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Testing a size sorting grid in the brown shrimp (*Crangon Crangon* Linnaeus, 1758) beam trawl fishery

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Abstract

The North Sea brown shrimp (*Crangon crangon* Linnaeus, 1758) fishery became Marine Stewardship Council (MSC) certified in 2017. As part of the certification, the fishermen proposed to incrementally increase the mesh size of the codend used from 22 mm to 26 mm. As this increase in mesh size could result in a substantial loss of marketable sized brown shrimp (shrimp with total length equal or higher than 50 mm), a combination of a size sorting grid with a bar spacing of 6 mm and a 22 mm codend was proposed by the Danish fishermen as a possible alternative to the increase in codend mesh size. The objective of the proposed gear was to release shrimp smaller than the marketable size before they reach the codend, while potentially limiting the loss of marketable sized shrimp. Therefore, the aim of this study was to investigate the size selective performance of brown shrimp in the above-mentioned gears. The results showed that the grid reduced catches of shrimp under the marketable size of 50 mm. Moreover, the combination of the grid and a 22 mm diamond mesh codend, with an estimated L_{50} of 44.9 mm and a selection range of 15.6 mm, had an overall selective performance similar to that of a 26 mm diamond mesh codend, both for shrimps under and above the marketable size.

Keywords: bar spacing, relative selectivity, absolute selectivity, size selectivity

Highlights

- A size-sorting grid, with 6 mm bar spacing, was tested in a brown shrimp fishery as an alternative to increasing the mesh size in the codend.
- The size-sorting grid led to an average reduction of 33.3% of undersized brown shrimp when compared to the mesh size currently used in the fishery (24 mm diamond mesh codend).
- When compared to the larger codend mesh size (26 mm diamond mesh) the size-sorting grid showed no significant difference.

Introduction

The brown shrimp (*Crangon crangon* Linnaeus, 1758) beam trawl fishery is one of the largest and most important fisheries in the North Sea. The fishery consists of approximately 550 beam trawlers with, since 1995, annual landings between 25000 to 35000 tonnes, except for 2017 where landings were around 22000 tonnes (Stäbler *et al*., 2016; Tulp *et al*., 2016; ICES, 2019). Since the mid-1980s, The Netherlands, Germany, and Denmark have been responsible for the majority of the annual landings, accounting for approximately 90% (ICES, 2019).

Fisheries targeting brown shrimp are largely unregulated in terms of landings and effort, with no Total Allowable Catch (TAC), fishing-effort restrictions or minimum landing size set for this species (Steenbergen *et al*., 2015; Tulp *et al*., 2016; Addison *et al*., 2017). However, under the European Union (EU) Regulation No 2019/1241 it is mandatory to use sieve nets to reduce bycatch and codends with a minimum diamond mesh size of 16 mm (Revill and Holst, 2004a; Addison *et al*., 2017), although most vessels currently use 22 mm diamond mesh. Additional management measures can be applied at the national level, such as limiting the number of licences given, defining closed areas to the fishery and restricting the number of fishing days (Addison *et al*., 2017; Steenbergen *et al*., 2017). Moreover, even though there is no minimum landing size for brown shrimp, there is a mandatory sieving process on land that must be conducted on a sieve with at minimum opening of 6.8 mm based on the carapace width of the shrimps (Addison et al., 2017). This corresponds approximately to retaining individuals equal or larger than 50 mm in total length, defined here as the marketable size for brown shrimp (Revill and Holst, 2004a; Sharawy, 2012; Addison *et al*., 2017).

In 2016, the Dutch, German, and Danish producer organizations initiated a Marine Stewardship Council (MSC) certification process for a sustainable and well-managed fishery; by December 2017 the three brown shrimp fisheries received the MSC certification until December 2022 (Addison *et al*., 2017). As part of the MSC certification process, it was noted that the 22 mm mesh size that was being used had an unsatisfactory size selection, resulting in a substantial fraction of the catch being below the marketable size of 50 mm, and thus being discarded. Consequently, as part of the MSC certification, an incremental increase of the minimum mesh size used in the codend was proposed to reduce growth overfishing of brown shrimp (Addison *et al*., 2017).

The MSC evaluation revealed that the selectivity of a 26 mm diamond mesh codend would reduce the catches of non-marketable sized brown shrimp considerably, with all the associated ecological effects of such reduction (Addison *et al*., 2017; Santos *et al*., 2018). Consequently, the MSC management plan stipulates that the minimum codend mesh size is to be progressively increased from 22 mm to 26 mm by 2021 (Addison *et al*., 2017). However, Santos *et al*. (2018) estimated that increasing the mesh size to 26 mm will result in considerable loss of brown shrimp above the marketable size. Therefore, concerned with this loss of marketable sized brown shrimp, the Danish fishermen proposed the use of a size sorting grid with a bar spacing of 6 mm in conjunction with a codend of 22 mm diamond mesh as a potential alternative to the 26 mm diamond mesh codend. The idea of the proposed gear was to allow for shrimp below the marketable size to escape through the grid before they reached the codend since a caparace width of 6 mm for brown shrimp corresponds to an average total length of 46 mm (Sharawy, 2012). Thus, releasing smaller shrimp before they reach the codend would enable the use of the 22 mm diamond mesh codend, which is the preferred mesh size by the fishermen.

Grids are commonly used in shrimp fisheries as bycatch reduction devices (Broadhurst, 2000; Polet, 2002; Graham, 2003; Fonseca *et al*., 2005). More recently, grids have also been tested for size sorting of the target species in a northern prawn (*Pandalus borealis* Krøyer, 1838) fishery (He and Balzano, 2012; 2013; Larsen *et al.*, 2018). Therefore, the aim of this study was to investigate the size selective performance for brown shrimp, in a dual sequential selectivity system, using a grid with 6 mm bar spacing in combination with a 22 mm diamond mesh codend. In particular, three research questions were addressed: i) How is the selective performance of the test gear compared to the 22 mm mesh size codend currently in use?; ii) How is the selective performance of the test gear compared to the 26 mm mesh size codend?; and iii) What is the test gear's overall size selectivity for brown shrimp?

Material and Methods

Description of grid, grid section, and codends

Fig. 1.

The size sorting grid consisted of a hardened plastic frame made from nylon (PA6) and was 50 cm wide and 73 cm long (Figs. 1 and 2). The grid's bars were 3.9 mm thick and 63 cm long, and constructed out of glass-fibre reinforced plastic. The grid had a nominal bar spacing of 6.0 mm, on average 6.01 mm ± a standard deviation (SD) of 0.06 mm (see Fig. 2 for more detailed information). The measurements for the bar spacing of the grid were obtained using a precision digital calliper (RAZE®) and by measuring a total of 45 distances between the bars (15 from the top, 15 from the middle, and 15 from the bottom of the grid). The grid was mounted in a four-panel extension piece made from 22 mm nominal diamond-mesh netting at an angle of 50° (Fig. 3). A guiding panel, made with 20 mm diamond-mesh netting, was placed in front of the grid (16 open meshes from the bottom panel and 8 open meshes from the grid) to guide the catch towards the lower part of the grid to increase the contact rate of the catch with the grid surface (Figs. 1 and 3). Individuals small enough to pass through the grid will escape by passing between the grid's bars, while larger individuals are led across the grid surface and into the codend through the opening above the grid. The opening above the grid is 15 open meshes high and 54 open mesh wide on the top (Fig. 1). To ensure the extension piece retained its shape during fishing while not interfering with the release of the escapees, a section with large diamond meshes (200 mm) was placed behind the grid in the bottom panel of the extension piece (left panel in Figs. 1 and 3). Three standard commercial diamond mesh codends were tested in this study, two codends with a nominal mesh size of 22 mm and one with a nominal mesh size of 26 mm (Fig. 3). All codends were constructed and mounted as they would be in the Danish brown shrimp fishery. The codends were made of a 200 meshes long single panel with a circumference of 294 open meshes and 6 meshes enclosed in the single selvedge. The codends were made of white PA nylon number 10 (210/30) netting. Net plans of the extension piece where the grid is mounted and the 22 and 26 mm diamond mesh codends are provided in the appendix, Figs. A1 and A2.

