175) would need an additional fishing effort of ~8% and ~12% to compensate for the catch losses of plaice and flounder, respectively (Figure 9). In return, the trawl equipped with the baseline roofless would have access to 373% and 347% more fishing opportunities for plaice and flounder (*nRf**; Equation (10)) than the reference trawl, respectively.

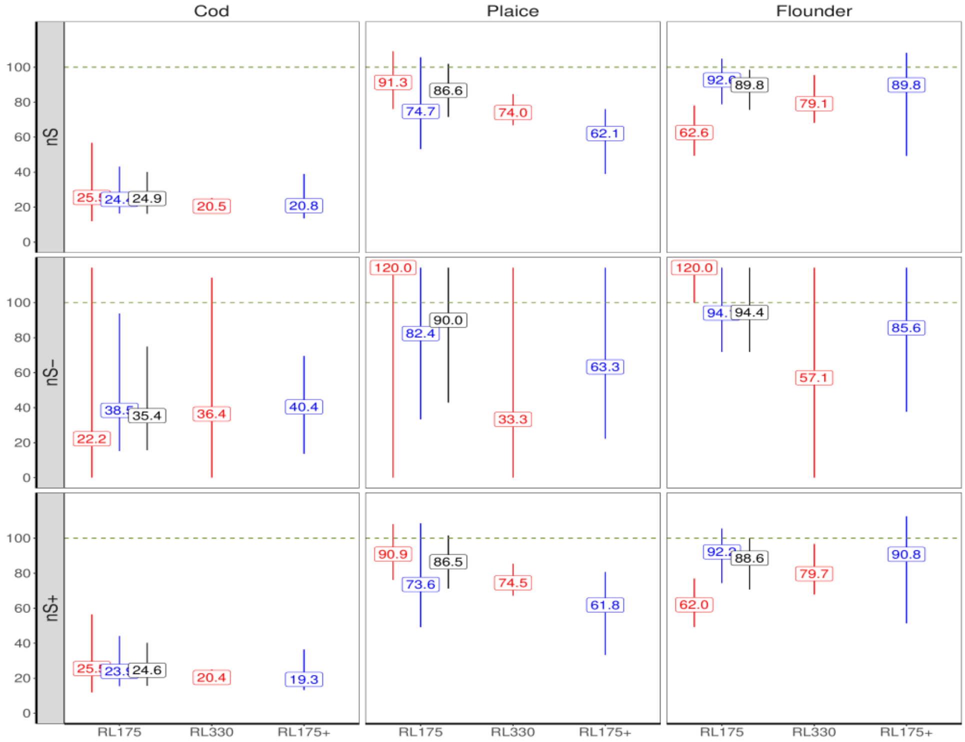

Figure 8. Catch ratio indicators (Equation (6)), by species, roofless design, and cruise (red = Cruise 1, blue = Cruise 2, black = combined). Rectangular labels indicate the average value of the estimated indicators. Vertical bars represent 95% confidence intervals.

