Bycatch reduction in the deep-water shrimp (Pandalus borealis) trawl fishery by increasing codend mesh openness

Jacques, Nadine; Pettersen, Hermann; Cerbule, Kristine; Herrmann, Bent; Ingólfsson, Ólafur Arnar; Sistiaga, Manu; Larsen, Roger B.; Brinkhof, Jesse; Grimaldo, Eduardo; Brčić, Jure

Total number of authors:
11

Published in:
Canadian Journal of Fisheries and Aquatic Sciences

Link to article, DOI:
10.1139/cjfas-2021-0045

Publication date:
2022

Document Version
Peer reviewed version

Citation (APA):
Jacques, N., Pettersen, H., Cerbule, K., Herrmann, B., Ingólfsson, Ó. A., Sistiaga, M., Larsen, R. B., Brinkhof, J., Grimaldo, E., Brčić, J., & Lilleng, D. (2022). Bycatch reduction in the deep-water shrimp (*Pandalus borealis*) trawl fishery by increasing codend mesh openness. *Canadian Journal of Fisheries and Aquatic Sciences*, *79*(2), 331-341. https://doi.org/10.1139/cjfas-2021-0045

Bycatch reduction in the deep-water shrimp (*Pandalus borealis*) trawl fishery by increasing codend mesh openness

Nadine Jacques[1, 2*], Hermann Pettersen[1], Kristine Cerbule[1, 2], Bent Herrmann[1, 2, 3], Ólafur Arnar Ingólfsson[4], Manu Sistiaga [4,5], Roger B. Larsen[1], Jesse Brinkhof [1], Eduardo Grimaldo[1, 2], Jure Brčić [6,] Dagfinn Lilleng [7]

[1] UiT The Arctic University of Norway, Tromsø, Norway

[2] Department of Fishing Gear Technology, SINTEF Ocean, Trondheim, Norway

[3] DTU Aqua, Denmark Technical University, Hirtshals, Denmark

[4] Fish capture division, Norwegian Institute of Marine Research, Bergen, Norway

[5] NTNU Norwegian University of Science and Technology, Otto Nielsens veg 10, N-7491 Trondheim, Norway

[6] Department of Marine Studies, University of Split, Split, Croatia

[7] Norwegian Directorate of Fisheries, Postbox 185 Sentrum, 5804 Bergen, Norway

[*] Corresponding author

e-mail: nadine.jacques@uit.no

Abstract

In most trawl fisheries, drag forces tend to close the meshes in large areas of diamond mesh codends, negatively affecting their selective potential. In the Barents Sea deep-water shrimp (*Pandalus borealis)* trawl fishery, selectivity is based on a sorting grid followed by a diamond mesh codend. However, the retention of juvenile fish as well as undersized shrimp is still a problem. In this study, we estimated the effect of applying different codend modifications, each aimed at affecting codend mesh openness and thereby selectivity. Changing from a 4-panel to a 2-panel construction of the codend did not affect size selectivity. Shortening the lastridge ropes of a 4-panel codend by 20% resulted in minor reductions for juvenile fish bycatch, but a 45% reduction of undersized shrimp was observed. Target-size catches of shrimp were nearly unaffected. When the codend mesh circumference was reduced while simultaneously shortening the lastridge ropes, the effect on catch efficiency for shrimp or juvenile fish bycatch was marginal compared to a 4-panel codend design with shortened lastridge ropes.

Keywords: Lastridge ropes, codend circumference, bottom trawl, selectivity, deep-water shrimp, bycatch reduction

1. Introduction

Various bycatch reduction measures are implemented in shrimp trawl fisheries globally, to restrict the bycatch of non-target species as well as undersized target species (Broadhurst and Kennelly 1995, Eayrs 2007). These include square mesh panels, sorting grids and trawl construction modifications (Isaksen et al. 1992; Broadhurst and Kennelly 1995; Hannah and Jones 2007, Ingólfsson and Jørgensen 2020). In the Barents Sea deep-water shrimp fishery (*Pandalus borealis*) the Nordmöre sorting grid, was developed in the early 1990's and mitigated the bycatch issues in the fishery (Isaksen et al. 1992; Grimaldo and Larsen 2005; Larsen et al. 2018a). The current regulation enforces the use of the Nordmöre grid with 19 mm bar spacing in combination with a 35 mm diamond mesh codend (Isaksen et al. 1992; Larsen et al. 2017). Even though the grid eliminates practically all medium and large sizes of fish that do not fit between the bar spacings, it fails to sort out most of the undersized shrimp (minimum legal size (MS) = 15 mm carapace length) and fish of the smallest length classes. Many undersized shrimp and small fish pass through the grid's 19 mm bar spacings together with the shrimp and then enter the diamond mesh codend. Large proportions of these individuals remain retained due to the small codend mesh size and the narrow opening angle that diamond mesh netting often exhibits in the codend (Grimaldo and Larsen 2005; Krag et al. 2014). As a result, the selectivity of these types of dual selection systems exhibits a bell-shaped curve (Larsen et al. 2019), whereby very small and large fish have a low retention probability, and fish of intermediate size exhibit a higher retention probability for a certain size range. In the Barents Sea, a fishing area is closed if the bycatch per 10 kg of shrimp is observed to exceed a certain number (Norwegian Directorate of Fisheries 2018). Additionally, in the fishing zone surrounding Svalbard, the catch cannot contain more than 10% by weight of deep-water shrimp below the MS (Norwegian Directorate of Fisheries 2018; Larsen et al, 2018b). When a fishing area is closed, this often adds to fuel costs and loss of revenue for the fishermen as they must move to different fishing areas. Excessive retention of non-regulated bycatch species such as American plaice (*Hippoglossoides platessoides*) and polar cod (*Boreogadus saida*), which can occur in large numbers, can greatly reduce the sorting efficiency of the catch onboard.

Previous studies have shown that to obtain an effective mesh size selection in the codend, sections of netting with a high degree of mesh openness are necessary (Herrmann 2005a; Sala et al. 2008; Sala and Lucchetti 2011). This can affect species that have more reduced swimming abilities, such as shrimp and juvenile fish, which will likely struggle if available escape openings are limited. For Norway lobster (*Nephrops norvegicus*), uniformity in mesh geometry is important, as selection in the trawl takes place along the entire length of the codend (Frandsen et al. 2010). Thus, we hypothesized that applying measures to increase mesh openness in the entire codend, would improve the size selection of shrimp below the MS and juvenile fish in the Barents Sea shrimp trawl fishery.

While fishing, the drag forces acting on the codend are transmitted along the mesh bars and the meshes become stretched longitudinally as a result. Therefore, the meshes become more closed, possessing a reduced opening angle and consequently a more limited size selectivity (Herrmann et al. 2007). In recent years, numerous attempts to address these problems have been carried out. For instance, by adjusting the codend configuration or the orientation of the meshes by turning them 90° with respect to the direction of towing (T90) (Einarsson et al. 2020). The results of these experiments however showed unfavourable losses for the target sizes of shrimp. In the Barents Sea, 4-panel grid sections and codends have been tested in different fisheries, and the results have shown that the gears that were constructed with four panels maintained a more stable shape while fishing (Grimaldo et al. 2015; Sistiaga et al. 2016; Larsen et al, 2018b). It is likely that due to the forces in the codend that are distributed over four selvedges instead of two, the netting in the former is less exposed to longitudinal forces that contribute to mesh closure. Thus, a codend built using four panels could have larger areas with greater mesh openness and therefore better size selective properties than 2-panel codends, which are still most widespread among the fleet. Another codend modification that can reduce the stretch in the codend meshes and consequently increase mesh openness while fishing is to shorten the lastridge ropes. When shortening the lastridge ropes, the load created by the catch is carried by the lastridge ropes and not along the mesh bars, avoiding the closure of the meshes in the codend (Isaksen and Valdemarsen 1990; Ingólfsson and Brinkhof 2020). Several studies have also shown that a higher opening angle of the diamond meshes can also be achieved by reducing the number of meshes in the circumference of the net (Sala and Lucchetti 2011; Sala et al. 2016; Herrmann et al. 2007). This is due to simple geometrical factors whereby the meshes become more stretched in the transversal direction while fishing when the mesh circumference number is reduced.

The present study was designed to investigate the performance of three codend modifications with respect to deep-water shrimp catch and bycatch of juvenile fish in the deep-water shrimp fishery. Using a 4-panel codend construction as the baseline, we tested a 2-panel codend, a 4-panel codend with shortened lastridges, and a 4-panel codend with shortened lastridges as well as reduced circumference. Specifically, our experiment was designed to answer the following research questions:

- How does the 2-panel diamond mesh codend construction used by the fleet perform compared to a 4-panel diamond mesh codend regarding shrimp catches and bycatch of juvenile fish?
- Can shortening the lastridge ropes by 20% reduce the bycatch of juvenile fish in a 4-panel diamond mesh construction?

- Does reducing the number of meshes in the codend circumference additionally contribute to reducing the bycatch of juveniles in a 4-panel diamond mesh codend with shortened lastridges?