Fig. 2.

Fig. 3.

Sea trials description

Three consecutive sea trials were conducted off the southwest coast of Denmark in the North Sea, on board a twin beam commercial trawler with 18 m LOA and 220 kW main engine, from 21st of January to the 25th of January, 2019. The vessel was equipped with two identical 10 m wide beam trawls, 15 m long and with a vertical opening of 0.6 m. In both trawls, a mandatory sieve net of 70 mm mesh size was mounted (see Revill and Holst, 2004b). In all three trials, the combination of the 6 mm size sorting grid with a 22 mm diamond mesh commercial codend (22.1 mm ± SD 0.5 mm) similar to those used in the Danish brown shrimp fishery, hereafter referred to as SG6M22, was used as the test gear. In the first and second trials, SG6M22 was tested, respectively, against a 22 mm (22.4 mm ± SD 0.5 mm) and 26 mm (26.1 mm ± SD 0.5 mm) diamond mesh commercial codend, hereafter referred to as M22 and M26, respectively. All codends mesh sizes were measured using an OMEGA gauge according to Fonteyne *et al.* (2007) and following the methodology described in ICES (2005), where a total of 60 meshes were measured for each codend after the experiments and by soaking in water the codends for at least 24 hours. Moreover, both trials were conducted as catch comparison trials (e.g. Krag *et al.*, 2014b) where the two beam trawls were towed in parallel to compare the length dependent catch efficiency between both gears. In the third trial, SG6M22 was tested against an 11 mm diamond mesh codend, hereafter referred to as M11. In this trial, M11 was used as the control to estimate the absolute selectivity of SG6M22 using the paired-gear method described in Wileman *et al*., 1996. The 11 mm mesh size codend has been considered to be adequate when estimating the selectivity of test gears in the brown shrimp fishery considering the range of lengths that are usually encountered in the brown shrimp fishery (*e.g*. Polet, 2000; 2002;

Santos et al., 2018). It was not possible to accurately measure the mesh sizes of M11, since the meshes size range was within the lower limit of measurable sizes by the Omega gauge (10 mm ± 1 mm precision). The average mesh size of M11 (11.4 mm ± SD 0.4 mm) was estimated based on a digital image analysis, using ImageJ, of two different scanned sections from a midpoint of the codend. From each scanned section, a row of 25 meshes dimensions and opening angles were measured (total of 50 measured meshes). These measurements were used to estimate the inner distance from knot to knot, for each mesh, at an opening angle of 5° (i.e. fully stretched mesh). A similar approach has been used to estimate the average size of stretched meshes in previous studies (*e.g*. Sistiaga *et al*., 2011; Krag *et al*., 2014a).

For every haul, total catch in weight for each gear was estimated by the scientific observer and the skipper based on the catch volume in the codend and the catch volume inside the pounder where the catch was dropped. Moreover, samples of approximately 4 kg were taken from the unsorted catch of each gear and frozen for subsequent length measurement on land. These samples were obtained by taking several scoops from different points of the pounder. This procedure ensures that the sample species and length composition is representative of the catch. The on-board samples were then unfrozen and sorted in the laboratory into different categories, such as, brown shrimp, fish and invertebrates species. The proportions of the different categories in the samples were used to estimate total catches for the respective catch categories. The total sampled weight for each fish species was recorded and raised to the respective estimated total catch. All brown shrimp was sorted and weighed, and a sub-sample of approximately 1000 individuals was weighed and length measured, with the remaining weight of the unmeasured shrimps added to the total catch of each gear. Total length measurements were obtained by digital image analysis by use of ridge detection in ImageJ, as described in Santos *et al*. (2018). The total lengths obtained were rounded down to the nearest millimetre for the subsequent statistical analyses.

Relative size selectivity

The number of shrimp per length class caught in the different codends in trials 1 and 2 were used to evaluate the relative length-based catch efficiency for brown shrimp of the test gear (SG6M22) in relation to the baseline gears (i.e. M22 and M26). To assess the relative length-dependent catch efficiency between the test and baseline gears, we used the catch comparison method described in Herrmann *et al*. (2017) and compared the catch data for the two types of gears fished simultaneously. This method models the length-dependent catch comparison rate (CC_{il}) summed over hauls:

$$CC_{il} = \frac{\sum_{i=1}^{m}\left\{\frac{\mathrm{nt}_{li}}{\mathrm{qt}_i}\right\}}{\sum_{i=1}^{m}\left\{\frac{\mathrm{nt}_{li}}{\mathrm{qt}_i}+\frac{\mathrm{nb}_{li}}{\mathrm{qb}_i}\right\}} \tag{1}$$

where nt_{li} and nb_{li} represent the number of shrimp of each length class l length measured in the i-th haul for the test and baseline gears, respectively. qt_i and qb_i are the corresponding sampling factors for test and baseline gears, respectively quantifying the fraction of the total catch in the *i-th* haul being length measured. *m* represents the total number of hauls. When the catch efficiency of the test gear and baseline gear is similar, the expected value for the summed catch comparison rate would be 0.5. The experimental CC_{il} was modelled by the function $CC(l,\boldsymbol{v})$, on the following form:

$$CC(l,\boldsymbol{v}) = \frac{exp\left(f(l,v_0,\dots,v_k)\right)}{1+exp\left(f(l,v_0,\dots,v_k)\right)} \tag{2}$$

where *f* is a polynomial of order *k* with coefficients v_0 to v_k. The modelling approach described in Veiga-Malta *et al*. (2019) for estimating $CC(l,\boldsymbol{v})$ was used in this study, where polynomials up to an order of 4 were considered and multi-model inference used to obtain a combined model. Based on the estimated catch comparison function $CC(l, \boldsymbol{v})$ we obtained the catch ratio, $CR(l,\boldsymbol{v})$, between the two gears by the following relationship (Veiga-Malta *et al.*, 2019):

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{\left(1-CC(l,\boldsymbol{v})\right)} \tag{3}$$

The catch ratio is a value that represents the relative catch efficiency of the test gear when compared to that of the baseline gear, where a $CR(l,\boldsymbol{v})$ of 1.0 means that both gears have equal catch efficiency for a give length class (Veiga-Malta *et al.*, 2019). Moreover, size-integrated average values for the catch ratio ($CR_{average}$) were estimated directly from the experimental catch data as indicators for the relative selective performance of the gears using the following equations:

$$CR_{average-} = 100 \times \frac{\sum_{l<ML}\sum_{i=1}^{m}\left\{\frac{nt_{li}}{qt_i}\right\}}{\sum_{l<ML}\sum_{i=1}^{m}\left\{\frac{nb_{li}}{qb_i}\right\}}$$
$$CR_{average+} = 100 \times \frac{\sum_{l\geq ML}\sum_{i=1}^{m}\left\{\frac{nt_{li}}{qt_i}\right\}}{\sum_{l\geq ML}\sum_{i=1}^{m}\left\{\frac{nb_{li}}{qb_i}\right\}} \qquad (4)$$

$CR_{average-}$ and $CR_{average+}$ compare the number of shrimp caught under and over the minimum marketable size (ML= 50 mm) between the test and the baseline gear for each trial, respectively. Values of 100 indicate that the test gear catches the same number of shrimp than the baseline gear. Therefore, $CR_{average-}$ should be as low as possible while $CR_{average+}$ should be as high as possible. Estimates of $CR_{average-}$ and $CR_{average+}$ are only considered statistically significant if the estimated 95% CI for each indicator does not include the value of 100.