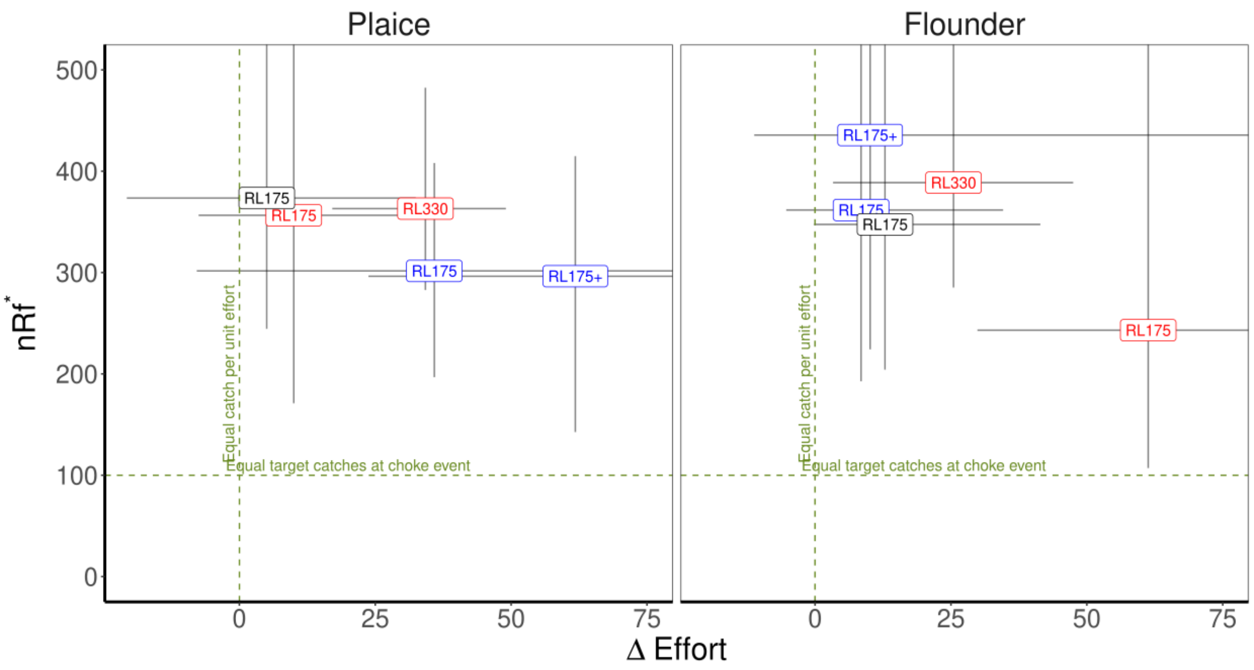

Figure 9. Relation of the increased effort needed to compensate for catch losses of targeted species derived from the use of the roofless device (indicator *ΔEffort*, Equation (7)) and projection of additional fishing possibilities caused by the reduced risk of a fishery choke event (indicator nRf^*; Equation (10)) by test gear and cruise (red = Cruise 1, blue = Cruise 2, black = combined). Rectangular labels indicate the relation between the average values from both indicators. Horizontal bars represent 95% confidence intervals associated with the average value of *ΔEffort*; vertical bars represent 95% confidence intervals associated with the average value of nRf^*.

Discussion

This study demonstrates that the bycatch of Baltic cod can be reduced significantly by simply removing a section of the upper net panel in the extension piece of the trawl. Results with the baseline design of the roofless device with a 175-cm-long escape opening (RL175) showed an average reduction in cod catches by ~75% that otherwise would be retained in commercial fishing using the mandatory T90 codend. The consistency in performance achieved during the two cruises, conducted with different vessels, using different trawls, and operating in different fishing grounds, is solid proof of the devices' functional reliability.

The roofless concept represents the latest development in the search for simple technical solutions that release Baltic cod from the trawl before they enter the codend. Earlier attempts using square mesh panels (SMP) inserted in a position in the trawl similar to that of the roofless device (Herrmann et al., 2014) resulted in very low escape efficiency for cod. The poor performance observed in Herrmann et al. (2014) might be explained by the natural behaviour of many fish species to stay clear of the surrounding netting once they enter the trawl (Glass et al., 1993): Although the SMP could be perceived as a clear escape possibility, fish tend to be reluctant to approach and try to penetrate the open meshes (Glass et al., 1995; Briggs, 1992). A recent attempt to improve the attractiveness of SMP on Baltic cod used very large meshes (~400 mm square-mesh size) to mitigate the "wall effect" of the SMP netting (ICES, 2019d). The poor results related to escape efficiency obtained with the 400 mm SMP motivated the search for the more radical roofless concept introduced in this study, one whose purpose is to maximise the sensorial stimuli for the activation of escape behaviour of Baltic cod.

The greatest concern associated with the roofless concept was the potential catch losses of targeted flatfish species. Overall results obtained with the baseline roofless design (RL175) by pooling the catch data from both cruises resulted in average values of *nS+* above 85%, for both plaice and flounder. This result agrees with previous behavioural observations of flatfish species, often seen swimming close to the bottom net panel of the extension piece of the trawl (Santos et al., 2020; Krag et al., 2009; He et al., 2008), without altering their path, even in the presence of selection devices (Santos et al., 2020). The *nS+* indicators estimated for plaice and flounder were associated to relatively large uncertainty (represented by confidence intervals with lower limits ~70%, and upper limits crossing 100%, the reference value for equal catches in test and reference gears). Causes for such uncertainty could be related to relatively large variation in performance between hauls, and the loss of efficiency observed when the catches of the analysed flatfish species were small (flounder in Cruise 1, plaice in Cruise 2). We could find no plausible explanation for such loss of efficiency other than the large variation in the binomial process related to the share of low-abundance catches among the paired gears. The behaviour of fish in relation to fishing gears, and more specifically to selection devices, can be influenced by extrinsic factors such as light conditions, or intrinsic factors such as the physiological condition of the fish (Winger et al., 2010; Walsh and Hickey, 1993). Further investigations that combine experimental fishing using the roofless device with behavioural investigations based on underwater video recordings are planned to assess and understand the performance of roofless devices under fishing and fish conditions different from those associated with the current study. In this respect, it is a priority to investigate potential diel variations in the performance of the roofless around the clock.

