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Industry-led fishing gear development: Can it facilitate the process?

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Abstract

In the reformed technical measures regulation, the European Union proposed a greater involvement of the fishing industry in the different managerial aspects of fisheries. However, having the industry as a main actor in gear development presents a new suite of challenges. The industry, while addressing an issue in the fishery, can modify several aspects of a fishing gear simultaneously, without considering that some of those changes might have opposing effects. Here we present a case study where a codend, with several modifications, was developed by the industry for the Baltic cod trawl demersal fishery. Our results, based on cumulative catch distribution, catch comparison, and usability indicators, showed that the industry can successfully develop gears with more suitable catch profiles than the one currently used. However, one modification to the codend, the increased circumference, had the opposite effect than expected by the industry, thus making it suboptimal. Having the industry as the main driver in the development of new fishing gears can facilitate the development of a larger number and more specialized technical solutions. However, an early and continuous involvement of scientists in the process is crucial, as it ensures that unnecessary and adverse modifications are not made to the gear.

Keywords

Industry-led; fishing gear development; Baltic Sea; gear selectivity; fisheries management

Introduction

In fisheries management, one of the most widely used and effective technical measures used to achieve different managerial objectives is the implementation of more selective fishing gears (Graham *et al.*, 2007; Enever *et al.*, 2009; Condie *et al.*, 2014). Despite their extensive use, there are examples where the implementation of new or modified fishing gears did not have the desired effect (e.g. Krag *et al.*, 2016). The main motivation for the industry to negate the selectivity of a newly legislated gear stems primarily from the reduction or perceived reduction in target catch, resulting in short-term economic losses (Suuronen and Sardà, 2007; Suuronen *et al.*, 2007; Krag *et al.*, 2016). This negation of selectivity can occur when the technical solutions that are available for use within an entire fishery and management area are perceived by the industry as inadequate, e.g. the size selectivity of the gear does not match the minimum conservation reference size (MCRS) of the target species (Suuronen *et al.*, 2007). Under the European Union (EU) Common Fisheries Policy (CFP) of 2013, the management setting has changed to one where technical solutions can play a much larger role in achieving sustainability objectives.

Under the 2013 CFP, all catches of quota regulated listed species are to be counted against the quota, formally known as the landing obligation (LO), and once a species quota is fished that species has the possibility to choke the fisheries (European Union, 2013). Therefore, unwanted catches now have a direct monetary cost to the industry, directly linking selectivity to economy in the fisheries. The risk of a species choking a fishery can occur at different times throughout the year. Consequently, technical measures need to be developed to resolve these issues as they arise, where the measures will be dependent on the species which is/are choking the fishery. The need for a larger number of more specific technical solutions is something which is suggested in the proposed technical measures framework (Eliasen *et al.*, 2019). Furthermore, effective solutions will need to be implemented relatively quickly. This is something which has been acknowledged in the 2013 CFP with the introduction of regional groups, with them being given the mandate to implement delegate acts (Eliasen *et al.*, 2019).

One way to potentially increase the number and acceptance of new technical measures, particularly new fishing gears, is to not only have the industry involved in the development and testing of those fishing gears (e.g. Suuronen and Sardà, 2007) but rather lead the entire process (ICES, 2018a). The increased involvement of industry in the identification, development and testing of new gears, as well as in the documentation of their selective performance is something which numerous European countries (Denmark, Sweden, Scotland, The Netherlands, Belgium and England) are working on (ICES, 2018a) and has theoretically been demonstrated to be possible (Veiga-Malta *et al.*, 2018). Veiga-Malta *et al.* (2018) demonstrated that it is possible for the fishing industry to collect preliminary selectivity data on the performance of a new gear design. The industry could therefore be able to lead the entire development process, from identifying the problems, developing and testing multiple solutions in parallel, to collecting the data necessary for a preliminary documentation of the gear's performance. Such a system changes the way gears are developed, giving the industry a much larger and more proactive role in the process. However, this can result in a new suite of challenges for managers and scientists.

In this study, we evaluate the effect on size selectivity and catch pattern of an industry-developed gear modification and investigate if it met the industry's objective. We used a case study from the Baltic Sea cod (*Gadus morhua* Linnaeus, 1758) demersal trawl fishery, the most important demersal fishery in the Baltic Sea (ICES, 2018b). The industry developed a codend following the development process outlined above and described in Veiga-Malta *et al.* (2018). The main selectivity process in a standard demersal trawl without any by-catch reduction device occurs in the codend (Wileman *et al.*, 1996). Thus, to adjust the trawl selectivity, several parameters of the codend can be modified, such as, mesh shape (e.g. Campos *et al*., 2003; Herrmann *et al.*, 2007), mesh size (e.g. Herrmann *et al.*, 2009; Wienbeck *et al.*, 2011; Wienbeck *et al.*, 2014), codend circumference (e.g. Reeves *et al.*, 1992; Graham *et al.*, 2009; Herrmann *et al.*, 2015), twine material and thickness (e.g. Ferro and O'Neill, 1994; Tokaç *et al.*, 2004), and through the use of lastridge ropes (e.g. Hickey *et al.*, 1993; Lök *et al.*, 1997). The industry developed a codend with several of these parameters modified. Their aim was to adjust the selectivity of the gear to better match the MCRS of 35 cm for Baltic cod. Furthermore, according to the industry, the two gears currently legislated, T90 120 mm and BACOMA 120 mm (EU Regulation no. 686/2010), are too selective due to changes in the cod population structure in recent years, something which has occurred due to the increased fishing pressure on larger cod (Svedäng and Hornborg, 2014; Svedäng and Hornborg, 2017). Finally, based on this case study, we identify and discuss the potential advantages and challenges of industry-led fishing gear development.