Finally, to investigate how well the size selectivity of the test and baseline gears matched the size structure of shrimp in the area fished, discard ratio (*DnRatio*) was estimated directly from the experimental catch data for each gear tested by:

$$DnRatio_{test} = 100 \times \frac{\sum_{l<ML}\sum_{i=1}^{m}\left\{\frac{nt_{li}}{qt_i}\right\}}{\sum_{l}\sum_{i=1}^{m}\left\{\frac{nt_{li}}{qt_i}\right\}}$$
$$DnRatio_{baseline} = 100 \times \frac{\sum_{l<ML}\sum_{i=1}^{m}\left\{\frac{nb_{li}}{qb_i}\right\}}{\sum_{l}\sum_{i=1}^{m}\left\{\frac{nb_{li}}{qb_i}\right\}} \qquad (5)$$

where the outer summation in the nominator includes the size classes in the catch that were under the marketable size of brown shrimp, while for the denominator, the outer summation is for all size classes in the catch. *DnRatio* is therefore the ratio between discards and total catch in numbers, thus it should be as low as possible, with 0 being the best possible situation where no discards occur. The value of *DnRatio* is affected by both the size selectivity of the gear and the size structure of the shrimps on the fishing grounds. Therefore, it provides an estimate that is specific for the population fished and it cannot be extrapolated to other areas and seasons.

Absolute size selectivity

Due to the experimental design, the catch data from the test (SG6M22) and control (M11) were collected simultaneously in the same hauls, thus they can be regarded as paired. The catch data from individual hauls were used to estimate the average size selectivity for the test gear by pooling data over hauls and applying the paired gear estimation method (Wileman *et al*., 1996). The average size selectivity in the test gear was therefore estimated based on the catch data summed over hauls by minimizing the following expression:

$$-\sum_l \sum_{i=1}^{m} \left\{ \frac{nT_{li}}{qT_i} \times ln\left(\frac{SP \times r(l,\boldsymbol{v})}{SP \times r(l,\boldsymbol{v})+1-SP}\right) + \frac{nC_{li}}{qC_i} \times ln\left(1.0 - \frac{SP \times r(l,\boldsymbol{v})}{SP \times r(l,\boldsymbol{v})+1-SP}\right)\right\} \quad (6)$$

where nT_{li} and nC_{li} represent the number of shrimp of each length class l length measured in the *i-th* haul for the test and control gear respectively. qT_i and qC_i are the corresponding sampling factors for test and control gear respectively quantifying the fraction of the total catch in the *i-th* haul being length measured. m represents the total number of hauls. SP is the split factor quantifying the sharing of the total catch between the test and control gears (Wileman *et al*., 1996). Minimizing equation (6) is equivalent to maximizing the likelihood for the observed experimental data. $\boldsymbol{v}$ is a vector of parameters describing the size selection model $r(l, \boldsymbol{v})$. Since the test gear was constructed with two selection devices placed sequentially after each other, where shrimp first would have the chance of getting size selected by the grid process ($r_{grid}(l)$) and shrimp that were not selected out in the grid process would be subsequently size selected by the codend meshes (($r_{codend}(l)$)) (Fig. 1). To be able to account for this dual and sequential nature of the size selection in the test gear we modelled the size selection in the test gear by:

$$r(l,\boldsymbol{v}) = r_{grid}(l,\boldsymbol{v}_{grid}) \times r_{codend}(l,\boldsymbol{v}_{codend}) \quad (7)$$

where $\boldsymbol{v} = (\boldsymbol{v}_{grid}, \boldsymbol{v}_{codend})$. Since the codend consisted of a single mesh type and size, we assumed that the size selection for the codend process could be described by a traditional s-shaped size selection model with increasing retention probability for shrimps of increasing size. Four different models were tested as candidates to describe $r_{codend}(l, \boldsymbol{v}_{codend})$: Logit, Probit, Gompertz and Richard. The first three models have two parameters $L_{50codend}$ (length of shrimp with 50% retention probability conditional on entering the codend) and SR_{codend} (selection range – range of lengths between 75% and 25% retention probabilities) whereas the last model has one additional parameter, $1/\delta_{codend}$ that enables an s-shaped curve with asymmetry (Wileman *et al.*, 1996). For the grid process in (7), besides considering the same s-shaped models as for the codend, we also considered the potential situation that only a fraction C of the shrimp will make contact with the grid to be size selected by it. Further, we considered the situation that none of the shrimp came in contact with the grid. Based on these considerations, nine different models for the grid process were considered. For more details on the different models please see appendix. In total, based on the combinations of equations for $r_{grid}(l, \boldsymbol{v}_{grid})$ and $r_{codend}(l, \boldsymbol{v}_{codend})$ in equation (7), 36 models were considered to describe the combined size selectivity for SG6M22. These 36 models were tested against each other and the one with the lowest AIC value (Akaike's Information Criterion; Akaike, 1974) was selected. For more details on the models considered see appendix.

Evaluation of goodness-of-fit of models

The ability of the models mentioned above (both for relative and absolute selectivity) to describe the experimental data was evaluated based on the *p*-value. This *p*-value quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct. Therefore, the *p*-value calculated based on the model deviance and the degrees of freedom should be >0.05 for the selection model to describe the experimental data sufficiently well, except from cases where the data were subjected to over-dispersion (Wileman *et al.*, 1996).

Estimation of confidence intervals

The confidence limits for the catch comparison and catch ratio curves were estimated using a double bootstrapping method (Millar, 1993; Herrmann *et al*., 2017). This bootstrapping method accounted for between-haul and within haul variation as described in Herrmann et al. (2017). To correctly account for the increased uncertainty due to subsampling, the data were raised by sampling factors after the inner resampling. However, contrary to the double bootstrapping method describe in Herrmann *et al*. (2017), the outer bootstrapping loop in the current study that accounted for the between haul-variation was performed pairwise for the test and baseline gears. Thus, taking full advantage of the experimental design in which both gears were deployed simultaneously. Moreover, in the case of relative selectivity, by using multi-model inference in each bootstrap iteration, the method also accounted for the uncertainty in model selection.

We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) confidence limits (CIs) for all analyses previously described. To identify sizes of shrimp with significant differences in relative catch efficiency, we checked for length classes in which the 95% confidence limits for the catch ratio curve did not contain the value 1.0. The CIs for the average $CR_{average-}$, $CR_{average+}$ and $DnRatios$ were estimated using the same double bootstrap routine used to estimate the CIs of the $CC(l,\boldsymbol{v})$ and $\mathrm{CR}(l,\boldsymbol{v})$ curves. All analyses described here were performed using the statistical analysis software SELNET (Herrmann *et al*., 2012).

Results

A total of 36 hauls were conducted during the three sea trials, with a total of 12 hauls for each trial (Table 1). Fishing operations were kept as similar as possible to normal commercial fishing activities during the first two trials, with a mean towing time of 2 hours per haul and a mean towing speed of 3.3 kn. For the third trial, due to the fact that a non-selective codend (M11) was used, the duration of the hauls was reduced to approximately one hour due to the potential of large catches in the M11 codend. The sorting grid had an average angle-of-attack of 47.1° ± SD 3.4°, with no issues been noticed during the towing periods (e.g. twisting of the netting, clogging of the grid). On average bycatches of both gears tested accounted for 29.8% (14.5%-48.6%), 24.3% (14.7%-45.0%), and 28.1% (7.0%-53.4%) of total catch weight for the first, second, and third trials, respectively. The majority of bycatch, 89.6% (63.9%-98.7%), consisted of fish species, such as, plaice (*Pleuronectes platessa*), dab (*Limanda limanda*), sprat (*Sprattus sprattus*), herring (*Clupea harengus*) and Gobiidae (*Pomatoschistus sp.*) while the rest was comprised of invertebrates, such as, small starfishes and small crabs. A total of 76046 shrimps were length measured for this study, with sub-sampling factors being on average 2.4%, but ranging from 0.5 to 7.4% (Table 1).

Table 1.

Datasets from trials 1 and 2 were analysed and catch comparison models fitted to assess the relative selective performance of the SG6M22 in relation to M22 (Fig. 4) and M26 (Fig. 5), respectively. For both models, *p*-values lower than 0.05 were found. Therefore, the models residuals were plotted against length (not shown) and how the models describe the experimental data visually inspected (Figs. 4 and 5) to assess the quality of the fit. No patterns were found in the residuals and the models were found to appropriately describe the trends in the data. Thus, the low *p*-values were assumed to be due to over-dispersion in the data, most likely caused by the use of subsampled data pooled over hauls. This phenomenon has been observed in previous studies (Brčić *et al*., 2015; Alzorriz *et al*., 2016; Notti *et al*., 2016). Moreover, the different indicators for brown shrimp were obtained for the trials 1 and 2 (Table 2).