Topless trawls are legal alternatives in fisheries of NW and NE Atlantic where the bycatch of gadoid species is an issue. Consequently, topless trawls could be also considered a potential technical solution to reduce the bycatch of cod in flatfish directed fisheries in the Baltic Sea. Fishing trials with topless trawls conducted in a US NE coastal flatfish fishery and US George Bank reported large bycatch reduction of cod (Chosid et al., 2008; Pol et al., 2003; respectively 56% and 85% reduction compared to standard trawls). Krag et al. (2015) found, however, that the efficiency of topless trawls in avoiding cod can be very sensitive to relatively small changes in design, which questions the potential of topless trawls as a consistent strategy for the reduction of cod bycatch in Baltic Sea fisheries. Considering the large catch losses of flatfish species in the topless trawl observed in the NW Atlantic trials (Chosid et al., 2008; Pol et al., 2003), applying topless trawls in the Baltic Sea might also reduce the catch efficiency on targeted flatfish species to unacceptable levels.

Recent studies have demonstrated the potential of using codend selectivity to reduce the bycatch of Baltic cod beyond species minimum conservation reference size, without affecting the catchability of flatfish species (Madsen et al., 2021; Wienbeck et al., 2014). In particular, commercial sea trials using a square-mesh codend (so-called New Bacoma) of ~125 mm mesh size significantly reduced cod catches up to 50 cm (Madsen et al., 2021). Although the technological adaptations of the current mandatory codends proposed by Madsen et al. (2021) and Wienbeck et al. (2014) are simple, straightforward, and effective solutions to reducing cod bycatch, it is important to consider the risks associated with this strategy, given the current status of the Baltic cod stocks. Fishing with highly size-selective codends would increase the fishing pressure on larger cod, which are already rare, especially in the eastern stock (ICES, 2020a; Eero et al., 2015). The highly selective removal of older and larger spawners can accelerate the decline in size and age at maturity in the population (Garcia et al., 2012; Berkeley et al., 2004), thus reducing the quantity and the quality of total egg production (Cerviño et al., 2013; Berkeley et al., 2004), and therefore reducing even further the already low production in the population. It must also be noted that, according to the definition of size selection (Wileman et al., 1996), the degree of bycatch achieved using highly selective codends will depend strongly on the population structure encountered by the trawl. For example, considering the current population structure of Eastern Baltic cod, applying highly selective codends would be a fast and simple solution to reducing species bycatch. Nevertheless, as the length structure of the population changes, i.e. fish in the population grow, the efficiency of bycatch reduction provided by the codend will be reduced. Therefore, the bycatch reduction performance of codends must be evaluated regularly.

Under the current technological development and state of the Baltic Sea cod stocks, we argue that combining the roofless device with a highly selective codend could lead to a large, balanced (across fish lengths), and stable reduction in cod bycatch without considerable catch losses of marketable flatfish. Future sea trials combining the roofless device with highly selective codends, such as those proposed by Madsen et al. (2021) and Wienbeck et al. (2014), should be conducted to assess the benefits and limitations of the proposed combined strategy.

The roofless device expands the available toolbox of technologies for reducing cod bycatch in demersal fisheries. The dual-species indicators estimated in this study reveal that, under a choking scenario, using the roofless device would help to increase the time during which other demersal resources may be fished, and it may provide individual fishers with flexibility to adapt the exploitation patterns and divide the annual quota use according to their own preferences. It should be noted that the roofless device could also be an effective solution for demersal fisheries in other regions, challenged by choking caused by limitations on cod bycatch or any other roundfish species.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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