2. Materials and methods

2.1. The fishing area, vessel and trawls

The sea trials were conducted in the deep-water shrimp fishing grounds of "Isfjorden" (Spitsbergen, Norway) between 78°12 N-78°27 N and 14°45 E-16°18 E and at depths that varied between 138 and 269 m (Table 1). The commercial shrimp trawler M/tr "Arctic Viking" was used (58 m overall length, 4600 HP and 1720 gross tonnage) in the period between the 24th and the 29th of October 2019. The trawler was rigged with a double trawl configuration using two identical Vonin four panel shrimp trawls with a 108 m fishing circle (2700 meshes in circumference, calculated in 40 mm mesh size). The trawl was 60 m long from the centre of the fishing line to the posterior part of the trawl belly, ending with 502 meshes in circumference. The bottom panels and most of the trawl belly were constructed with 50 mm meshes. The side panels had 40 and 50 mm meshes. The top panels had 100 mm meshes in the 6 m long roof section, and otherwise 50 mm meshes. The trawls had a 68 m long fishing line, a 61 m long headline and a 58 m long rock hopper ground gear which was composed of approximately 53 cm rubber discs. Sea hunter trawl doors (Sp/f Rock Trawl-doors, FO-900 Vágur, Faroe Islands), each weighing 6 tonnes with a size of 13.2 m^2, and a central roller clump (weighing approximately 7 tonnes) were used. These were attached to the trawl by 30 m long sweeps. Sorting grids were mounted between the trawl belly and the extension piece (10 m length of 50 mm mesh size) in front of the codend in each of the trawls. The grids used followed the requirements set by the Norwegian authorities (Norwegian Directorate of Fisheries 2020), with outer dimensions of 170 x 240 cm and with rectangular bars (1 cm wide and 2 cm deep) and 19 mm bar spacings. The frame of the grid was made of nylon while the bars were a combination of plastic and fiberglass. The four different codend designs used were constructed with a combination of twisted nylon (PA) (2xNo. 20 (~1.6 mm)) and braided polyethylene (PE) (1x1.8 mm) twine. The codends were about 17 m long (2-panel codend: 17.1 m, 4-panel codend: 17.5 m) not accounting for shortening of lastridge ropes as was done in the second and third experiments, with the foremost part of tapered cut. The mesh sizes of the codends were measured using an OMEGA mesh measuring gauge while the nets were wet (Fonteyne 2005).

The sea trials were carried out using the following four codend designs: a) a 2-panel diamond mesh codend (mean ± SD mesh size, 35.0 ± 0.82 mm), with 250 meshes in circumference b) a 4-panel diamond mesh codend (mean ± SD mesh size, 33.6 ± 1.1 mm) with 250 meshes in circumference (top and bottom panels 75 meshes in width, side panels 50 meshes, Fig. 1), which was used as the baseline; c) a 4-panel codend identical to the baseline (mean ± SD mesh size, 33.3 ±1.2 mm) but with lastridge ropes shortened by 20% (Fig. 1); d) a 4-panel codend identical in design to codend (c) but with a reduced codend circumference from 250 to 200 meshes (all panels 50 meshes in width), keeping the 20% lastridge shortening (Fig. 1).

2.2. *Experimental design and data collection*

Catch data were collected using a double trawl configuration for three series of experiments:

- Series 1 compared the effect on shrimp and bycatch retention between the 4-panel codend (baseline) (b) and the 2-panel codend (test) (a).
- Series 2 tested the effect of the 4-panel codend with 20% shortened lastridge ropes (test) (c) against the 4-panel codend (baseline) (b).
- Series 3 tested the combined effect of a 4-panel codend with a 20% reduction of the codend circumference combined with 20% shortened lastridge ropes (test) (d) against the 4-panel codend (baseline) (b).

Fig. 1. Schematic view of the sorting grid and the experimental codend designs.

The trawls were switched between the port and the starboard side of the vessel halfway through each series to account for variation that may have occurred as a result of this variable. Once each trawl was hauled on deck, the catch of each codend was emptied separately so that no mixing could occur between the two. The bycatch species': American plaice, and polar cod, were then sorted from the shrimp catch for each codend. The total weight for each species was taken and measurements of all bycatch individuals were made to the nearest half centimetre below (e.g., 10.0-10.49=10.0 cm, 10.50-10.99=10.5 cm). Randomly selected subsamples were taken for bycatch species when time constraints or conditions at sea did not allow for the total catch to be measured. A randomly selected subsample of approximately 1.5-2 kg was taken for length measuring from the total shrimp catch in each successful haul. The carapace length of each shrimp in the subsample was measured using calipers, measuring to the nearest half millimetre below (e.g., 20.00-20.49=20.00 mm, 20.50-20.99=20.50 mm).

2.3. *Catch comparison and catch ratio analysis*

Using the catch data from the sea trials, we conducted length-dependent catch comparison and catch ratio analyses (Herrmann et al. 2017; Sistiaga et al. 2015). The purpose of the analysis is to obtain a practical estimate for the relative change in size dependent capture efficiency from the baseline gear to each of the treatment gears for each of the species investigated. The analysis was carried out independently for each species following the description below.

To assess the relative length-dependent catch comparison rate (CC_l) of changing from the baseline to the test gear, we used Eq. 1:

$$CC_l = \frac{\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}+\frac{nt_{lj}}{qt_j}\right\}} \qquad (1)$$

where nb_{lj} and nt_{lj} are the number n of individuals of the species investigated caught per length class l for the baseline (b) and test (t) gear, respectively, in pair j of the fishing hauls with the specific baseline and test gear. Terms qb_j and qt_j are the subsampling ratios to account for that not all of the catch was length measured in the test or baseline codend in paired haul j. In Eq. 1, h is the number of paired hauls.

The experimental CC_l in (1) was modeled by the function $CC(l,\mathbf{v})$:

$$CC(l,\boldsymbol{v}) = \frac{\exp([f(l,v_0,\ldots,v_k)])}{1+\exp([f(l,v_0,\ldots,v_k)])} \qquad (2)$$

In Eq. 2, *f* is a polynomial of order *k* with coefficients v_0-v_k. The values of the parameters $\boldsymbol{v}$ describing $CC(l,\boldsymbol{v})$ are estimated by minimizing the following expression:

$$-\sum_{j=1}^{h}\sum_{l}\left\{\frac{nt_{lj}}{qt_j}\times\ln([CC(l,\boldsymbol{v})])+\frac{nb_{lj}}{qb_j}\times\ln([1.0-CC(l,\boldsymbol{v})])\right\} \qquad (3)$$

Minimizing expression (3) is equivalent to maximizing the likelihood for the observed data based on a maximum likelihood formulation for binominal data. Expression (3) is similar in structure to the SELECT model (Millar, 1992) for data pooled over hauls which is often applied in the analysis of fishing gear size selectivity (Wileman et al., 1996). The estimation is assuming the raised catches are binomially distributed and ignores between-haul variation in the estimation. When the catch efficiency of the two trawls is equal, the catch comparison rate becomes 0.5. A catch comparison rate below 0.5 implies that there are fewer shrimp or fish of length class *l* caught in the test gear compared to the baseline gear, and vice versa for a catch comparison rate above 0.5.

Based on experience from prior studies (Krag et al. 2015; Santos et al. 2016), we considered *f* of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Considering lower order models as well by leaving out one or more of the parameters $v_0 \ldots v_4$, at a time resulted in four additional candidate models (intercept only model, a linear model, a quadratic and a cubic) for the catch comparison function $CC(l,\boldsymbol{v})$. Among these models, the catch comparison rate was estimated using multi-model inference to obtain a combined model (Burnham and Anderson 2002; Herrmann et al. 2017). Specifically, these models are averaged using Akaike weights as described by Herrmann et al. (2017). The obtained weights are ad-hoc because subsampling and between-haul variation are ignored in the estimation based on minimizing expression (3).

To provide a direct relative value of the catch efficiency between fishing the test and the baseline gear we used catch ratio $CR(l,\boldsymbol{v})$, which relates to $CC(l,\boldsymbol{v})$ by the following equation:

$$CR(l,v) = \frac{CC(l,v)}{([1-CC(l,v)])} \qquad (4)$$

Thus, if the catch efficiency of both gears is equal, $CR(l,\boldsymbol{v})$ will be 1.0.

We used a double bootstrapping method to estimate the 95% confidence intervals (CI) for *CC(l,***v***)* and *CR(l,***v***)*. Specifically, the procedure applied here accounts for uncertainty due to between tow variation by selecting *h* paired tows with replacement from the *h* paired tows available during each bootstrap repetition. Within each resampled tow, the data for each length class was resampled in an inner bootstrap to account for the uncertainty in the tow due to a finite number of shrimp or fish being caught and length measured in the paired tow. The inner resampling of the data in each length class was performed prior to the raising of the data with subsampling factors qb_j and qt_j to account for the additional uncertainty due to the subsampling (Eigaard et al. 2012). The resulting data set obtained from each bootstrap repetition was analyzed as described above and therefore also accounted for uncertainty in model selection because the multimodel inference was included (Grimaldo et al. 2018). Based on the bootstrap results, we estimated the Efron percentile 95% CIs (Efron 1982) for both the catch comparison and catch ratio curve. We performed 1000 bootstrap repetitions. The catch comparison and catch ratio analysis was conducted with the analysis tool SELNET (Herrmann et al. 2012).