Fig. 4.

The SG6M22 caught significantly less brown shrimp for lengths between 34 and 52 mm than M22 (Fig. 4). According to the catch ratio curve, the largest reduction in the catch of brown shrimp occurred for the length of 40 mm; at this length SG6M22 caught at least ~26% less brown shrimp and on average ~42% less. At the minimum marketable market size of 50 mm, SG6M22 caught at least ~10% less and on average ~18% less. Moreover, the estimated curves also show a significant decrease in the catch of lengths between 69 and 73 mm for the SG6M22; for the length of 72 mm this gear caught at least ~8% less (on average ~30% reduction). No significant differences were found for the remaining lengths classes. Furthermore, the $CR_{average-}$ estimated for the first trial shows that SG6M22 significantly reduced the catch of brown shrimp below marketable size by 33.3% (95% CI from 47.2 to 22.2%; Table 2). Although no significant difference was found for the catch of shrimp larger than 50 mm, the results indicate that SG6M22 caught on average 8% less marketable shrimp ($CR_{average+}$ for trial 1 in Table 2).

Fig. 5.

For two length classes, 57 and 58 mm, a significant difference was found, with SG6M22 catching at least, respectively, 0.5% and 0.4% more (in number of individuals) shrimp for these length classes than M26 (Fig. 5). No significant differences were found for all the other lengths between the catch size structures from SG6M22 and M26. Furthermore, the indicators for the second trial show no significant difference between SG6M22 and M26 (Table 2). Nevertheless, there is the non-significant indication that SG6M22 caught on average 4% less of below marketable size shrimps and 5% more marketable sized brown shrimp than M26.

Table 2.

The catch sharing curve obtained from comparing the selective performance of SG6M22 to that of a small mesh codend, M11, in the third trial made it possible to estimate the overall absolute selectivity of SG6M22 (Fig. 6). As for the catch comparison models, the fit statistics from the catch sharing model indicated issues with the model fit. The analysis of the model residuals and visual inspection of the model fit suggested that the poor fit statistics obtained were again due to over-dispersion in the data. The best model, with the lowest AIC, describing the overall absolute selectivity of SG6M22 was a combination of Richards model for the first process (grid) and Gompertz model for the second process (codend). A L_{50} of 44.9 mm (95% CI from 42.4 to 49.6 mm) and a SR of 15.6 mm (95% CI from 13.3 to 23.6 mm) was estimated for the absolute selectivity of SG6M22. A split of 0.51 (95% CI from 0.46 to 0.60) was estimated from the catch sharing model. The estimated L_{50} of SG6M22 is below the 50 mm minimum marketable size for brown shrimp, while the retention probability for this length was estimated to be 73% (95% CI from 53 to 83%). The selectivity parameters, L_{50} and SR, estimated for each of the 12 hauls from trial 3 were plotted to determine whether there were any outliers. Although a relatively large variability was observed, no outliers were found (Fig. 7).

Fig.6.

Fig. 7.

Discussion

Sorting grids have been used as a way to reduce the catch of small shrimps in a northern prawn fishery in Gulf of Maine (He and Balzano, 2007; 2012) and Norwegian northern prawn fishery (Larsen et al., 2018). In this study, we demonstrate the ability of a size-sorting grid to reduce the catch of brown shrimp below marketable size. The combination of a size-sorting grid with a bar spacing of 6 mm and a 22 mm diamond mesh codend (SG6M22) significantly reduced the catch of brown shrimp below marketable size when compared to the 22 mm diamond mesh codend (M22). As the size-sorting grid was the main difference between both fishing gears in terms of the overall selective process, the reduction of shrimp catches below marketable size was assumed to be the result of the grid. The reduction of shrimp under the marketable size was expected, since individuals below 46 mm in total length have a carapace width of 6 mm or less (Sharawy, 2012), and therefore are able to pass between the bars. The SG6M22 was found to significantly retain less individuals down to 34 mm, while no significant difference was observed for the lower length classes as these are similarly selected out of both gears by either the grid or the 22 mm codend.

When considering the selective performance of SG6M22 compared to the 26 mm diamond mesh codend (M26), the results show that the selectivity of the gears were equivalent in terms of releasing shrimp below marketable size. In terms of marketable catch, despite a significant difference being found for two length classes (57 and 58 mm), the overall selective performance of both gears was similar. This means that SG6M22 could be an alternative for the fishermen to meet the MSC requirements. However, the uptake by the fishermen of this more complex gear design would only be justified if it prevented the loss of marketable sized shrimp when compared to M26. Despite the results of this study not being conclusive, there was a non-significant indication that SG6M22 caught slightly more marketable sized brown shrimp than M26. Indeed, a significant increase in catch rate was found for few length classes above the marketable size of 50 mm, and the indicators obtained also seem to support this indication of an increase in marketable size shrimp, although not significantly. This indication could derive from the fact that a portion of the catch will not contact the surface of the grid, as shown from previous studies (e.g. Stepputtis *et al*., 2016). Therefore, this portion of the catch will only be subjected to the size selection of the M22 codend, which has a lower L_{50} and SR than the M26 (Santos *et al*., 2018). In contrast, a part of the marketable sized shrimp that contact the grid is selected out. This loss of shrimp above marketable size is evident when considering the results of the third trial, where the overall selectivity of SG6M22 was estimated.

The estimated absolute selectivity of SG6M22 showed that full retention was achieved at the length of 55 mm, while for a 22 mm diamond mesh codend full retention has been found to occur at approximately 51.5 mm (Santos *et al*., 2018). The higher selectivity for SG6M22 could be explained by the release of shrimp below marketable size due to the grid, coupled with a potentially higher codend selectivity due to smaller catch sizes. Polet (2002) previously observed that smaller catches resulted in higher selectivity (L_{50}'s) than larger catches. The full retention of brown shrimp for SG6M22 estimated to occur at the length of 55 mm, partly contrast with the results obtained in the first trial, where SG6M22 was compared to M22. Here, a significant loss of larger shrimp (69 to 73 mm) was estimated by the model. We believe that this result was most likely an artefact due to the large sub-sampling, which increases the uncertainty around the length classes less represented in the catch (tail areas of the length structure of the catch).

The selectivity parameters estimated for brown shrimp for SG6M22 were within the range previously observed for a 26 mm diamond mesh codend (Santos *et al*., 2018). However, the SR estimated for SG6M22 appears to be larger than the ones obtained by Santos et al. (2018). The larger values obtained in this study can potentially be explained by the higher complexity of the gear tested in this study, different fishing grounds, and/or seasons (e.g. O'Neill *et al*., 2006; Fryer *et al*., 2016; Melli *et* *al.*, 2020). Furthermore, the level of variability observed in this study for the selectivity parameters at the haul level is similar to those reported by Polet (2002). Polet (2002) found this high variability to be related to occasional clogging issues due to seaweed and other invertebrates. Throughout the three trials, no issues with the grid becoming clogged were observed. This may be due to the fact that the grid was placed aft of the sieve net, and therefore the majority of algae, jellyfish and marine litter typically responsible for clogging does not reach the grid. Moreover, in Danish waters, clogging is not usually an issue as it is in other areas, and therefore the use of sieve nets is mandatory throughout the entire year. In areas where clogging can be an issue, fishermen may remove the sieve net in certain periods (Addison *et al*., 2017). The removal of the sieve net can potentially affect the selective performance of the grid and, thus, needs to be further investigated to determine if SG6M22 could be used in different fishing grounds.