Material and Methods

The codend developed by the industry had four modifications compared to the one currently used by the fleet, a T90 120 mm codend with 50 meshes in the circumference; a larger circumference, smaller mesh size, shortened lastridge ropes, and twine made of polyethylene (PE) instead of polyester (PES). A T90 codend is a diamond mesh codend where the meshes are turned 90 degrees, with the intention of keeping the meshes open during the fishing process (Herrmann *et al.*, 2007). Lastridge ropes are ropes that are attached to the selvedges of the codend, that when shortened ensure the meshes remain open during the fishing process (Hickey *et al.*, 1993). Since the codend proposed by the industry had several modifications, we disentangle the effects of the different modifications. Describing and understanding the effects of the individual modifications makes it possible to optimise the performance of the new fishing gear and facilitate its implementation in legislation (Eliasen *et al.*, 2019). Therefore, three consecutive gear selectivity trials were conducted.

The size selectivity and catch patterns of the codends tested were compared in each of the three trials. In the first trial, the industry-developed codend, hereby referred to as IND, was compared to the standard T90 codend made from polyester (PES), hereby referred to as PES. In the second trial, IND was compared to the standard T90 codend constructed from polyethylene (PE), hereby referred to as PE. In the third trial, a codend similar to PE but with a larger circumference of 92 meshes around, hereby referred to as LC codend, was compared to PE. For further details on the four codends tested see Table 1.

Table 1. Description of the technical specifications of the four codends tested in the sea trials.

Characteristic	(IND)	(PES)	(PE)	LC
Mesh orientation	T90	T90	T90	T90
Nominal mesh size (mm)	110	120	120	120
Measured mesh size (mm)	109.1	121.4	123.1	122.8
Standard deviation	2.4	1.9	2.2	2.2
Codend circumference (no. open meshes)	92	50	50	92
Twine thickness	4 mm double	4 mm double	4 mm double	4 mm double
Shortened lastridge ropes	Yes	No	No	No
Net material	Polyethylene (PE)	Polyester (PES)	Polyethylene (PE)	Polyethylene (PE)
Codend length (m)	10.5	8	8	8
No. of selvedges	2	2	2	2
Number of mesh in each selvedge	4	4	4	4

The sea trials were conducted in the Baltic Sea off the coast of Bornholm on board of the commercial vessel R 218 Judith Bechmann (a twin-rig trawler with 25.9 m length and 485 Kw), during 17th to 27th of June 2017. The fishing grounds were chosen by the skipper based on his experience, so that the size structure of the cod population available to the gears was representative of commercial trips. The vessel was equipped with two identical trawls where the only difference was the codends used. The sea trials were conducted as catch comparison trials (Krag *et al.*, 2014) where two trawls were towed in a twin-rig setting, with the position of the tested codends being swapped every 3-5 hauls, to account for systematic trawl side effects. Towing both trawls in parallel ensures that on a haul-by haul basis both codends tested are subjected to the same varying fishing conditions, population structures and sizes. Additionally, not using covers around the codend ensured that the fishing conditions were kept as similar as possible to commercial fishing conditions. Furthermore, the order in which the codends were retrieved was also taken into account by alternating every second haul which codend was retrieved first, the starboard or port side, respectively. The second codend was hanging loosely beside the vessel for approximately 5 to 10 min. All cod caught were length measured and rounded down to the nearest centimetre.

Statistical analyses

The number of individuals per length class caught in the different codends in each of the trials was used to evaluate the length dependent relative catch efficiency for cod in the test gears in relation to the baseline gears. Moreover, the number of individuals per length class provides an estimate of the size selectivity between the two codends, thus comparing the length-dependent catching efficiency of both gears. The portion of the total catch caught by the test gear was obtained through the use of the catch comparison equation (CC; Krag *et al.*, 2014):

$$\mathrm{CC}_{il} = \frac{\sum_{i=1}^{h} n\mathrm{t}_{li}}{\sum_{i=1}^{h} n\mathrm{t}_{li} + \sum_{i=1}^{h} n\mathrm{b}_{lj}} \qquad (1)$$

where $n\mathrm{t}_{il}$ is the number of individuals caught per length class l and haul i in the test codend, and $n\mathrm{b}_{il}$ is the equivalent for the codends used as the baseline in the different trials. The total number of hauls in the trial is represented by h. From the catch comparison values obtained experimentally, the length-dependent relative catch efficiency was modelled through the use of the catch comparison function $\mathrm{CC}(l, \boldsymbol{q})$, (Krag *et al.*, 2014):

$$CC(l, \boldsymbol{q}) = \frac{\exp(f\ (l, q_0, \ldots, q_k))}{1 + \exp(f\ (l, q_0, \ldots, q_k))} \qquad (2)$$

where f is a polynomial of order k with coefficients q_0 to q_k so $\boldsymbol{q}$ = (q_0,…, q_k). f was considered up to an order of 4 with parameters q_0, q_1, q_2, q_3 and q_4. Leaving out one or more of the parameters q_1, …, q_4 led to 31 additional models that were also considered potential models for the catch comparison function $CC(l,\boldsymbol{q})$. The selection of the final models was based on multimodel inference (Burnham and Anderson, 2002). In this approach, an average of the best models, weighted by their respective Akaike's Information Criterion (AIC) values (Akaike, 1974), is chosen rather than selecting the model with the lowest AIC value. This method allows for an overall better fit of the estimated curves of the model and their associated uncertainties. Here, all models were used where the difference between their respective AIC values and the lowest AIC value was 10 or lower (Katsanevakis, 2006). How well the combined model results fitted the experimental data was evaluated through the *p*-value, residuals deviance and how it relates to the degrees of freedom, and the visual inspection of the residuals distribution (Wileman *et al.*, 1996). The *p*-value expresses the likelihood for obtaining by coincidence a discrepancy equal to or larger than the observed discrepancy between the fitted model and the experimental data, thus the *p*-value should not be <0.05 (Wileman *et al.*, 1996). Moreover, residual deviances and the degrees of freedom should show values within the same order of magnitude (Wileman *et al.*, 1996).