2.4. *Inference of the difference in catch ratio curves between different test codends*

To infer the effect of changing from one codend (*Y)* to another (*Z*) on the catch ratio curve $CR_{codend}(l,v_{codend})$, where both catch ratio curves are obtained against the same baseline design, the length-dependent change $CR_{Z/Y}(l)$ in the values was estimated by:

$$CR_{Z/Y}(l) = \frac{CR_Z(l)}{CR_Y(l)} \qquad (5)$$

where $CR_Y(l)$ represents the value for $CR_{codend}(l,v_{codend})$for codend design *Y*, and $CR_Z(l)$ represents the value for codend design *Z*. Efron 95% percentile confidence limits for $CR_{Z/Y}(l)$ were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) for both $CR_Y(l)$ and $CR_Z(l)$. As they were obtained independently, a new bootstrap population of results was created for $CR_{Z/Y}(l)$ by:

$$CR_{Z/Y}(l)_i = \frac{CR_Z(l)_i}{CR_Y(l)_i} i \in [1 \ldots 1000] \qquad (6),$$

where *i* denotes the bootstrap repetition index. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on (6) using the two independently generated bootstrap files (Herrmann et al. 2018). Based on the bootstrap population, Efron 95% percentile confidence limits were obtained for $CR_{Z/Y}(l)$.

2.5. *Estimating the size-integrated catch ratio*

Size-integrated average values for the catch ratio ($CR_{average}$) were estimated directly from the experimental catch data using the following equations:

$$
\begin{aligned}
CR_{average-} &= \frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\right\}} \\
CR_{average+} &= \frac{\sum_{l\geq MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l\geq MLS}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\right\}}
\end{aligned}
\qquad (7)
$$

where the outer summations include the size classes in the catch during the experimental fishing period that were under (for $CR_{average-}$) and over (for $CR_{average+}$) the minimum size (*MS* = 15 mm carapace length) of deep-water shrimp. For bycatch fish species $CR_{average}$was estimated summed over all sizes. In contrast to the size-dependent evaluation of the catch ratio *CR(l, v)*, $CR_{average-}$, $CR_{average+}$ and $CR_{average}$ are specific for the population structure encountered during the experimental trials. Therefore, those values are specific for the size structure in the fishery at the time the trials were carried out and cannot be extrapolated to other scenarios in which the size structure of the shrimp and bycatch fish species may be different.

2.6. *Estimating shrimp discard ratio*

The discard ratios for the shrimp were estimated directly from the experimental catch data by:

$$
\begin{aligned}
NDRatio_{Test} &= 100 \times \frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\right\}} \\
NDRatio_{Baseline} &= 100 \times \frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\right\}}{\sum_{l}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\right\}}
\end{aligned}
\qquad (8)
$$

where the outer summations include the size classes in the catch during the experimental fishing period that were under the minimum target size for deep-water shrimp (in the nominator) and overall (in the denominator). *NDRatio* quantifies the fraction of the catch (in %) in the codend that consists of shrimp below the MS, and ideally should be as low as possible. The value of *NDRatio* is affected by both the size selectivity of the gear and the size structure of the shrimp in the fishing grounds. Therefore, it provides an estimate that is specific for the population fished and it could not be extrapolated to other areas and seasons.

Equation (8) was also used to estimate the ratio between the discard ratios for the test and the baseline configurations.

Finally, besides the indicator values given based on the number of individuals as provided by Eq. (7) and Eq. (8), similar measures were estimated based on weight:

$$\begin{aligned} CRW_{average-} &= \frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\times a\times l^b\right\}}{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\times a\times l^b\right\}} \\ CRW_{average+} &= \frac{\sum_{l\geq MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\times a\times l^b\right\}}{\sum_{l\geq MLS}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\times a\times l^b\right\}} \end{aligned} \qquad (9)$$

$$\begin{aligned} WDRatio_{Test} &= 100\times\frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\times a\times l^b\right\}}{\sum_{l}\sum_{j=1}^{h}\left\{\frac{nt_{lj}}{qt_j}\times a\times l^b\right\}} \\ WDRatio_{Baseline} &= 100\times\frac{\sum_{l<MLS}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\times a\times l^b\right\}}{\sum_{l}\sum_{j=1}^{h}\left\{\frac{nb_{lj}}{qb_j}\times a\times l^b\right\}} \end{aligned} \qquad (10)$$

In (9) and (10) we have assumed a length-weight relationship following the power model (11):

$$w(l) = a\times l^b \qquad (11)$$

For the parameters *a* and *b* in (11) we use the values obtained by Wieland (2002).

Uncertainty in terms of 95% confidence intervals was estimated for $CR_{average}$, *NDRatio*, $CRW_{average}$ and *WDRatio* by incorporating the estimation of these measures in the double bootstrapping method described above.

3. Results

A total of 30 hauls were valid for statistical analyses, 11 for series 1, 10 for series 2 and 9 for series 3. The towing time for each haul ranged between 2 hours and 30 minutes and 6 hours and 45 minutes (Table 1). In total, 24 160 deep-water shrimp, 21 716 polar cod and 15 413 American plaice were length measured and included in the analysis. Further details of the catch data and the subsampling ratios can be found in Table 1.

Table 1. Catch data used for the catch comparison and catch ratio analysis. Values in parentheses are the subsample ratios of length measurement from the total catch when applicable.

The catch comparison analyses were performed on the datasets from each of the three series of experiments separately. The modelled catch comparison curves followed the main trends in the experimental data without indicating any systematic patterns in deviations for the data (fig. 2-4).

3.1. Comparison of a 2-panel codend with a 4-panel codend

The deep-water shrimp caught with the 2-panel (test) and the 4-panel (baseline) codends had similar length distributions, with carapace lengths between 8 and 25 mm. No significant differences in retention could be detected between the two configurations, both for shrimp and for the fish species (Fig. 2, Table 2). The indicators for weight calculated for shrimp also indicated no significant difference between the gears as a result of reducing the number of panels. The percentage of undersized individuals is higher than the maximum allowable limit for both the test and the baseline codends (*WDRatio*).

Fig. 2. Left column; the size frequency plots for series 1 in the test (black) and the baseline (grey). Middle column; the catch comparison rate (black solid curve) with 95% CI's (black stippled curves), the experimental rates (black circle marks). Right column; the catch ratio curve (black solid curve) with 95% CI's (black stippled curves). The horizontal line at 0.5 (grey stippled line) represents the point at which both setups have an equal catch rate. The vertical line at 15 mm in the shrimp catch comparison and catch ratio plots (*b* and *c*) (grey stippled line) indicates the MS for shrimp in this area.

Table 2. Catch ratio results (%) for all species for series 1 in the test and the baseline. The values in parentheses represent 95% CI's. * applies to all species except for shrimp which is given in mm.

3.2. The effect of shortening the lastridge ropes

The effect of shortening the lastridge ropes by 20% significantly changed the catch efficiency of the codend (Fig. 3). A significant reduction of small shrimp was observed compared to that of the 4 panel codend (Figs. 3*a*, 3*b* and 3*c*, Table 3). 39.2% of shrimp below the MS ($CR_{average\,-}$) were released from the test codend. Specifically, this difference was statistically significant between the test and the baseline between the lengths of 5 and 15 mm. No shrimp above the MS were released from the test setup compared to the baseline ($CR_{average\,+}$) (Table 3). By number, the *NDRatios* indicated for the test and the baseline that there was a significant difference between the two setups (Table 3). By weight, the proportions that were undersized also differed significantly between the test and the baseline for shrimp (*WDRatio*) (Table 3). By weight, the reduction of undersized shrimp was also significantly different, whereby 39.4% of undersized shrimp were released in the test, compared to the baseline codend ($CRW_{average}$-).

Fig. 3. Left column; the size frequency plots for series 2 in the test (black) and the baseline (grey). Middle column; the catch comparison rate (black solid curve) with 95% CI's (black stippled curves), the experimental rates (black circle marks). Right column; the catch ratio curve (black solid curve) with 95% CI's (black stippled curves). The horizontal line at 0.5 (grey stippled line) represents the point at which both setups have an equal catch rate. The vertical line at 15 mm in the shrimp catch comparison and catch ratio plots (*b* and *c*) (grey stippled line) indicates the MS for shrimp.

Table 3. Catch ratio results (%) for all species for series 2 in the test and the baseline. The values in parentheses represent 95% CI’s. * applies to all species except for shrimp which is given in mm.

For polar cod, the results showed a significant length dependent reduction for the smallest individuals up to those that are 13 cm in length in the test compared to the baseline. Fig. 3*f* indicated a reduction of at least 63% for polar cod of 5 cm length (CR: 12.77% CI: 3.7-36.6) (Table 3) and a reduction over all length classes on average of 34.1% (Table 3). A significant effect was observed for a small range of American plaice (Figs. 3*g*, 3*h* and 3*i*) (reducing approximately 5% of the American plaice between 3 and 7 cm). Individuals from these length classes however were caught at very low frequencies, therefore, the impact on the total catch for this species was minor.