The towing times in trial 3 were similar to those used in previous brown shrimp absolute selectivity studies (Polet, 2000; 2002; Santos *et al.,* 2018), although longer towing times have been found to increase the codend selectivity for brown shrimp (Polet, 2000). Moreover, the study was conducted in January, which is typically a period where catch rates of brown shrimp are lower, although this seasonal difference is less pronounced for the Danish fleet as it is for the Dutch and German fleets (ICES, 2019). The effect of larger catch sizes, such as the ones seen in Dutch and German waters, on the selective performance of SG6M22 should be further investigated. Furthermore, the relatively high proportion of bycatch caught during this study is similar to that reported for the brown shrimp fishery (ICES, 2015). Nevertheless, the bycatch of fish and small invertebrates may have also affected the overall selective performance of SG6M22 since it has been reported that larger and less homogeneous catches can hinder the codend selectivity for brown shrimp (Polet 2000; 2002).

The size-sorting grid in this study was designed to maximize the flow through the grid by reducing the width of the bars, thus increasing its porosity, and by using drop shaped bars. Veiga-Malta *et al*. (2020) showed that, for the same bar spacing (6 mm), porosity is indeed an important factor to reduce the resistance of the grid to the flow of water. This raises the question of how grids should be specified in the legislation? In the case of grids for reducing bycatch, setting maximum bar spacing for a grid should be enough (e.g. Council Regulation (EC) No 27/2005) as fishermen will not reduce the bar spacing since they risk losing a portion of the target species. For example, in Polet (2002), issues with water flow and clogging in grids have been associated with a reduction in the catch of target species. On the other hand, when the objective is to avoid the capture of undersized individuals, setting only a minimum bar spacing could lead to highly ineffective size sorting grids to be legally used in a fishery. For example, increasing the bar thickness from 4mm to 8mm in grids with 6 mm bar spacing has been shown to reduce the water flow in front of a grid by approximately 30 % (Veiga-Malta *et al*., 2020). This reduction in water flow, could lead to a reduction in the selective performance of the grid.

In conclusion, we found that the combination of a size-sorting grid with a bar spacing of 6 mm and a 22 mm diamond mesh codend can serve as an alternative to the 26 mm diamond mesh codend when it comes to sorting out brown shrimp below marketable size. Despite the higher complexity of the gear design tested in this study, no issues with the gear were observed during the fishing process, such as clogging issues or twisting of the gear. Furthermore, the fishermen were satisfied with the handling of the gear during fishing, the retrieval process and on board the vessel. To maximize the potential of the grid's selective performance, and thus its potential uptake by the fishermen, further investigation should be performed to minimize the loss of marketable size shrimp while maximizing escape of shrimp below marketable size. Estimating the catch's contact rate with the grid would allow guiding the direction for future research.

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Table 3. Estimated values for the different indicators for brown shrimp. Values within parenthesis are the Efron 95% confidence intervals. $CR_{average-}$ and $CR_{average+}$ are the size-integrated average values for the catch ratio of all length classes, respectively, under and above the minimum marketable size of brown shrimp (50 mm). DnRatio represents the discard ratios in numbers.

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Table 4. Summary of the valid hauls for the three sea trials. Values within parenthesis are the range of the data.

	Trial 1		Trial 2		Trial 3	
Gear	6 mm Grid + 22 mm codend (SG6M22)	22 mm codend (M22)	6 mm Grid + 22 mm codend (SG6M22)	26 mm codend (M26)	6 mm Grid + 22 mm codend (SG6M22)	11 mm codend (M11)
No. of hauls	12		12		12	
Mean haul duration (min)	120 (115-130)		120 (120-120)		63 (40-100)	
Mean towing speed (kn)	3.3 (3.0-3.5)		3.3 (2.8-3-4)		3.3 (3.1-3.5)	
Mean fishing depth (m)	5.8 (3.0-8.0)		6.8 (5.0-9.0)		7.6 (6.0-10.0)	
Mean shrimp catch size (kg)	93.8 (16.8-264.7)	105.4 (22.2-257.1)	74.7 (27.8-127.4)	75.2 (32.4-138.7)	33.3 (12.9-65.2)	51.0 (20.5-87.3)
Number measured	12464	12741	12654	12504	12739	12944
Mean sub-sample factor (%)	2.6 (0.5-6.6)	2.1 (0.5-5.4)	1.8 (0.9-5.0)	1.8 (0.8-4.6)	3.5 (1.3-7.4)	2.2 (1.1-6.7)

Table 5. Estimated values for the different indicators for brown shrimp. Values within parenthesis are the Efron 95% confidence intervals. $\mathrm{CR}_{\mathrm{average}-}$ and $\mathrm{CR}_{\mathrm{average}+}$ are the size-integrated average values for the catch ratio of all length classes, respectively, under and above the minimum marketable size of brown shrimp (50 mm). DnRatio represents the discard ratios in numbers.

	Trial 1		**Trial 2**	
Gear	6 mm Grid + 22 mm codend (SG6M22)	22 mm codend (M22)	6 mm Grid + 22 mm codend (SG6M22)	26 mm codend (M26)
n <50 mm (in thousands)	244.8 (139.8-362.2)	367.3 (233.9-508.0)	282.8 (215.4-344.7)	293.9 (221.4-366.1)
n >=50 mm (in thousands)	695.7 (404.7-1033.7)	755.7 (459.5-1072.5)	539.2 (430.1-652.2)	512.6 (399.1-642.3)
DnRatio (%)	26.0 (23.5-28.5)	32.7 (30.5-35.8)	34.4 (30.8-38.1)	36.4 (32.3-40.9)
$CR_{average-}$ **(%)**	66.7 (52.8-77.8)		96.2 (80.6-117.0)	
$CR_{average+}$ **(%)**	92.1 (81.1-102.0)		105.2 (96.6-114.2)	

Fig. 1. Size sorting grid for brown shrimp (left panel) with 6 mm bar spacing, mounted in an extension piece (right panel) in front of the codend. Note the opening to the codend in the top (arrow A), the escape panel behind the grid (arrow B) and the guiding panel in the bottom (black netting; arrow C).

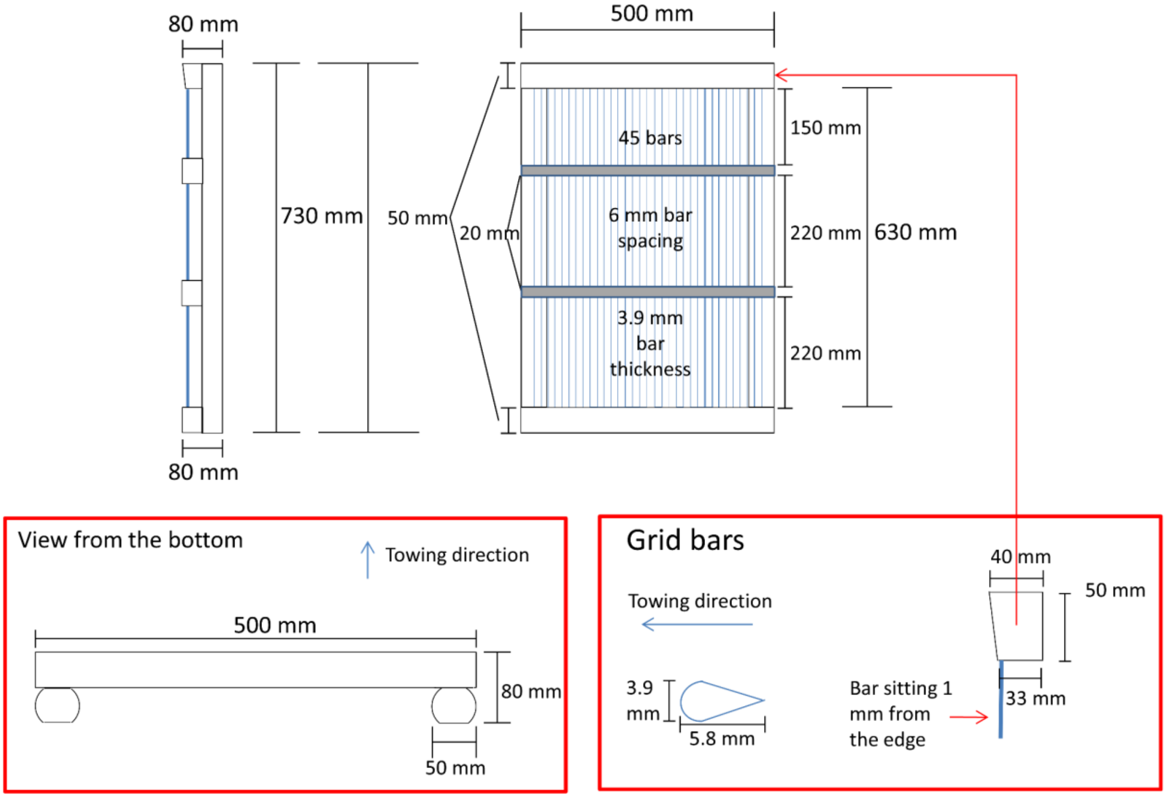

Fig. 2. Description of the 6 mm size-sorting grid with drop shaped bars that was used during this study.