The $CC(l,\boldsymbol{q})$ descriptor does not provides a direct estimate for the relative catch efficiency for both gears, therefore catch ratio was used since it provides such direct comparison and can be easily derived from $CC(l,\boldsymbol{q})$. This direct comparison provides an easier interpretation of results for fisheries managers and fishermen (Veiga-Malta *et al.*, 2018).

$$\mathrm{CR}(l,\boldsymbol{q}) = \frac{\mathrm{CC}(l,\boldsymbol{q})}{1-\mathrm{CC}(l,\boldsymbol{q})} \quad (3).$$

where CR can have values equal to or higher than 0. A CR value of 1 means the catch efficiency for both gears at length *l* is equal, while a CR equal to 0.5 and 1.5 means that the test gear is catching 50% less or more, respectively, at length *l* for a given species. The CI for the average $CC(l,\boldsymbol{q})$ and $\mathrm{CR}(l,\boldsymbol{q})$ were estimated using a double bootstrap approach. By using this approach, both within and between haul variations were taken into account. A total of 1000 bootstrap iterations were performed to estimate the Efron percentile 95% confidence limits (Efron, 1982) for all relevant length classes.

Because the gear which was used as a baseline in trials 1 and 2 remained the same, it was possible to indirectly assess the effect the net material had on the catch efficiency of cod. This was performed by calculating the ratio between the catch ratio curves obtained from the first and second trials using the following equation:

$$CR(l,\boldsymbol{q})_{PES/PE} = \frac{\mathrm{CR}(l,\boldsymbol{q})_{trial1}}{\mathrm{CR}(l,\boldsymbol{q})_{trial2}} \quad (4)$$

where in both catch ratio analyses the numerator was the test gear. This simple mathematical manipulation makes it possible to infer the selectivity of the codend made of PES in relation to the codend made of PE.

The 95% confidence intervals (CI) for $CR(l,\boldsymbol{q})_{PES/PE}$ were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) from each CR model estimated for the first and second trials. Since both bootstrap populations were obtained independently and the sampling to obtain those populations of results was performed randomly and independently, a new population of results with 1000 bootstrap iterations was created for $CR(l,\boldsymbol{q})_{PES/PE}$ following (Herrmann *et al.*, 2018):

$$CR(l,\boldsymbol{q})_{PES/PEi} = \frac{\mathrm{CR}(l,q)_{trial1i}}{\mathrm{CR}(l,q)_{trial2i}}\ i\ \in\ [1 \cdots 1000] \quad (5)$$

where *i* represents the bootstrap repetition index. Based on this new population the Efron 95% CI for the $CR(l,\boldsymbol{q})_{PES/PE}$ were obtained.

Catch comparison and catch ratio analyses, by being population independent, are good tools for generalizing the results obtained from comparing the selectivity of two gears in a given fishery to other fisheries. However, if the aim is to better understand the impacts of that difference in selectivity to the stock where the new gear was tested or catch length pattern obtained by the fishermen, cumulative distribution analysis of the catch weight gives a better understanding and quantification of such impacts. Therefore, cumulative distribution analyses of the catch weight were performed for the catches of each codend used in the three sea trials and the difference between both cumulative distributions within each trial was calculated, henceforth referred to as delta. Cumulative distribution analysis provides the proportion of the total catch up to a given length for the tested gear when fished in that stock population, thus being highly relevant for management purposes. Moreover, the cumulative catch weight distribution analysis is non-parametric and thus independent of any modelling assumptions and is described in this study by:

$$CD\_catch(L) = \frac{\sum_i \{\sum_{l=0}^{l \leq L} [n_{il} \times (a \times l^b)]\}}{\sum_i \{\sum_l n_{il}\}} \quad (6)$$

where the sum of i is for hauls and l is for length classes, while *a* and *b* are the coefficients from the length-weight equation for Baltic cod. The delta allows quantifying the length dependent difference between the catch weight distributions of the both codends tested in each sea trial, and can be described by:

$$Delta\_CD = CD\_catch(L)_t - CD\_catch(L)_b \quad (7)$$

where the indices *t* and *b* represent, respectively, the test and baseline codends in each of the three trials. The Efron percentile 95% confidence limits were estimated using a double bootstrap approach. Since, for all three trials both tested codends were fished in parallel and therefore subjected to the same fishing conditions and cod populations, the bootstrapping procedures for each cumulative catch weight distribution curves were performed in the same loop. This approach allows accounting for differences that might have come from variability within the trials.