3.3. Combined effect of reducing the number of meshes of circumference and shortening the lastridge ropes

Compared to the conventional codend these codend modifications significantly reduced the bycatch of shrimp smaller than 12 mm carapace length without altering the catch of larger and commercially important length classes (Figs. 4*a*, 4*b* and 4*c*). However, when averaged over all lengths, the reduction of shrimp was not significant between the test and the baseline codends both in terms of $CR_{average+}$ *and* $CR_{average-}$ (Table 4). Furthermore, in terms of numbers (*NDRatio*) and weight (*WDratio,* $CRW_{average}$), no significant reduction of shrimp below the MS was demonstrated (Table 4). However, there was a significant effect on the reduction of polar cod (<10 cm) and American plaice (<6 cm). For the smallest polar cod, the modified codend in this series released 80% more compared to the regular 4-panel codend (Figs. 4*d*, 4*e* and 4*f*) which had almost 10% additional escape when averaged over all length classes. For the smallest American plaice an additional 60% was released from the modified 4-panel codend and on average more than 11% additional American plaice were released (Figs. 4*g*, 4*h* and 4*i*, Table 4).

Table 4. Catch ratio results (%) for all species for series 3 in the test and the baseline. The values in parentheses represent 95% CI's. * applies to all species except for shrimp which is given in mm.

Fig. 4. Left column; size frequency plots for series 3 in the test (black) and the baseline (grey). Middle column; the catch comparison rate (black solid curve) with 95% CI's (black stippled curves), the experimental rates (black circle marks). Right column; the catch ratio curve (black solid curve) with 95% CI's (black stippled curves). The horizontal line at 0.5 (grey stippled line) represents the point at which both codends have an equal catch rate. The vertical line at 15 mm in the shrimp catch comparison and catch ratio plots (*b* and *c*) (grey stippled line) indicates the MS for shrimp.

3.5 The added effect of reducing the number of meshes of circumference

An added effect of reducing the codend mesh circumference compared to shortening the lastridge ropes was only present for polar cod for a small length interval of individuals (Fig. 5). The remaining species analysed did not exhibit differences in retention between the configurations tested.

Fig 5: The catch ratio analysis estimating the effect of reducing the number of meshes of circumference alone. The horizontal grey stippled line at 1.0 represents the point at which both codends have an equal catch rate. The black stippled curves represent the 95% CI's for the estimated catch ratio curve (black solid curve). For shrimp, the vertical grey stippled line at 15 mm indicates the MS.

3.3. **Discussion**

This study sought to alleviate the consequences that arise in deep-water shrimp fisheries as a result of insufficient codend mesh openings (Cheng et al. 2020). In order to increase codend mesh openness and thus enabling an increase in escape of deep-water shrimp below the MS and juvenile fish, two approaches were taken. First, the lastridge ropes were added, 20% shorter than the codend netting, and later, the circumference of the codend was reduced from 250 to 200 meshes. Finally, a 2-panel codend, which is the codend construction normally applied in the fleet, was compared to the 4-panel baseline codend used in the trials. Our results show that the number of panels used to configure the codend does not affect size selectivity for any of the species caught in this study. The short lastridge ropes significantly reduced catches of shrimp below the MS and reduced catches of polar cod and juvenile American Plaice. Reducing the codend mesh circumference did not yield a significant reduction in retention for any of the aforementioned species.

By changing the number of panels from four to two, no effect on size selection was detected (series 1) (Table 2, Fig. 2). This can be attributed to that no modifications were made to the codend which enabled a reduction in the longitudinal forces acting on the meshes, and thus, mesh openness. The drag forces were not dispersed differently, as the selvedges have the same length as the codend itself. Therefore, both designs can be expected to deform equally as a function of catch size and towing speed (Herrmann 2005ab; Priour et al. 2009).

Shortening the codend's lastridge ropes by 20% significantly reduced the capture efficiency of shrimp below the MS, while leading to no significant loss of target sizes of shrimp (Table 3, Figs. 3*a*, 3*b* and 3*c*). This is highlighted in the discard ratios in terms of weight that were obtained ($WDRatio_{Test}$). For the baseline this was significantly higher than the 10% limit which is allowed in the fisheries regulation (15.58% (13.50 – 17.11)). When the codend lastridge ropes were shortened, this value reduced so that it did not significantly exceed this limit (10.18% (8.57 – 11.97)). Therefore, this modification would enable fishermen to tolerate fishing on a wider range of population structures before crossing the legal 10% limit and needing to move to a different area. For the bycatch species, this configuration enabled a large reduction of polar cod (Table 3, Figs. 3*d*, 3*e* and 3*f*) and a small reduction of American plaice (Table 3, Figs. 3*g*, 3*h* and 3*i*). These findings agree with those from previous research regarding evaluations of the efficiency of lastridge ropes to improve codend selectivity (Isaksen and Valdemarsen 1990; Lök et al. 1997; Ingólfsson and Brinkhof 2020). Ingólfsson and Brinkhof (2020) reported a 90% additional release of undersized cod when the codend was shortened by 30% in the Barents Sea trawl fishery. In fish trawls, Isaksen and Valdemarsen (1990) and Lök et al. (1997) both presented increases in the selection factor when the codends were shortened by approximately 15%. Isaksen and Valdemarsen (1990) highlighted the improved ability for the shortened codend to maintain its shape while fishing compared to the regular codend. This can mean improved mesh openness. Furthermore, the slack that the shortened lastridges add to the netting of the codend and the resulting undulation may stimulate more of the bycatch to attempt to escape. Shortening lastridge ropes is a strategy that has a low associated cost and is relatively easy to implement and handle in a commercial trawl. We thereby present this gear modification as a means to reduce the retention of excessive amounts of juvenile shrimp and bycatch in deep-water shrimp fisheries.

Reducing the codend mesh circumference while simultaneously shortening the lastridge ropes did not lead to significant changes in selectivity compared to shortening the lastridge ropes alone (Fig. 3, 4). Minor differences were observed for the smallest sizes of bycatch species (Fig. 3, 4) however the number of individuals caught at these lengths was limited and therefore drawing exact conclusions for these is difficult. For shrimp, the discard ratio by weight of undersized individuals ($WDRatio_{Test}$) using this configuration was lower compared to the codend used in the fishery today, however it was still significantly higher than the 10% legal catch limit. To discern the effect of mesh circumference more in detail, the added effect of reducing the mesh circumference on selectivity was investigated, compared to when the lastridge ropes alone were shortened (section 3.5) (Fig. 5). This confirmed that reducing the mesh circumference had no significant additional impact on retention for the species analysed except for a small length class of Polar cod. Therefore, our investigation shows that combining these two modifications does not lead to improved selectivity, and from a management perspective, shortening the lastridge ropes alone provides the highest reduction for undersized shrimp. Reducing the retention of undersized catch by reducing the mesh circumference has been achieved in previous studies (Broadhurst and Millar 2009; Sala and Lucchetti 2011; Sala et al. 2016). For a conventional codend, excessive circumference meshes are likely to result in increased retention of smaller specimens, as the meshes tend to close more laterally (Lowry and Robertson 1996; Lök et al. 1997). Moderate changes (20% reduction in our case) may have had marginal effects, that can be difficult to detect due to both within- and between-haul variation in the data. In addition, the selectivity, may not be linearly related to the circumference, i.e., it is possible that differences in selectivity due to codend circumference begin to cease when a “modest” level is achieved. Measures to increase mesh openings may have dominating effects, such that circumference may play a minor role. For example, when a reduced mesh circumference was compared to the effect of changing mesh orientation in the Baltic Sea cod fishery it was found that mesh orientation contributed 47% less to total retention compared to changing the mesh circumference (Herrmann et al. 2007). However, due to that there is likely to be an interaction factor influencing the results from series 3, the effect contributed by reduced mesh circumference alone could not be inferred. Under these circumstances only the added effect of reduced mesh circumference could be extracted. Research by Lök et al. (1997) found the added effect of reducing the mesh circumference inferior to that from shortening the total codend length, as is observed in the present study. However, field data for the effect of mesh circumference was only available in the present study when tested simultaneously with shortened lastridge ropes. More studies are required where the individual effect of the codend mesh circumference can be observed. Other adjustments that function to support codend meshes with a wider lateral opening such as increased tapering should also be explored in comparison to lastridge shortening in order to establish optimal selectivity in this fishery.

Optimizing the mesh characteristics to the fishery in question can have high utility in addressing concerns reported by the industry regarding drag forces and associated fuel costs as well as issues of high bycatch (Sterling and Eayrs 2010). Broadhurst et al. (2014) highlighted the importance for reducing the twine area in the posterior section of a shrimp trawl by for example improving the lateral opening of the meshes. As the twine typically makes up >70% (Broadhurst et al. 2014) of the total area of a shrimp trawl, optimizing mesh openness can lead to significant reductions in operational costs by reducing the drag as well as improving the catch composition.

Attempting to mitigate the high proportion of juvenile bycatch that is retained when fishing for deep-water shrimp is an important step in ensuring future sustainability of the fishery. The present study demonstrates that shortening the lastridge ropes of the standard gear used in the fishery today can benefit fishermen as well as the ecosystem where the fishing takes place by reducing the retention of juveniles in the catch. Further, lastridge shortening and the mesh circumference have complex interactions and can have favourable species and size selectivity compared to the number of panels used in demersal shrimp trawls. The parameters that are explored in the present study are fundamental in the construction of this gear and should not be overlooked when addressing codend design.