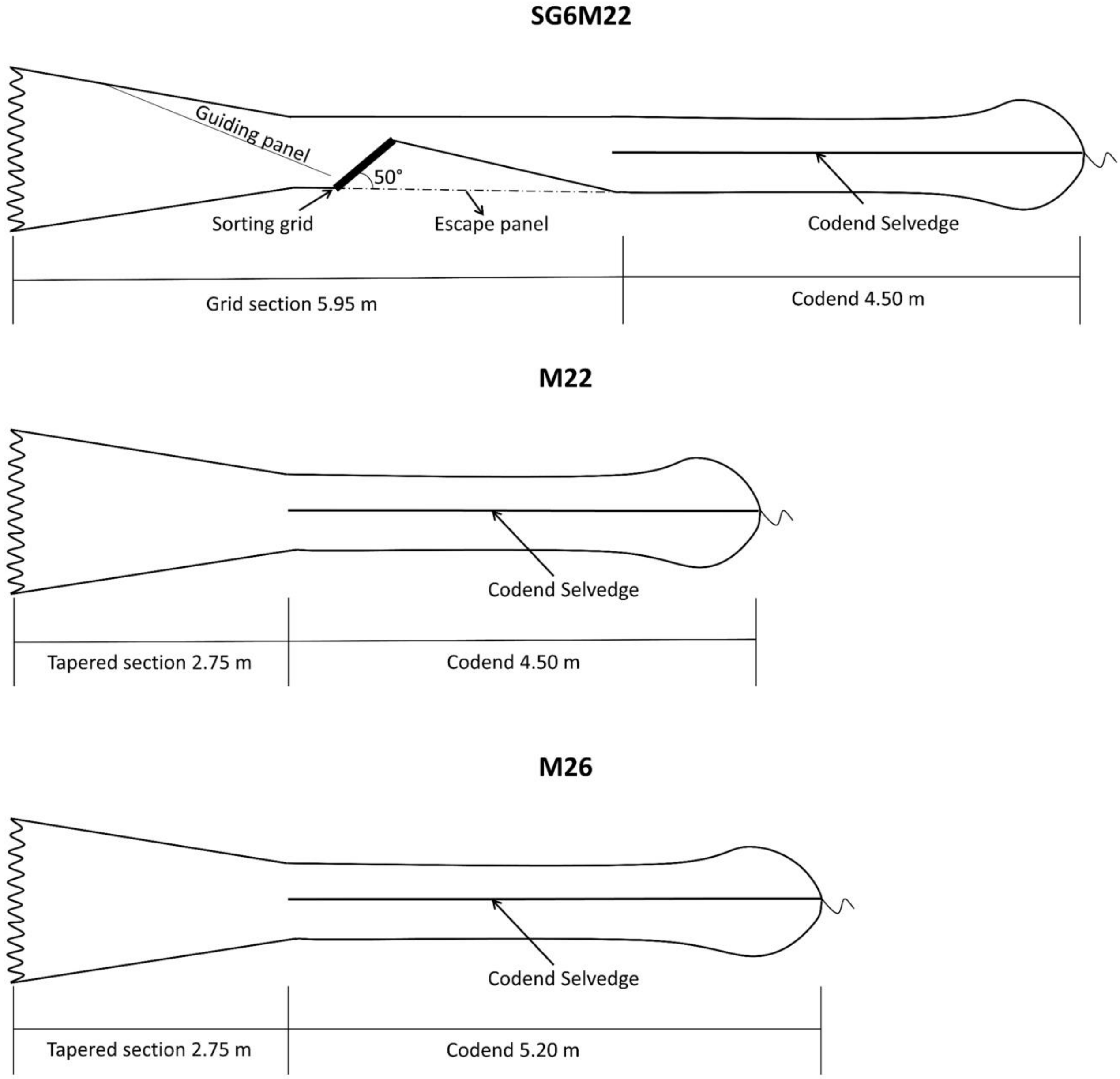

Fig. 3. Schematic drawing illustrating the three different gear concepts tested in this study.

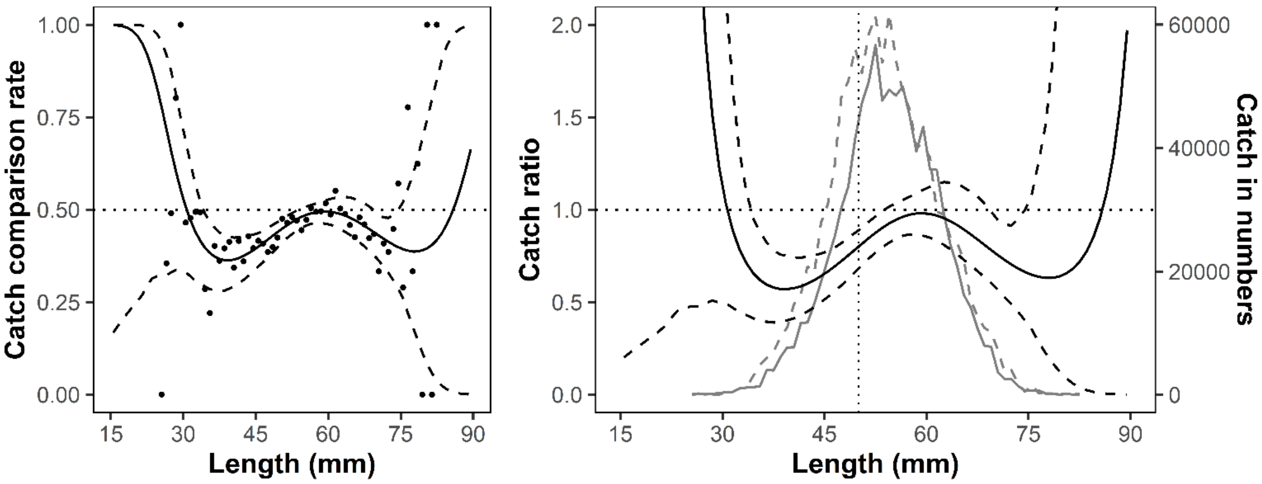

Fig. 4. Estimated average catch comparison with experimental data points (left panel) and catch ratio (right panel) curves (solid black line) and 95% confidence intervals (broken black lines) for brown shrimp obtained when comparing SGM22 and M22. Dotted grey horizontal lines represent when both gears are fishing equally efficient. Grey lines represent the catch length structure of brown shrimp for SG6M22 (solid grey line) and M22 (broken grey line). The dotted vertical line represents the minimum marketable size for brown shrimp (50 mm).