The evaluation of the different codend's overall performance can also be complemented and summarized using usability indicators. The indicators were adapted from Wienbeck *et al.* (2014) and Santos *et al.* (2016) so that they could be used for catch comparison data instead of cover codend data. Moreover, the indicators were modified to provide the values in weight and not numbers caught to be even more relevant for managers and fishermen. These indicators depend directly on the size structure of the fished population, in contrast to the catch comparison and catch ratio that provide population independent information. Thus, the results are specific to the three trials in this study. However, since the trials were undertaken under commercial conditions and targeting common fishing grounds, the results contain information regarding the usability of the codends in the fishery. Three different codend usability indicators were used:

$$wP_{-} = \frac{\sum_i\{\sum_{l<MCRS} n\mathrm{t}_{il}\times(a\times l^b)\}}{\sum_i\{\sum_{l<MCRS} n\mathrm{b}_{il}\times(a\times l^b)\}} \quad (8)$$

$$wP_{+} = \frac{\sum_i\{\sum_{l\geq MCRS} n\mathrm{t}_{il}\times(a\times l^b)\}}{\sum_i\{\sum_{l\geq MCRS} n\mathrm{b}_{il}\times(a\times l^b)\}} \quad (9)$$

$$dwRatio = 100 \times \frac{\sum_i\{\sum_{l<MCRS} n_{il}\times(a\times l^b)\}}{\sum_i\{\sum_{l} n_{il}\times(a\times l^b)\}} \quad (10)$$

where the sum of i is for hauls and l is for length classes and *a* and *b* are the coefficients from the length-weight equation for Baltic cod obtained from Danish bottom trawl surveys in the first and fourth quarters of the years 2015 to 2017 in the ICES areas 24 and 25 of the Baltic Sea. wP_{-} and wP_{+} compare the catches weights under and over the MCRS between the test and the baseline codends for each trial. Values of 100 indicate that the test gear catches equally as much as the baseline gear. Therefore, wP_{-} should be as low as possible while wP_{+} should be as high as possible, meaning that no losses ($wP_{+} \approx 1$) or even an increase in the catch above the MCRS ($wP_{+} > 1$) occurred for the test codend in relation to the baseline codend. $dwRatio$ is the ratio between discards and total catch in weight, thus it should be as low as possible, with 0 being the optimal situation where no discards occur. The weight per hour caught for cod above and under the MRCS was also used as a usability indicator for each trial and codend.

The CI for the average nP_{-}, nP_{+} and $dwRatio$ were estimated using a double bootstrap approach. By using this approach, both within and between haul variations were taken into account. A total of 1000 bootstrap iterations were performed to estimate the Efron percentile 95% confidence limits (Efron, 1982) for all relevant length classes.

Results

A total of 26 out of 27 hauls were considered valid, with 6 being from the first trial, 10 from the second, and 10 from the third (Table 2). The invalid haul was due to excessive mud in the codend of the test gear. Furthermore, fishing operations were kept as similar as possible to commercial fishing activities, with haul duration, towing speed and fishing depth ranging from 100 to 465 min, 3.1 to 3.4 knots, and 40 to 73 m, respectively. Total catches of cod per haul ranged from 243 to 1763 kg during the three sea trials and all cod caught was length measured. Further details regarding the sea trials are shown in Table 2.

Table 2. Summary of the hauls used for the catch comparison analysis of cod. Values within parenthesis are the calculated standard deviations.

	Trial 1	**Trial 2**	**Trial 3**
No. of hauls	6	10	10
No. cod caught	5 856	9 770	14 254
Average cod catch size (kg)	1130 (±368)	782 (±344)	691 (±159)
Average haul duration (min)	317 (±83)	258 (±66)	304 (±76)
Average towing speed (knots)	3.2 (±0.08)	3.2 (±0.04)	3.2 (±0.04)
Average fishing depth (m)	54 (±10)	62 (±11)	66 (±3)

Catch comparison analyses were performed on the datasets from each of the three trials. The analysis of model fits did not reveal any issues. The *p*-values and the ratio between residual deviance and degrees of freedom did not indicate any fitting problems for any of the three models (Table 3). Furthermore, plotting the residuals against the length did not show any structure in the residuals from any of the three catch comparison models (plots not shown).

Table 3. Fit statistics for the modelled catch comparison rates.

Trial	***p*-value**	**Residual Deviance**	**DOF**

1	0.80	37.66	46
2	0.12	62.12	50
3	0.11	65.74	53

The results obtained from the first trial are shown in Figure 1. The catch ratio, $CR(l, \boldsymbol{q})$, curve obtained showed that the IND codend caught significantly more cod between 45 and 48 cm than PES, while no significant difference was found for the remaining length classes. The largest significant difference occurred for the length of 47 cm, where IND caught at least 1.02 times (estimated to be on average 1.20 times) more cod than PES. The cumulative catch weight distribution curves obtained from both codends showed similar catch patterns. However, the $Delta\_CD$ shows that the cumulative catch profiles of IND and PES are significantly different for the lengths between 35 and 40 cm. $Delta\_CD$ shows that the cumulative catch, in weight, for the lengths 35 to 40 cm is lower for IND, with the largest absolute difference occurring at 39 cm, -5.6% (CI from -12.1 to -0.8). This significant difference comes from the cumulative effect of IND catching less cod up to the length of 39 cm, as seen in the $CR(l, \boldsymbol{q})$, despite not been significant in the $CR(l, \boldsymbol{q})$. The usability indicators for cod for the first trial show that IND, when tested against PES, currently being used in the fishery, reduced the catch of undersized cod by 27% (wP-) while increasing the catch of oversized cod (wP+) by 7%. Moreover, IND showed a lower discard ratio ($dwRatio$) than PES, 3.7% (CI from 2.2 to 4.8) and 5.2% (CI from 3.5 to 7.6), respectively. Despite on average indicating an overall positive performance of IND, wP- and wP+ were not significant since in both cases the CIs included the value of 1.