Acknowledgments

We would like to thank the crew of M/Tr “Arctic Viking” for their assistance and support during the cruise. This study was financed by the Norwegian Directorate of Fisheries and the Norwegian Seafood Research Fund (FHF) (Grant number 901303).

Competing Interests:

The authors declare there are no competing interests.

References

Broadhurst, M.K. and Kennelly, S.J. 1995. A trouser-trawl experiment to assess codends that exclude juvenile mulloway (*Argyrosomus hololepidotus*) in the Hawkesbury River prawn-trawl fishery. Mar. Freshw. Res 46: 953-958.

Broadhurst, M.K. and Millar, R.B. 2009. Square-mesh codend circumference and selectivity. ICES J. Mar. Sci. 66: 566-572.

Broadhurst, M.K., Sterling, D.J., and Millar, R.B. 2014. Configuring the mesh size, side taper and wing depth of penaeid trawls to reduce environmental impacts. PLoS ONE 9(6): e99434.

Burnham, K.P., and Anderson, D.R. 2002. A practical information-theoretic approach. Model selection and multimodel inference. 2nd ed. Springer, New York. 2.

Cheng, Z., Winger, P.D., Bayse, S.M., Kebede, G.E., DeLouche, H., Einarsson, H.A., Pol, M.V., Kelly, D., and Walsh, S.J. 2020. Out with the old and in with the new: T90 codends improve size selectivity in the Canadian redfish (*Sebastes mentella*) trawl fishery. Can. J. Fish. Aquat. Sci. 77(10): 1711-1720.

Eayrs, S. 2007. A guide to bycatch reduction in tropical shrimp-trawl fisheries. Revised ed. Food and Agriculture Organization of the United Nations, Rome. ISBN: 978-92-5-105674-5

Efron, B. 1982. The jackknife, the bootstrap and other resampling plans. SIAM Monograph No. 38, CBSM-NSF.

Eigaard, O.R., Herrmann, B. and Nielsen, J.R. 2012. Influence of grid orientation and time of day on grid sorting in a small-meshed trawl fishery for Norway pout (*Trisopterus esmarkii*). Aquat. Liv. Res. 25(1):15-26.

Einarsson, H.A., Cheng, Z., Bayse, S.M., Herrmann, B., and Winger, P.D. 2020. Comparing the size selectivity of a novel T90 mesh codend to two conventional codends in the northern shrimp (*Pandalus borealis*) trawl fishery. Aquacult. Fish.

Fonteyne, R. 2005. Protocol for the use of an objective mesh gauge for scientific purposes (No. 279). ICES Cooperative Research Report. No. 279.

Frandsen, R.P., Herrmann, B., and Madsen, N. 2010. A simulation-based attempt to quantify the morphological component of size selection of *Nephrops norvegicus* in trawl codends. Fish. Res. 101: 156-167.

Grimaldo, E., and Larsen, R.B. 2005. The cosmos grid: A new design for reducing by-catch in the Nordic shrimp fishery. Fish. Res. 76: 187-197.

Grimaldo, E., Sistiaga, M., Herrmann, B., Gjøsund, S. H., & Jørgensen, T. 2015. Effect of the lifting panel on selectivity of a compulsory grid section (Sort-V) used by the demersal trawler fleet in the Barents Sea cod fishery. Fish. Res. 170: 158-165.

Grimaldo, E., Herrmann, B., Vollstad, J., Su, B., Moe Føre, H., Larsen, R. B., & Tatone, I. 2018. Fishing efficiency of biodegradable PBSAT gillnets and conventional nylon gillnets used in Norwegian cod (*Gadus morhua*) and saithe (*Pollachius virens*) fisheries. ICES J. Mar Sci. 75: 2245-2256.

Hannah, R.W., and Jones, S.A. 2007. Effectiveness of bycatch reduction devices (BRDs) in the ocean shrimp (*Pandalus jordani*) trawl fishery. Fish. Res. 85: 217-225.

Herrmann, B. 2005a. Effect of catch size and shape on the selectivity of diamond mesh cod-ends: I. Model development. Fish. Res. 71: 1-13.

Herrmann, B. 2005b. Effect of catch size and shape on the selectivity of diamond mesh cod-ends: II. Theoretical study of haddock selection. Fish. Res. 71: 15-26.

Herrmann, B., Priour, D., and Krag, L.A. 2007. Simulation-based study of the combined effect on cod-end size selection of turned meshes by 90° and reducing the number of meshes in the circumference for round fish. Fish. Res. 84: 222-232.

Herrmann, B., Sistiaga, M.B., Nielsen, K.N., and Larsen, R.B. 2012. Understanding the size selectivity of redfish (*Sebastes* spp.) in North Atlantic trawl codends. J. North Atl. Fish. Sci. 44: 113.

Herrmann, B., Sistiaga, M., Rindahl, L., and Tatone, I. 2017. Estimation of the effect of gear design changes on catch efficiency: methodology and a case study for a Spanish longline fishery targeting hake (*Merluccius merluccius*). Fish. Res. 185: 153-160.

Herrmann, B., Krag, L.A., and Krafft, B.A. 2018. Size selection of Antarctic krill (*Euphausia superba*) in a commercial codend and trawl body. Fish. Res. 207: 49-54.

ICES. 2018. Northern shrimp (*Pandalus borealis*) in subareas 1 and 2 (Northeast Arctic). DOI: 10.17895/ices.pub.4593

Isaksen, B., and Valdemarsen, J.W. 1990. Codend with short lastridge ropes to improve size selectivity in fish trawls. ICES, CM. 46: 8.

Isaksen, B., Valdemarsen, J.W., Larsen, R.B., and Karlsen, L. 1992. Reduction of fish by-catch in shrimp trawl using a rigid separator grid in the aft belly. Fish Res. 13: 335-352.

Ingólfsson, Ó.A., and Brinkhof, J. 2020. Relative size selectivity of a four-panel codend with short lastridge ropes compared to a flexigrid with a regular codend in the Barents Sea gadoid trawl fishery. Fish. Res. 232: 105724.

Ingólfsson, Ó.A., and Jørgensen, T. 2020. Shorter trawls improve size selection of northern shrimp. Can. J. Fish. Aquat. Sci. 77(1): 202-211.

Krag, L.A., Herrmann, B., Iversen, S.A., Engås, A., Nordrum, S., and Krafft, B.A. 2014. Size selection of Antarctic krill (*Euphausia superba*) in trawls. PloS ONE. 9(8): e102168.

Krag, L.A., Herrmann, B., Karlsen, J.D., and Mieske. B. 2015. Species selectivity in different sized topless trawl designs - does size matter?. Fish Res. 172: 243-249.

Larsen, R.B., Herrmann, B., Sistiaga, M., Brinkhof, J., Tatone, I., and Langård, L. 2017. Performance of the Nordmøre grid in shrimp trawling and potential effects of guiding funnel length and light stimulation. Mar. Coast. Fish. 9(1): 479-492.

Larsen, R.B., Herrmann, B., Sistiaga, M., Brinkhof, J., and Grimaldo, E. 2018a. Bycatch reduction in the Norwegian Deep-water Shrimp (*Pandalus borealis*) fishery with a double grid selection system. Fish. Res. 208: 267-273.

Larsen, R. B., Herrmann, B., Sistiaga, M., Brinkhof, J., Tatone, I., and Langård, L. 2018. New approach for modelling size selectivity in shrimp trawl fisheries. ICES J. Mar. Sci., 75(1): 351-360.

Lök, A., Tokaç, A., Tosunoğlu, Z., Metin, C., and Ferro, R.S.T. 1997. The effects of different codend design on bottom trawl selectivity in Turkish fisheries of the Aegean Sea. Fish. Res. 32: 149-156.

Lowry, N., and Robertson, J.H.B. 1996. The effect of twine thickness on codend selectivity of trawls for haddock in the North Sea. Fish. Res. 26: 353-363.

Millar, R.B., 1992. Estimating the size-selectivity of fishing gear by conditioning on the total catch. J. Am. Stat. Assoc. 87, 962–968.

Norwegian Directorate of Fisheries. 2018. Regulation on Mesh Size, Bycatch and Minimum Landing Sizes, etc. During Fishery in the Svalbard Zone (in Norwegian). Available from: https://www.fiskeridir.no/Yrkesfiske/Regelverk-og-reguleringer/Jmeldinger/Gjeldende -J-meldinger/J-23-2018.

Norwegian Directorate of Fisheries. 2020. Regulations on the design and installation of sorting grids in shrimp trawls. Available from: https://www.fiskeridir.no/Yrkesfiske/Regelverk-og-reguleringer/J-meldinger/Gjeldende-J-meldinger/J-26-2020

Priour, D., Herrmann, B., and O'Neill, F.G. 2009. Modelling axisymmetric cod-ends made of different mesh types. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment. 223(1):137-144.

Sala, A., Lucchetti, A., Piccinetti, C., and Ferretti, M. 2008. Size selection by diamond-and square-mesh codends in multi-species Mediterranean demersal trawl fisheries. Fish. Res. 93: 8-21.

Sala, A., and Lucchetti, A. 2011. Effect of mesh size and codend circumference on selectivity in the Mediterranean demersal trawl fisheries. Fish. Res. 110: 252-258.