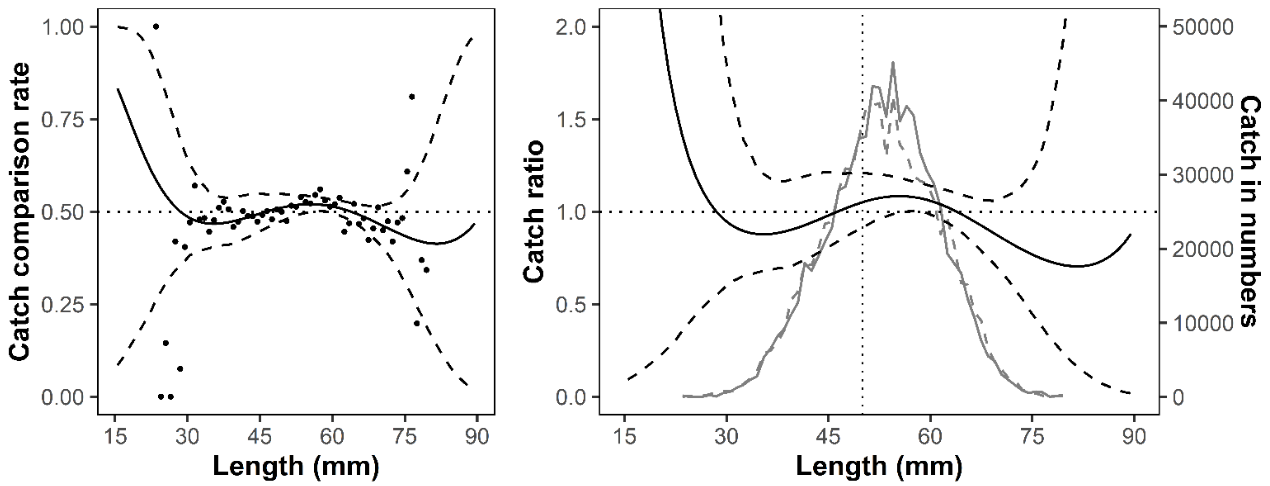

Fig. 5. Estimated average catch comparison with experimental data points (left panel) and catch ratio (right panel) curves (solid black line) and 95% confidence intervals (broken black lines) for brown shrimp obtained when comparing SG6M22 and M26. Dotted grey horizontal lines represent when both gears are fishing equally efficient. Grey lines represent the catch length structure of brown shrimp for SG6M22 (solid grey line) and M26 (broken grey line). The dotted vertical line represents the minimum marketable size for brown shrimp (50 mm).

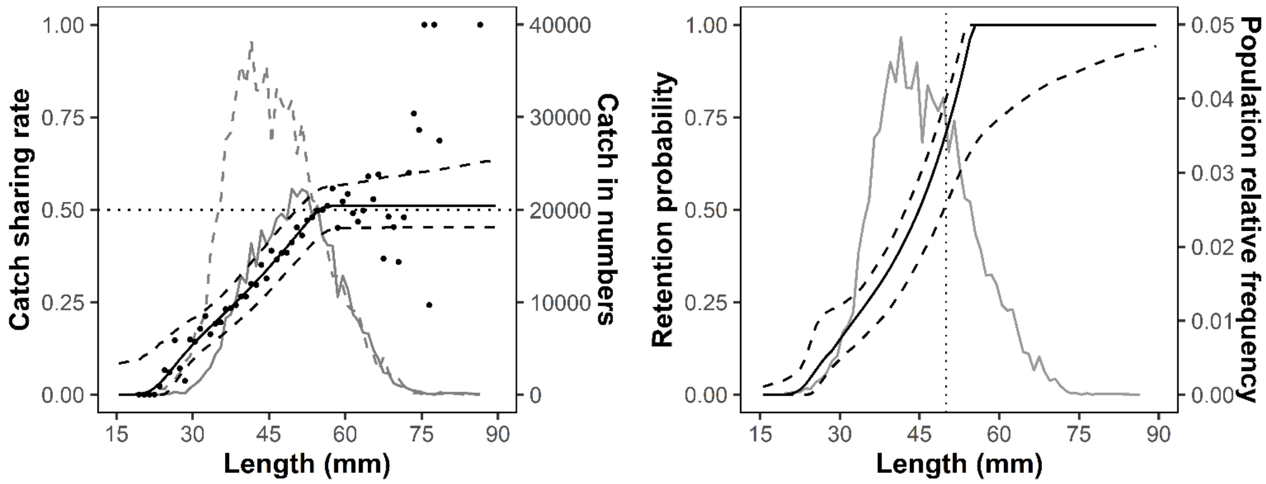

Fig. 6. Estimated catch sharing rate with experimental data points (left panel) and absolute size selectivity (right panel) curves (solid black lines) and 95% confidence intervals (broken black lines) obtained for brown shrimp when comparing SG6M22 and M11 (non-selective codend). Dotted grey horizontal line represents when both gears are fishing equally efficient. Grey lines in left panel represent the catch length structure of brown shrimp for SG6M22 (solid grey line) and M11 (broken grey line). Grey line in the right panel represents the relative length structure of the population encountered by the trawl. The dotted vertical line represents the minimum marketable size for brown shrimp (50 mm).

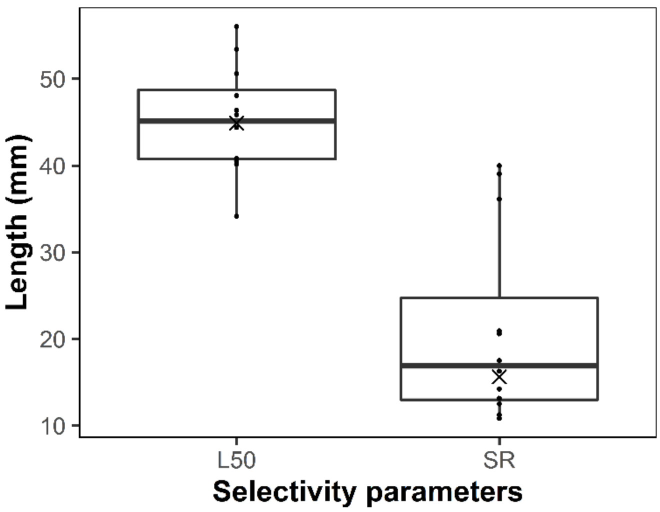

Fig. 7. Box and whisker plot depicting the variability of the selectivity parameters, L50 and SR, estimated for SG6M22 for each of the individuals hauls of trial 3 (points). The estimated L50 and SR from trial 3 are represented by “x”.