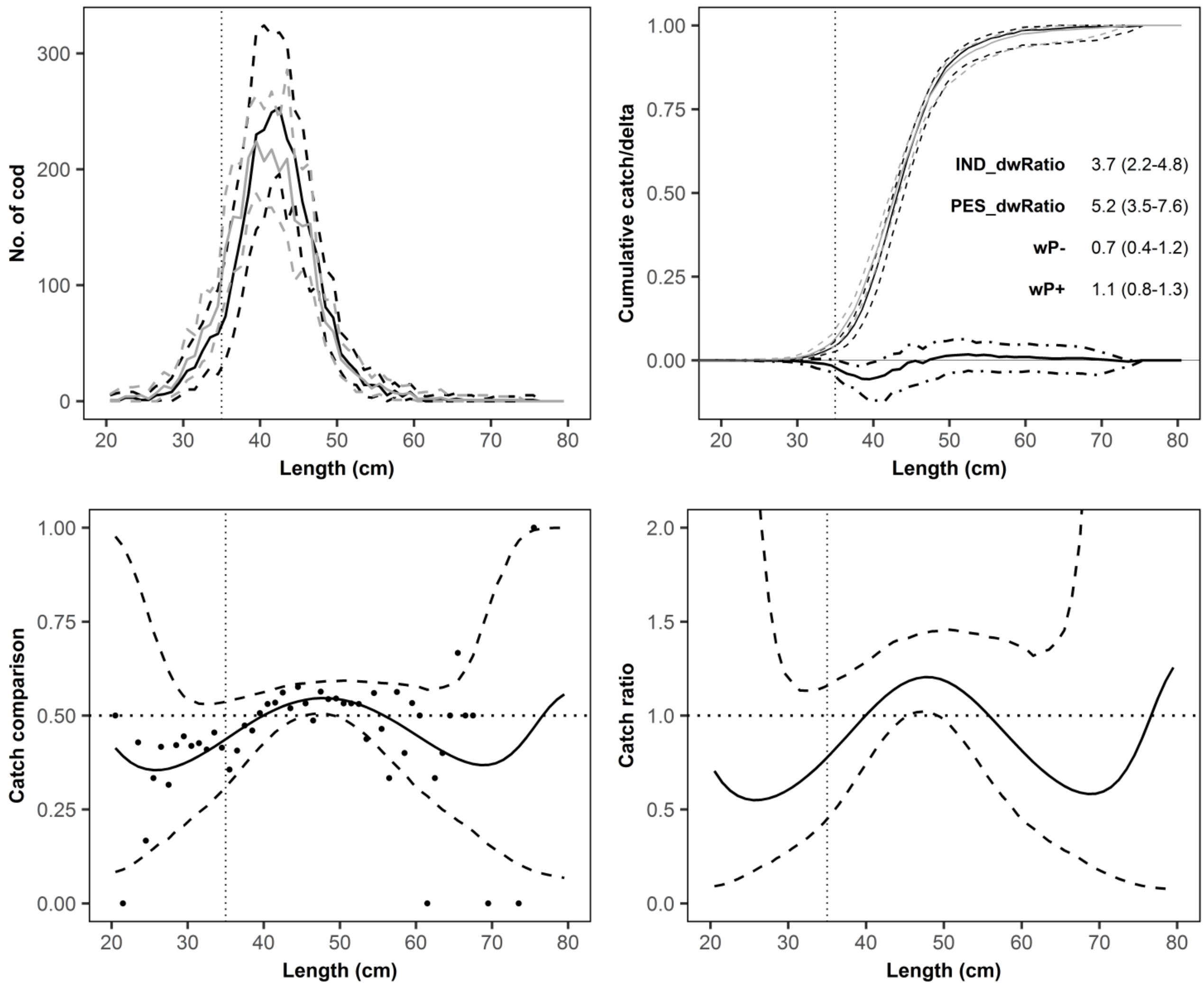

Figure 1 Results from trial 1. Top-left panel shows the population caught in numbers by IND (black line) and PES (grey line). Top-right panel shows the cumulative catch weight distributions for IND (black thin line) and PES (grey thin line) and respective delta (black thick line). The usability indicators are also shown in the top-right panel. Estimated average catch comparison and catch ratio curves are shown in the bottom-left and bottom-right panels, respectively. Dotted grey horizontal lines represent when both gears are fishing equally efficient. The 95% confidence intervals estimated for all curves in all panels are shown in the respective broken lines. The vertical dotted line shows the minimum conservation reference size of 35 cm for Baltic cod.

In the second trial, where PES was changed to PE, the IND codend caught significantly more cod at the length classes between 26 and 47 cm, while no significant difference was found for the other length classes (Figure 2). At the MCRS, IND caught at least 2 times more cod (on average 4 times more) than PE. Moreover, the cumulative catch distributions curves obtained for IND and PE also show two distinct catch profiles. The $Delta\_CD$ shows that IND caught, in weight, significantly more cod than PE for the lengths between 34 and 53 cm, with the largest delta occurring at 44 cm with a total difference of 17.8% (CI from 10.35 to 25.10). Although $CR(l, \boldsymbol{q})$ showed that IND has relatively higher catch rates of smaller cod, this increase in catch rates starts to impact the cumulative catch profile only at the length of 34 cm. Furthermore, the usability indicators also showed a significantly higher retention of cod under the MCRS, 413%, and a significant increase of cod above the MCRS, although of a lower magnitude, 45%. Although the relative increase in undersized cod being around 9 times higher than the increase of oversized cod, the absolute increase in catch between both codends for both undersized and oversized cod showed opposite results as shown by the $Delta\_CD$ and the absolute catches. Regarding the discard ratio of cod in weight, IND showed values approximately 3.5 times higher than PE, 3.8% (CI from 1.4 to 6.6) and 1.1% (CI from 0.6 to 1.5], respectively, although still being a relatively low discard ratio ($dwRatio$).