Sala, A., Herrmann, B., De Carlo, F., Lucchetti, A., and Brčić, J. 2016. Effect of codend circumference on the size selection of square-mesh codends in trawl fisheries. PLoS ONE. 11(7): e0160354.

Santos, J., Herrmann, B., Mieske, B., Stepputtis, D., Krumme, U., and Nilsson, H. 2016. Reducing flatfish bycatch in roundfish fisheries. Fish. Res. 184: 64-73.

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R.B., and Tatone, I. 2015. Effect of lifting the sweeps on bottom trawling catch efficiency: A study based on the Northeast Arctic cod (*Gadus morhua*) trawl fishery. Fish Res. 167: 164-173.

Sistiaga, M., Brinkhof, J., Herrmann, B., Grimaldo, E., Langård, L., and Lilleng, D. 2016. Size selective performance of two flexible sorting grid designs in the Northeast Arctic cod (Gadus morhua) and haddock (*Melanogrammus aeglefinus*) fishery. Fish. Res. 183: 340-351.

Sterling, D., and Eayrs, S. 2010. Trawl-gear innovations to improve the energy efficiency of Australian prawn trawling. In 1st International Symposium on Fishing Vessel Energy Efficiency. Vigo, Spain.

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., and Millar, R.B. 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES. Coop. Res. Rep. 1-126.

Wieland, K. 2002. A new length-weight relationship for northern shrimp (*Pandalus borealis*) off West Greenland (NAFO Subareas 0+1). NAFO Scr Doc. 02/144

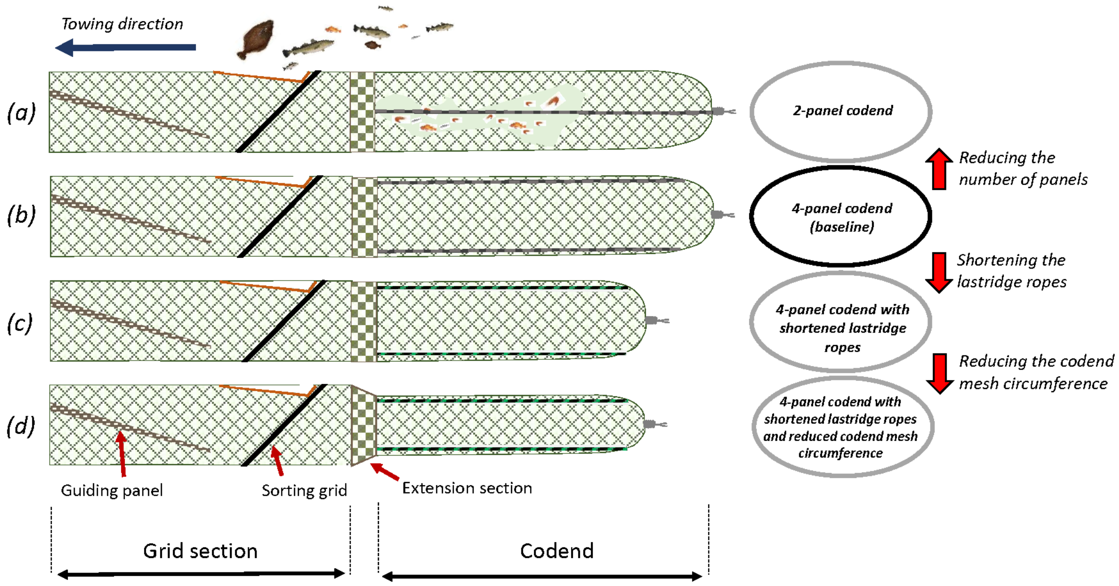

Fig. 1. Schematic view of the sorting grid and the experimental codend designs.

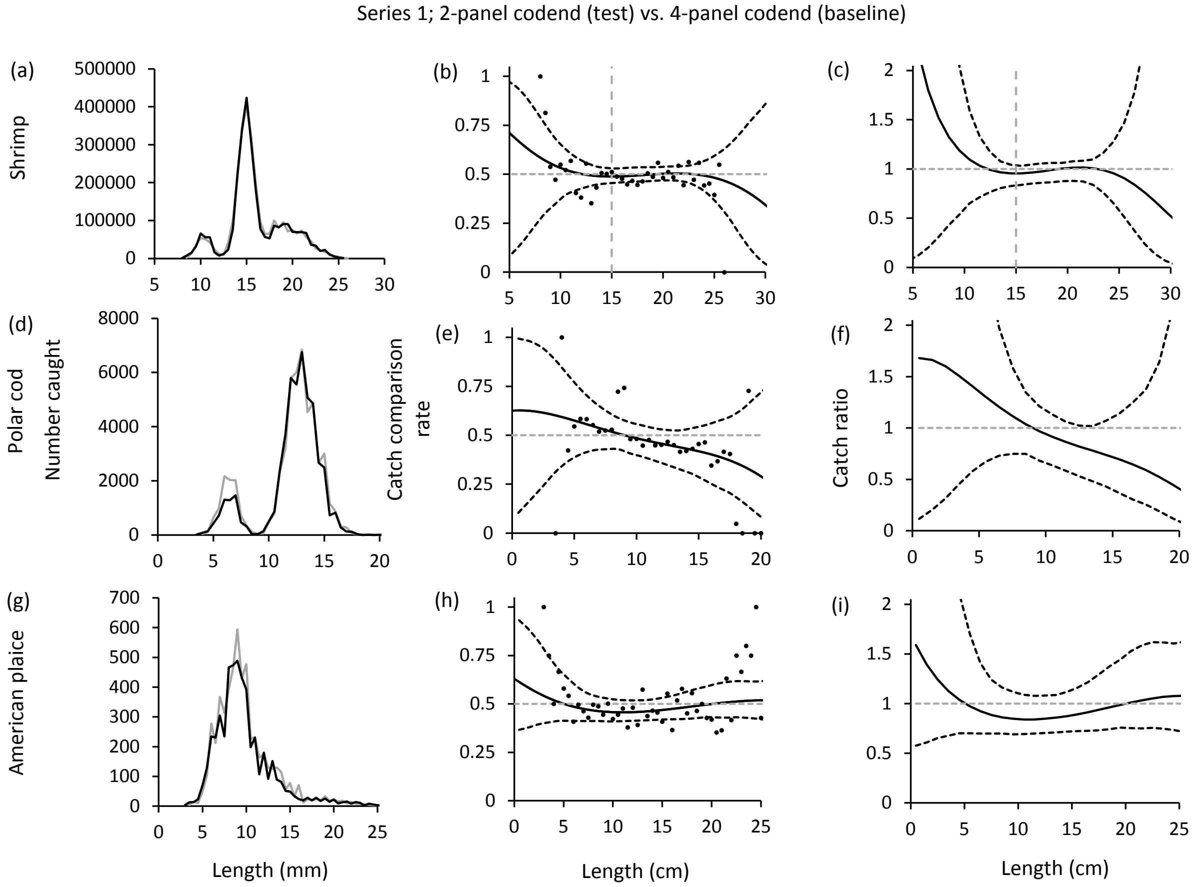

Fig. 2. Left column; the size frequency plots for series 1 in the test (black) and the baseline (grey). Middle column; the catch comparison rate (black solid curve) with 95% CI's (black stippled curves), the experimental rates (black circle marks). Right column; the catch ratio curve (black solid curve) with 95% CI's (black stippled curves). The horizontal line at 0.5 (grey stippled line) represents the point at which both setups have an equal catch rate. The vertical line at 15 mm in the shrimp catch comparison and catch ratio plots (*b* and *c*) (grey stippled line) indicates the MS for shrimp in this area.