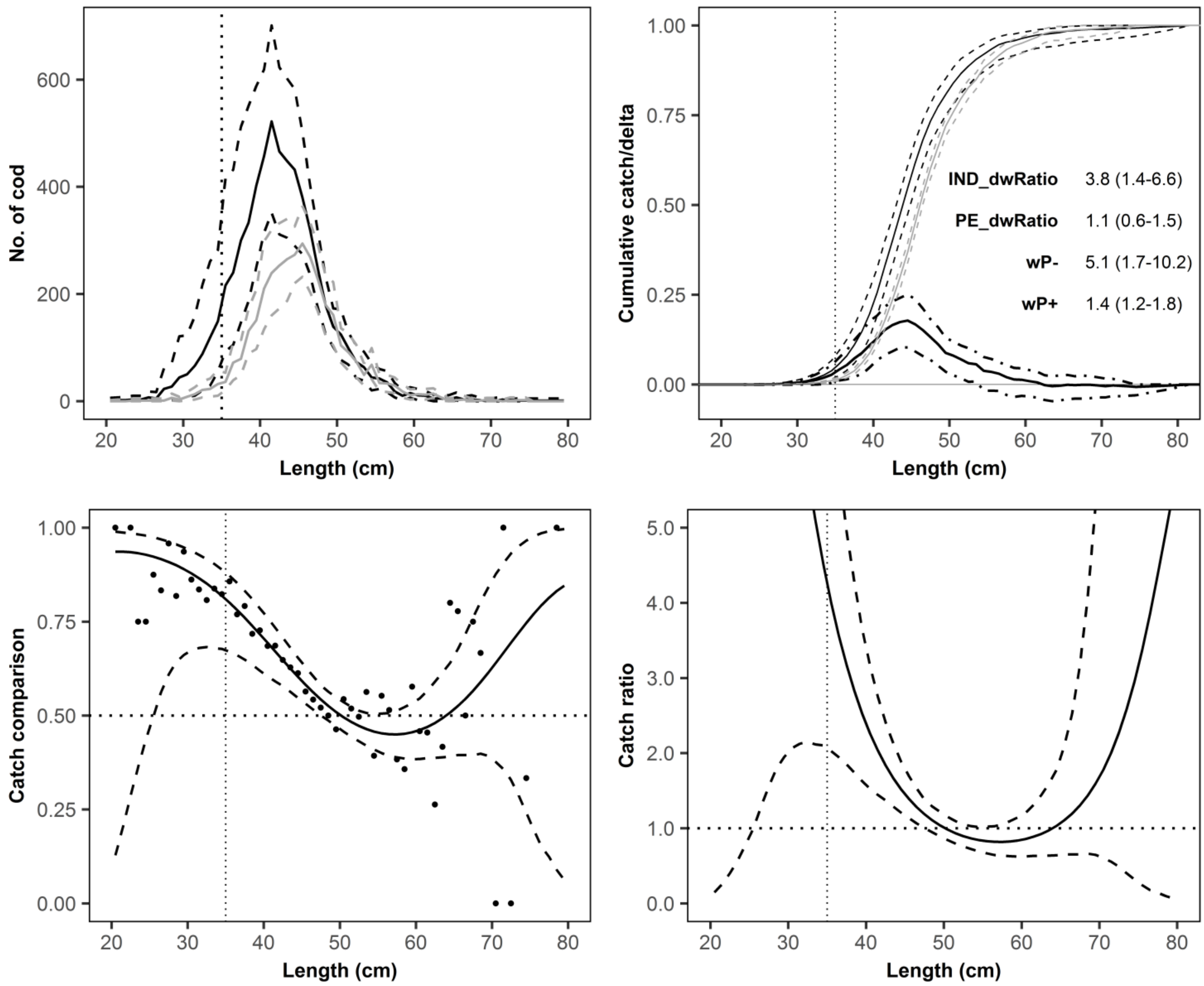

Figure 2 Results from trial 2. Top-left panel shows the population caught in numbers by IND (black line) and PE (grey line). Top-right panel shows the cumulative catch weight distributions for IND (black thin line) and PE (grey thin line) and respective delta (black thick line). The usability indicators are also shown in the top-right panel. Estimated average catch comparison and catch ratio curves are shown in the bottom-left and bottom-right panels, respectively. Dotted grey horizontal lines represent when both gears are fishing equally efficient. The 95% confidence intervals estimated for all curves in all panels are shown in the respective broken lines. The vertical dotted line shows the minimum conservation reference size of 35 cm for Baltic cod.

The effect of increasing the circumference was tested in the third trial and the results shown in Figure 3. The LC codend caught significantly more cod below 45 cm when compared to the PE codend, while catching significantly less cod between 47 and 60 cm. No significant difference was found for other lengths. The increase in circumference from 50 to 92 open meshes led to a minimum increase of 40% (on average 74%) of the catch of cod at the MCRS. The $Delta\_CD$

obtained from the cumulative catch curves for both codends showed a significant difference in the cumulative catch profile for lengths between 30 and 47 cm. Moreover, the largest delta value occurs at 42 cm with a total difference of 8.2% (CI from4.2 to 12.3). This significant difference between the cumulative catch profiles of both codends, LC and PE, comes from the large increase of catches of undersized cod, affecting the catch profile up to 47 cm. The increase in codend circumference resulted in an increase of 2.2 times of undersized cod and no change in the catches of oversized cod (respectively, wP- and wP+ in Figure 3). Moreover, the LC showed a discard ratio of 3.4% (CI from 2.3 to 4.6) while PE showed a discard ratio of 1.6% (CI from 1.1 to 2.1).