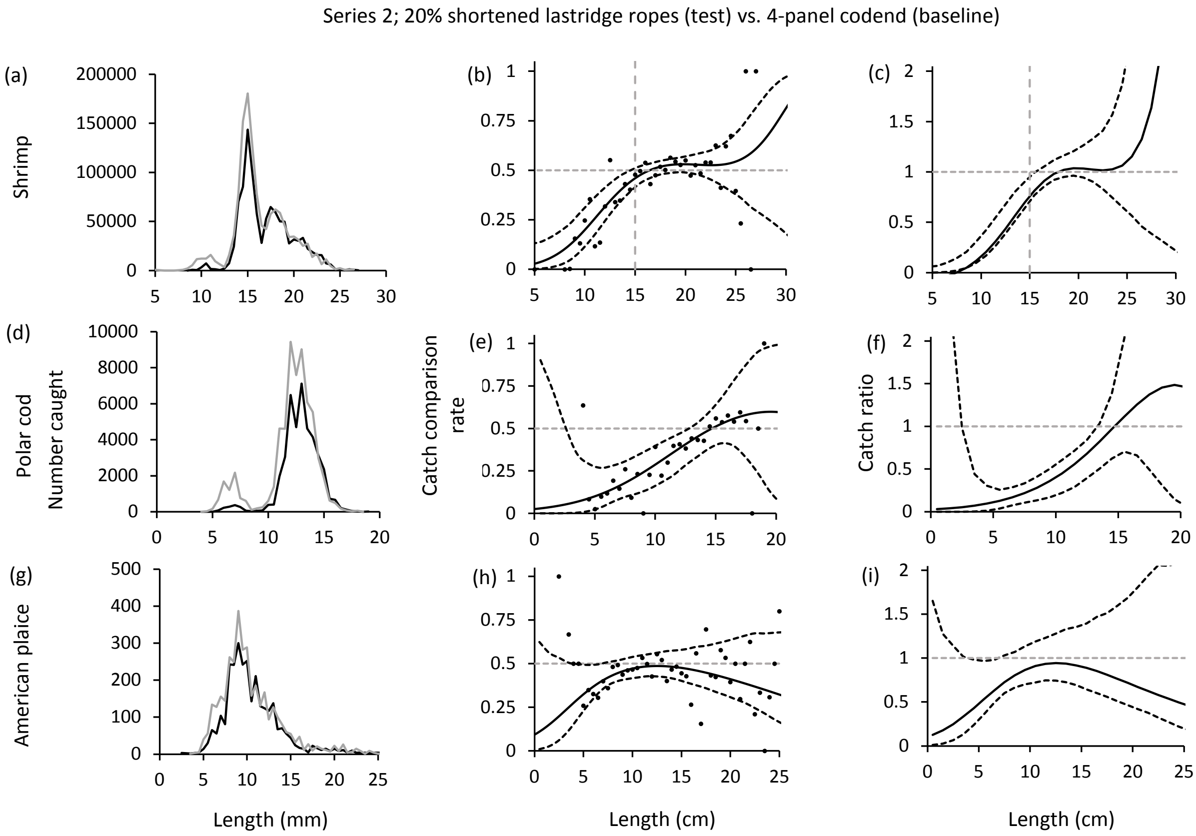

Fig. 3. Left column; the size frequency plots for series 2 in the test (black) and the baseline (grey). Middle column; the catch comparison rate (black solid curve) with 95% CI's (black stippled curves), the experimental rates (black circle marks). Right column; the catch ratio curve (black solid curve) with 95% CI's (black stippled curves). The horizontal line at 0.5 (grey stippled line) represents the point at which both setups have an equal catch rate. The vertical line at 15 mm in the shrimp catch comparison and catch ratio plots (*b* and *c*) (grey stippled line) indicates the MS for shrimp.

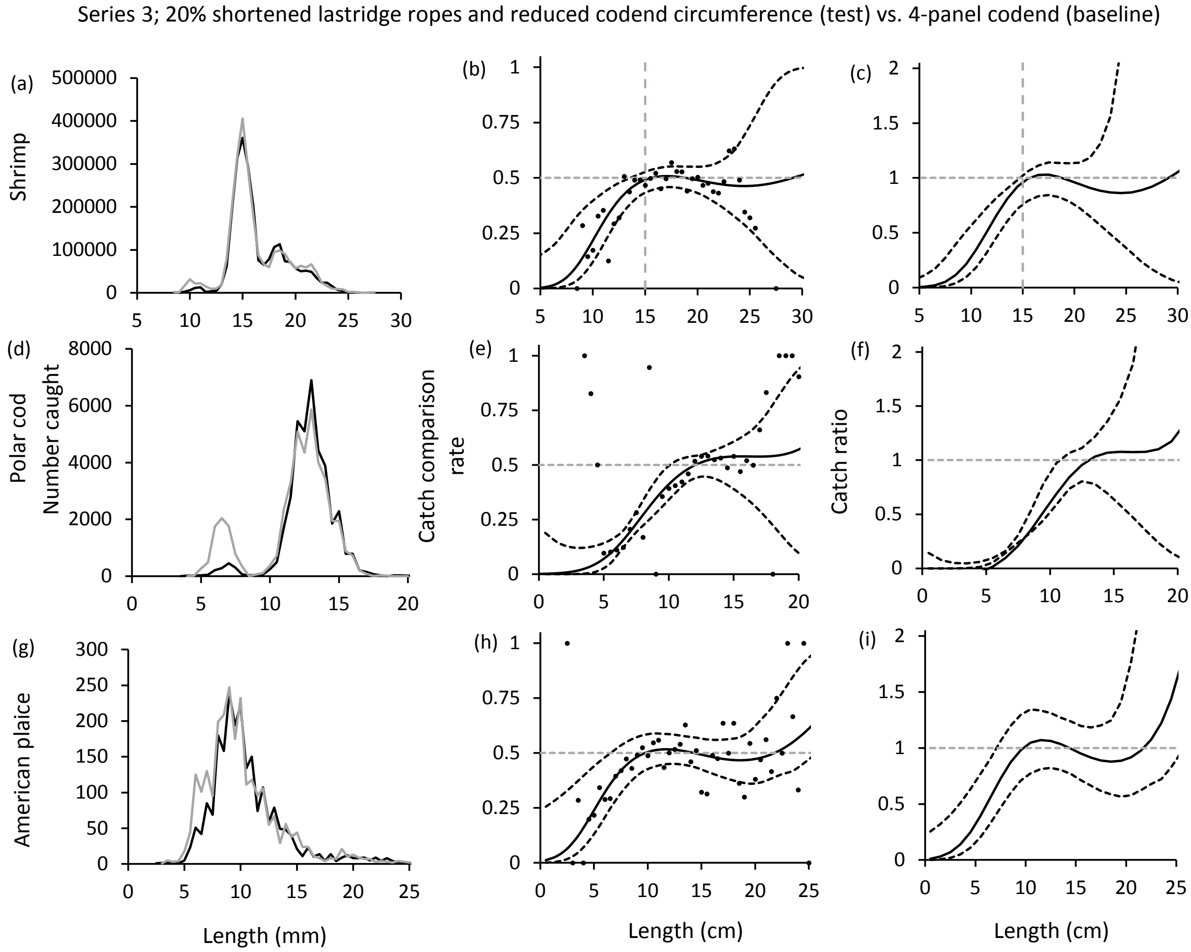
Series 3; 20% shortened lastridge ropes and reduced codend circumference (test) vs. 4-panel codend (baseline)

Fig. 4. Left column; size frequency plots for series 3 in the test (black) and the baseline (grey). Middle column; the catch comparison rate (black solid curve) with 95% CI's (black stippled curves), the experimental rates (black circle marks). Right column; the catch ratio curve (black solid curve) with 95% CI's (black stippled curves). The horizontal line at 0.5 (grey stippled line) represents the point at which both codends have an equal catch rate. The vertical line at 15 mm in the shrimp catch comparison and catch ratio plots (*b* and *c*) (grey stippled line) indicates the MS for shrimp.

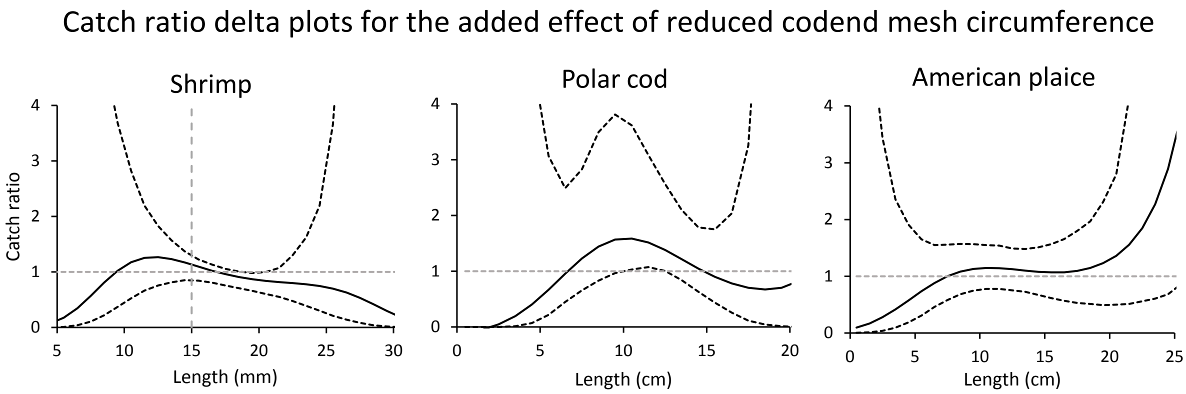
Catch ratio delta plots for the added effect of reduced codend mesh circumference

Fig 5: The catch ratio analysis estimating the effect of reducing the number of meshes of circumference alone. The horizontal grey stippled line at 1.0 represents the point at which both codends have an equal catch rate. The black stippled curves represent the 95% CI’s for the estimated catch ratio curve (black solid curve). For shrimp, the vertical grey stippled line at 15 mm indicates the MS.