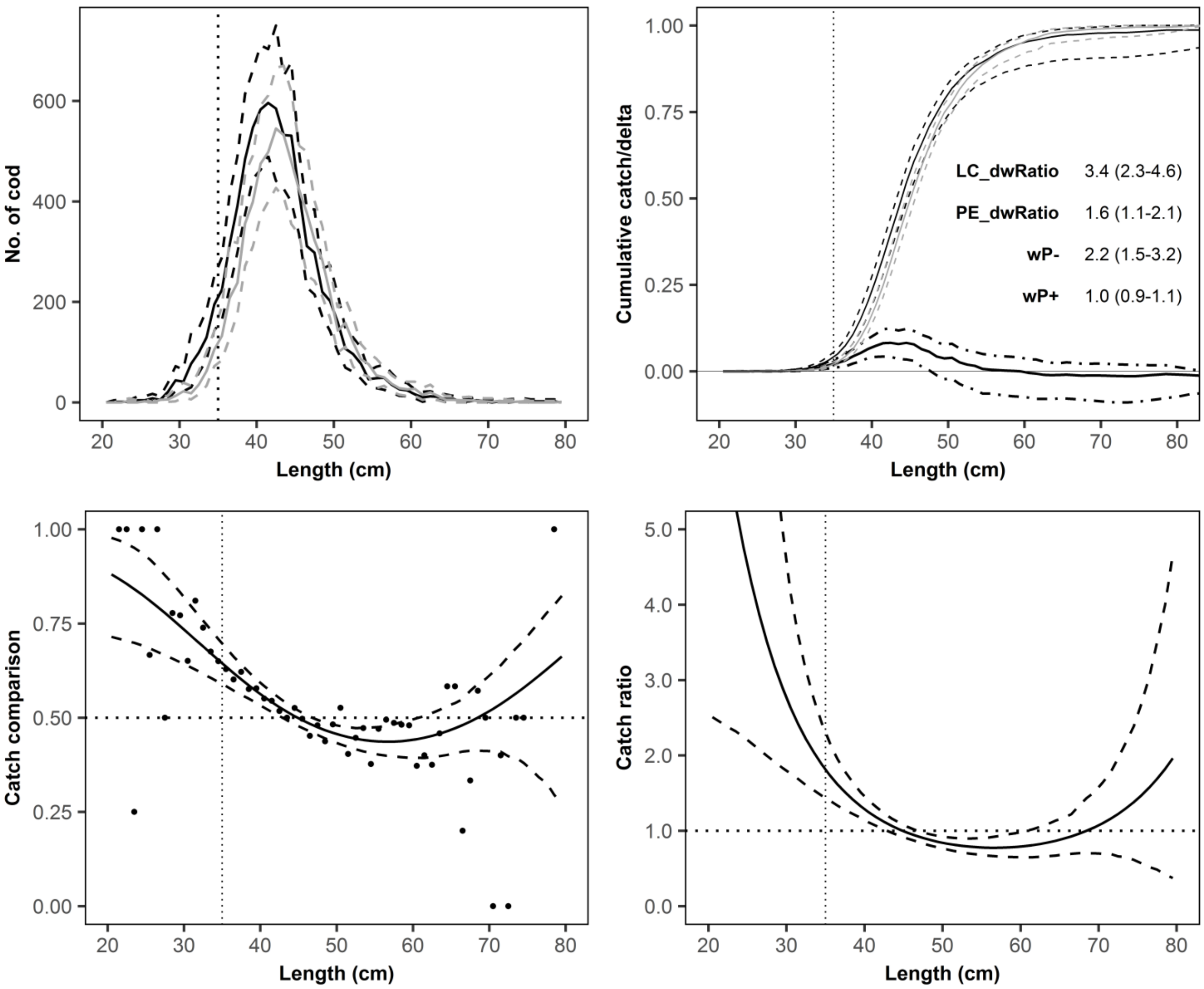

Figure 3 Results from trial 3. Top-left panel shows the population caught in numbers by LC (black line) and PE (grey line). Top-right panel shows the cumulative catch weight distributions for LC (black thin line) and PE (grey thin line) and respective delta (black thick line). The usability indicators are also shown in the top-right panel. Estimated average catch comparison and catch ratio curves are shown in the bottom-left and bottom-right panels, respectively. Dotted grey horizontal lines represent when both gears are fishing equally efficient. The 95% confidence intervals estimated for all curves in all panels are shown in the respective broken lines. The vertical dotted line shows the minimum conservation reference size of 35 cm for Baltic cod.

Changing the net material from polyethylene (PE) to polyester (PES) significantly increased the catch of cod between 26 and 43 cm, inclusive, while showing no significant differences for the other length classes (Figure 4b). At the MRCS, the PES codend caught at least 2.2 times (on average 5 times) more cod than the PE.

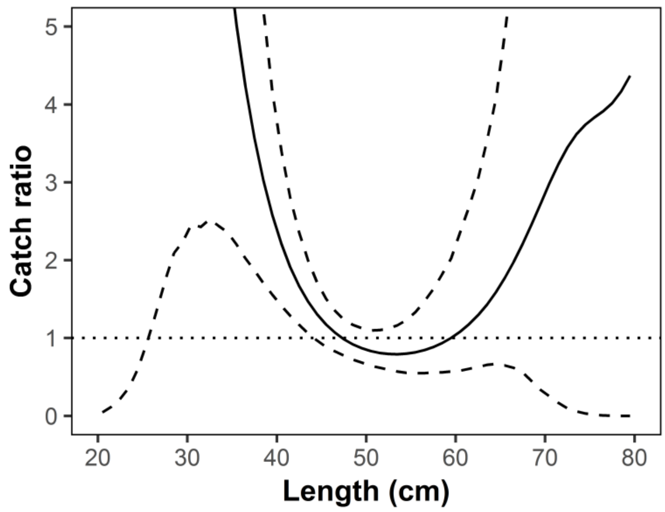

Figure 4 Estimated catch ratio curve (solid black line) and 95% confidence intervals (broken black lines) for cod obtained when changing the material of the codend from polyethylene to polyester in a T90 120 mm standard codend. Dotted grey horizontal line represents when both codends have equal catch efficiency.