					Shrimp (*n*) Length range (5.0-30.0 mm)		**Polar cod (*n*)** Length range (3.5-31.5 cm)		**American Place (*n*)** Length range (2.5-35.0 cm)	
Series	**Haul**	**Coordinates**	**Fishing time (hh:mm)**	**Depth (m)**	**Test**	**Baseline**	**Test**	**Baseline**	**Test**	**Baseline**
1	1	78,22 N 15,41 E	4:10	201	360 (0.004)	348 (0.004)	445 (0.107)	418 (0.100)	189	119 (0.864)
1	2	78,26 N 15,58 E	4:00	159	500 (0.001)	447 (0.001)	409 (0.232)	326 (0.271)	670	353 (0.368)
1	3	78,22 N 15,24 E	4:15	248	404 (0.001)	431 (0.001)	390 (0.096)	366 (0.108)	375 (0.368)	346 (0.510)
1	4	78,22 N 15, 24 E	4:10	248	440 (<0.001)	445 (<0.001)	457 (0.041)	432 (0.034)	253 (0.853)	133 (0.454)
1	5	78,21 N 15,32 E	4:12	226	377 (0.001)	370 (0.001)	341 (0.062)	332 (0.079)	242	115
1	6	78,22 N 15,40 E	4:30	194	420 (0.002)	473 (0.002)	364 (0.227)	289 (0.405)	437 (0.566)	369 (0.471)
1	7	78,26 N 15,55 E	4:48	138	436 (0.001)	404 (0.001)	323 (0.244)	387 (0.325)	309 (0.507)	375 (0.428)
1	8	78,22 N 15,45 E	3:05	184	410 (0.001)	406 (0.002)	337 (0.127)	348 (0.157)	303 (0.568)	331 (0.443)
1	9	78,22 N 14,45 E	6:45	180	368 (0.001)	465 (0.001)	338 (0.076)	416 (0.063)	398 (0.493)	520
1	10	78,20 N 15,02 E	5:47	240	411 (0.001)	441 (0.001)	460 (0.059)	357 (0.055)	124	242
1	11	78,18 N 15,03 E	5:23	253	361 (<0.001)	398 (<0.001)	403 (0.050)	383 (0.061)	174	174
2	12	78,16 N 15,14 E	5:10	256	422 (0.002)	364 (0.001)	338 (0.056)	411 (0.040)	207	91 (0.505)
2	13	78,23 N 15,36 E	5:25	208	390 (0.001)	381 (<0.001)	308 (0.030)	397 (0.025)	115 (0.404)	70 (0.315)
2	14	78,23 N 15,38 E	3:40	218	345 (0.005)	426 (0.004)	256	389	235	283
2	15	78,19 N 15,15 E	3:08	269	341 (0.008)	315 (0.006)	600 (0.176)	322 (0.148)	249	106
2	16	78,12 N 15,08 E	2:30	220	371 (0.012)	327 (0.009)	308 (0.075)	300 (0.071)	45	39
2	17	78,21 N 15,21 E	5:09	266	311 (0.001)	336 (0.001)	352 (0.027)	334 (0.025)	52 (0.539)	47 (0.299)
2	18	78,18 N 15,06 E	5:33	253	391 (0.001)	430 (0.001)	556 (0.145)	487 (0.030)	59	65 (0.228)
2	19	78,25 N 16,02 E	4:11	140	420 (0.001)	404 (0.002)	208	286	382	414
2	20	78,27 N 15,55 E	4:28	139	398 (0.002)	469 (0.001)	117	256	302	406
2	21	78,27 N 15,57 E	5:48	138	369 (0.090)	466 (0.074)	-	-	1068	888 (0.590)
3	22	78,20 N 15,16 E	4:00	250	467 (0.002)	464 (0.002)	424 (0.030)	455 (0.039)	45 (0.330)	83 (0.350)
3	23	78,22 N 15,00 E	4:05	210	450 (0.001)	361 (<0.001)	340 (0.035)	623 (0.060)	61 (0.477)	113 (0.507)
3	24	78,26 N 15,08 E	4:04	214	323 (0.006)	363 (0.007)	316 (0.806)	360 (0.747)	84	112
3	25	78,23 N 16,03 E	3:48	148	358 (0.003)	344 (0.003)	452 (0.580)	488 (0.528)	293	404
3	26	78,27 N 15,44 E	4:05	219	443 (0.002)	522 (0.002)	209	576	278	308 (0.529)
3	27	78,22 N 15,13 E	4:08	258	385 (<0.001)	475 (<0.001)	514 (0.109)	558 (0.069)	274	125 (0.595)
3	28	78,25 N 16,04 E	4:10	255	421 (<0.001)	426 (<0.001)	459 (0.053)	374 (0.037)	117 (0.542)	99 (0.634)
3	29	78,18 N 15,32 E	4:07	151	330 (0.004)	436 (0.003)	406	523	495	446
3	30	78,22 N 16,18 E	3:38	192	349 (0.003)	452 (0.003)	55	38	295	107
Total					24160		21716		15413	

Length (mm/cm)	**Shrimp**	**Polar cod**	**American plaice**
5	220.02 (12.06 - 2062.24)	130.28 (67.20 - 276.59)	97.25 (70.10 - 170.07)
10	109.50 (64.99 - 168.46)	91.32 (63.69 - 122.15)	90.02 (71.14 - 120.08)
15	95.58 (83.82 - 112.51)	69.65 (36.75 - 123.01)	89.22 (72.29 - 116.06)
20	101.31 (87.93 - 117.08)	36.76 (6.25 - 298.79)	101.07 (75.34 - 152.89)
25	90.48 (51.09 - 156.46)	-	107.89 (71.24 - 162.50)
30	47.34 (2.71 - 801.03)	-	-
$CR_{average-}$	99.43 (80.93 - 122.32)	-	-
$CR_{average+}$	97.71 (84.94 - 115.34)	-	-
$CR_{average}$	-	83.91 (53.59 - 120.76)	87.77 (72.64 - 115.07)
$CRW_{average-}$	98.04 (80.76 - 118.32)	-	-
$CRW_{average+}$	98.32 (87.23 - 112.75)	-	-
$NDRatio_{Test}$	33.38 (28.03 - 39.19)	-	-
$NDRatio_{Baseline}$	33.00 (28.95 - 37.52)	-	-
$NDRatio_{Test/Baseline}$	101.17 (85.27 - 118.32)	-	-
$WDRatio_{Test}$	16.92 (13.95 - 20.48)	-	-
$WDRatio_{Baseline}$	16.95 (14.29 - 20.25)	-	-
$WDRatio_{Test/Baseline}$	99.77 (81.40 - 122.26)	-	-

Length (mm/cm)	**Shrimp**	**Polar cod**	**American plaice**
5	3.67 (0.27 - 15.85)	12.77 (3.65 - 36.55)	53.18 (36.06 - 96.79)
10	29.42 (16.87 - 51.07)	44.96 (22.19 - 71.34)	91.00 (72.39 - 118.86)
15	90.66 (77.14 - 108.56)	111.59 (70.39 - 214.11)	88.80 (64.48 - 139.59)
20	112.47 (94.54 - 135.34)	145.83 (5.81 - 239.75)	67.23 (42.04 - 180.69)
25	124.35 (56.42 - 250.01)	-	45.52 (17.64 - 210.94)
30	574.39 (118.50 - 5814.45)	-	27.69 (4.80 - 152.48)
$CR_{average-}$	60.77 (47.90 - 83.83)	-	-
$CR_{average+}$	103.22 (89.21 - 119.20)	-	-
$CR_{average}$	-	65.91 (39.83 - 96.49)	81.99 (67.89 - 116.98)
$CRW_{average-}$	65.12 (51.05 - 91.01)	-	-
$CRW_{average+}$	105.98 (93.30 - 122.65)	-	-
$NDRatio_{Test}$	20.00 (17.13 - 23.37)	-	-
$NDRatio_{Baseline}$	29.80 (26.82 - 32.16)	-	-
$NDRatio_{Test/Baseline}$	67.10 (56.24 - 81.10)	-	-
$WDRatio_{Test}$	10.18 (8.57 - 11.97)	-	-
$WDRatio_{Baseline}$	15.58 (13.50 - 17.11)	-	-
$WDRatio_{Test/Baseline}$	65.37 (53.70 - 80.71)	-	-

Length (mm/cm)	**Shrimp**	**Polar cod**	**American plaice**
5	0.64 (0.07 - 20.05)	10.44 (5.12 - 18.46)	39.29 (20.27 - 85.66)
10	34.58 (18.35 - 70.84)	78.08 (58.88 - 106.61)	104.76 (77.42 - 143.16)
15	99.36 (79.14 - 115.07)	116.91 (58.43 - 165.34)	95.11 (71.16 - 128.29)
20	94.30 (72.61 - 122.82)	141.77 (7.88 - 26.11)	91.76 (57.82 - 185.53)
25	86.85 (31.85 - 349.96)	-	174.49 (96.10 - 2082.67)
30	108.54 (4.91 - 55137.30)	-	664.13 (212.26 - 876293.30)
$CR_{average-}$	83.76 (59.40 - 105.51)	-	-
$CR_{average+}$	96.37 (77.17 - 120.38)	-	-
$CR_{average}$	-	90.19 (64.52 - 109.77)	88.87 (63.85 - 128.53)
$CRW_{average-}$	89.58 (65.92 - 111.55)	-	-
$CRW_{average+}$	95.88 (76.34 - 121.47)	-	-
$NDRatio_{Test}$	26.51 (21.50 - 31.17)	-	-
$NDRatio_{Baseline}$	29.33 (25.55 - 33.58)	-	-
$NDRatio_{Test/Baseline}$	90.38 (66.84 - 116.14)	-	-
$WDRatio_{Test}$	14.88 (11.65 - 17.88)	-	-
$WDRatio_{Baseline}$	15.76 (13.23 - 18.62)	-	-
$WDRatio_{Test/Baseline}$	94.40 (65.77 - 127.23)	-	-