Discussion

The results from the first and second trials showed that the industry were able to develop a codend, IND, with a size selectivity better suited to the current cod population structure in the Baltic Sea. Moreover, the industry-developed codend showed a better selectivity when compared to the codends presently being used by the Baltic cod trawl fleet. The industry being able to successfully develop gears with more suitable catch profiles than the one's currently used has been described in previous studies (Catchpole and Gray, 2010). However, the objectives of the fishing industry and scientists are not completely aligned.

While both industry and scientists have the objectives of optimising catch values and reducing discards to increase profit, scientists also need to understand the effect of the single design parameters of a fishing gear. Thus, industry can change several design parameters of a gear to achieve their objectives, as shown in this case study. To understand the individual effects of the different parameters changed in the fishing gear proposed by the industry we tested two of these modifications scientifically, material type and codend circumference, and discuss the effect of the two other modifications, mesh size and lastridge ropes.

The results describing the effect of twine material on cod selectivity showed that PES significantly reduced the selectivity for cod when compared to PE. Previous studies reported that for diamond meshes (T0°) twine materials softer than PE, such as PES, increase the codend selectivity (Ferro and O'Neill, 1994; Tokaç *et al.*, 2004). Softer materials allow for an easier escape of individuals when the codend has already some catch build-up. These findings contradict the results obtained in this study, although here diamond meshes turned 90° degrees were used instead of T0°. The objective of turning diamond shaped meshes 90° degrees is to allow the meshes to retain their shape and remain open during the fishing process (Herrmann *et al.*, 2007). A stiffer twine material in a T90° netting will further enhance its effects, as it will help retain the mesh opening angle of the meshes (Herrmann *et al.*, 2009). On the other hand, a softer twine material can considerably hamper the effect of T90° netting by reducing the opening angle of the meshes. As our results show, the twine material stiffness in a T0° codend appears to have the opposite effect in a T90°.

The results obtained describing the effect of codend circumference on the selectivity of cod showed that increasing the circumference of the codend from 50 to 92 open meshes significantly decreased the selectivity of cod. Previous studies presented similar results for cod in the Baltic Sea (Wienbeck *et al.*, 2011; Herrmann *et al.*, 2015), North Sea (Reeves *et al.*, 1992) and based on simulations (Herrmann *et al.*, 2007). The optimal opening angle of the meshes in codends with smaller circumferences is typically reached earlier in the fishing process, and thus facilitating the escapement of smaller cod (Herrmann *et al*., 2007).

The effects of reducing mesh size and adding lastridge ropes were not tested in this study. The effect of reducing mesh size on cod selectivity is well known and documented, where a reduction in mesh size reduces selectivity (e.g. Herrmann *et al.*, 2009; Wienbeck *et al.*, 2011; Wienbeck *et al.*, 2014). While being less well documented, the objective of lastridge ropes is to maintain a high OA of the meshes in the codend throughout the fishing process, therefore increasing selectivity (Hickey *et al.*, 1993; Lök *et al.*, 1997).

This case study shows that the industry can, in the terms of overall size selectivity, develop a gear to suit their needs and those of management. This approach also provides them with a more active role in the process, where they are able to develop and test multiple solutions in parallel which are tailored to their specific fisheries. Moreover, the experimental design applied in this study, where the new gear was tested directly against a baseline using the catch comparison method, is particularly well-suited for industry-led gear development trials as it does not interfere with the commercial fishing operation. Furthermore, developing gears in such a manner introduces a proper iterative development and testing phase under commercial fishing conditions, something which has previously been lacking. Undertaking the development and testing in such a manner can potentially lead to a faster implementation and uptake of gears in the fisheries. However, the speed in the process of introducing new fishing gears can be reduced by the industry putting forward overly complicated gears requiring a complex and costly documentation process.

As seen in this case study, the industry put forward a gear design where multiple design parameters were modified. A total of four modifications were made, where one was found to have opposite effects to what the industry had anticipated (codend circumference) and another perceived not to influence the selectivity (material type). The effects of these parameters would not have been disclosed if the selectivity of the industry-developed gear had only been compared to the baseline. Not dissociating the effects of the different modifications can potentially result in unfavourable modifications being introduced into legislation. The selectivity obtained by the overly complicated gear design put forward by the industry could most likely have been obtained through a simple reduction in mesh size. Moreover, the scientific testing and documenting of such overly complicated gear designs becomes more expensive and time consuming, more difficult to understand, as well as resulting in an over complication of the gear specifications in legislation and difficulties in enforcement. This can potentially reduce the benefits of industry-led gear development.

Having the industry as the main driver in the development of new fishing gears can facilitate the development of a larger number and more specialized technical solutions. Moreover, it can reduce the time outlay associated with gear development, and increase the acceptance of the new gear by the industry. However, there needs to be an early and continuous involvement from scientists in the development process to advise on expected effects of modifying different design parameters. This early involvement ensures that unnecessary and adverse modifications are not made to the gear, thus facilitating the scientific testing and documentation process for possible implementation in legislation. Furthermore, by understanding the effect of each modification, the response time to new issues in a fishery can be greatly reduced by knowing exactly which gear modifications should be further improved or removed.

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