Appendix

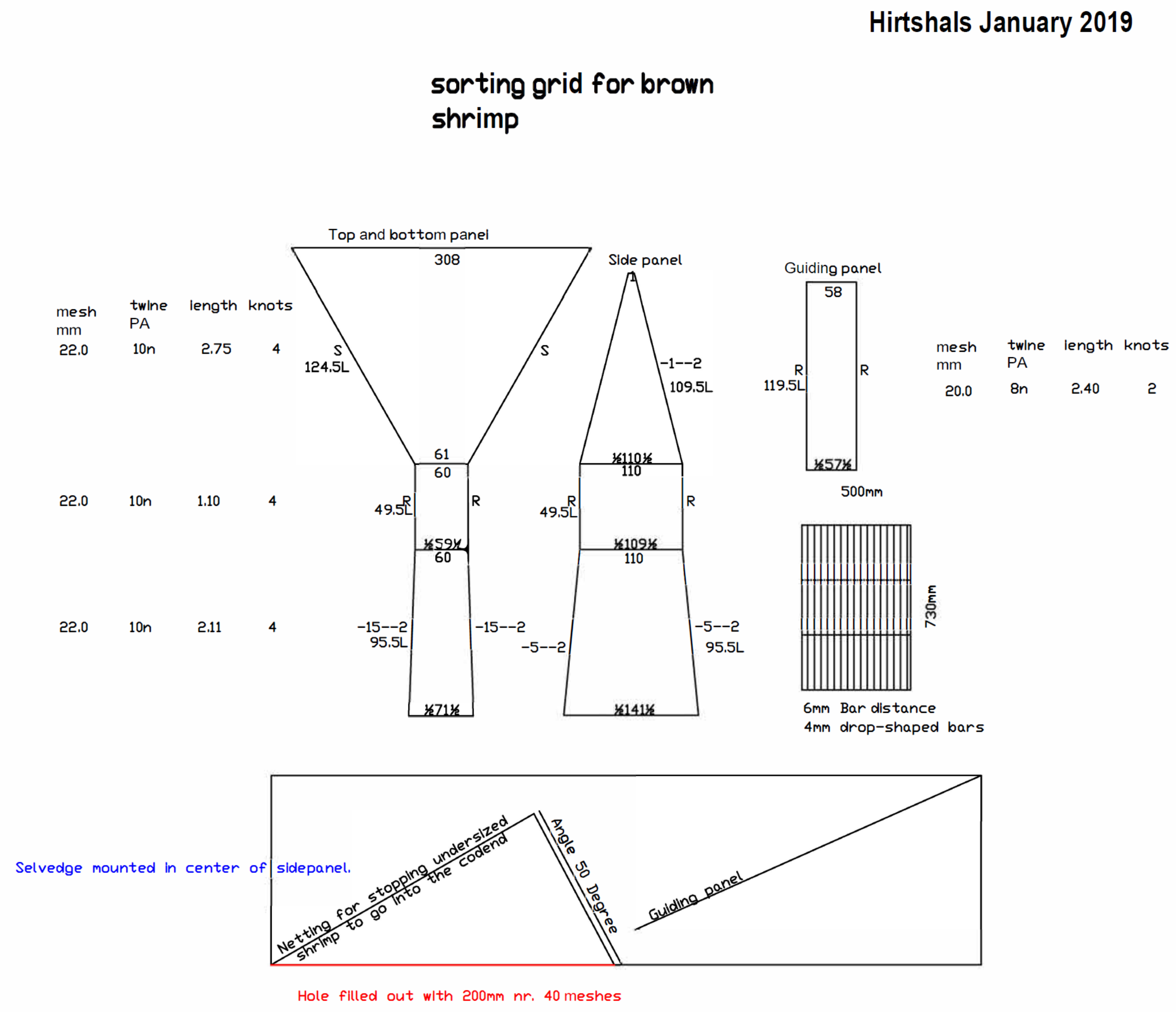

Figure A3. Net plan of the grid section of SG6M22.

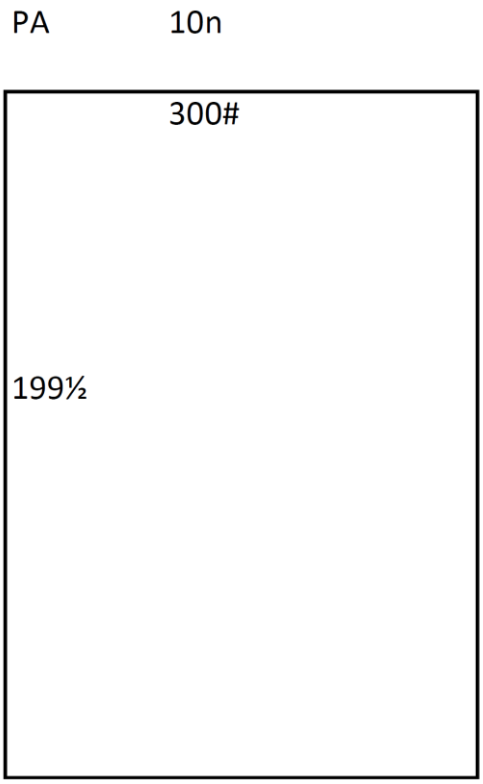

Figure A4. Net plan of both the 22 and 26 mm diamond mesh codends.

Size selection models

The basic size selection models used in the present study are presented below (Wileman *et al*.,1996).

The Logistic (*Logit*) size selection curve is the cumulative distribution function of a logistic random variable:

$$Logit(l) = \frac{\exp(a + bl)}{1 + \exp(a + bl)}$$

Where *a* and *b* are the parameters of the model. $Logit(l)$ quantifies the length-dependent retention probability with *l* being the length of the fish or shrimp. The above equation can be rewritten in terms of the parameters *L50* and *SR*, where:

$$L50 = -\,{}^{a}\!/_{b}\ ,\quad \mathrm{SR} = \frac{2 \times \ln(3)}{b} = \frac{\ln(9)}{b}$$

Leading to:

$$Logit(l, L50, SR) = \left(\frac{exp\left(\frac{\ln(9)}{SR} \times (l - L50)\right)}{1 + exp\left(\frac{\ln(9)}{SR} \times (l - L50)\right)} \right)$$

The *Probit* size selection curve (Normal probability ogive) is the cumulative distribution of a normal random variable,

$$Probit(l) = \Phi(a + bl)$$

Where Φ is the cumulative distribution function of a standard normal random variable, and *a* and *b* are the parameters of the model. The *Probit* can be rewritten in terms of parameters *L50* and *SR*, where:

$$L50 = -\,{}^{a}\!/_{b}\ ,\quad \mathrm{SR} = \frac{2 \times Probit(0.75 - 0.25)}{b} \approx \frac{1.349}{b}$$

Leading to:

$$Probit(l, L50, SR) \approx \left(\frac{exp\left(\frac{1.349}{SR}(l - L50)\right)}{1 + exp\left(\frac{1.349}{SR}(l - L50)\right)} \right)$$

The *Gompertz* size selection curve is expressed by the following equation:

$$Gompertz(l) = \exp(-\exp(-(a + bl)))$$

It can be rewritten in terms of the parameters *L50* and *SR*, where:

$$L50 = \frac{-\ln(-ln(0.5)) - a}{b} \approx \frac{0.3665 - a}{b} \quad , \quad \mathrm{SR} = \frac{\ln\left(\frac{\ln(0.25)}{\ln(0.75)}\right)}{b} \approx \frac{1.573}{b}$$

Leading to:

$$Gompertz(l, L50, SR) \approx \exp\left(-\exp\left(-\left(0.3665 + \frac{1.573}{SR}(l - L50)\right)\right)\right)$$

The last of the four basic size selection curves considered here is the *Richard* curve, which has an extra parameter, named *1/*δ. This parameter controls the degree of asymmetry of the curve. When δ = 1 the curve is identical to the *Logit* curve. The equation for a Richard size selection curve is the following:

$$Richard(l, \delta) = \left(\frac{\exp(a + bl)}{1 + \exp(a + bl)}\right)^{1/\delta}$$

Rewritten in terms of the parameters *L50* and *SR* with:

$$L50 = \frac{Logit(0.5^{\delta}) - a}{b}$$

$$\mathrm{SR} = \frac{Logit(0.75^{\delta}) - Logit(0.25^{\delta})}{b}$$

Leading to:

$$Richard(l, L50, SR, \delta) = \left(\frac{exp\left(Logit(0.5^{\delta}) + \left(\frac{Logit(0.75^{\delta}) - Logit(0.25^{\delta})}{SR}\right)(l - L50\right)}{1 + exp\left(Logit(0.5^{\delta}) + \left(\frac{Logit(0.75^{\delta}) - Logit(0.25^{\delta})}{SR}\right)(l - L50\right)} \right)^{1/\delta}$$

Combining grid and codend size selection processes

Since the test gear was constructed with two selection devices placed sequentially after each other, where shrimp first would have the chance of getting size selected by the grid process ($r_{grid}(l)$) and shrimp that were not selected out in the grid process would be subsequently size selected by the codend meshes ($r_{codend}(l)$). To be able to account for this dual and sequential nature of the size selection in the test gear we modelled the size selection in the test gear by:

$$r(l, \boldsymbol{v}) = r_{grid}(l, \boldsymbol{v}_{grid}) \times r_{codend}(l, \boldsymbol{v}_{codend}).$$

Therefore, four different models were considered to describe the size selection process ($r_{codend}(l, \boldsymbol{v}_{codend})$) in the codend (Wileman *et al.*, 1996):

$$r_{codend}(l, \boldsymbol{v}_{codend}) = \begin{cases} logit(l, L50_{codend}, SR_{codend}) \\ probit(l, L50_{codend}, SR_{codend}) \\ gompertz(l, L50_{codend}, SR_{codend}) \\ richard(l, L50_{codend}, SR_{codend}, 1/\delta_{codend}) \end{cases}$$

The first three models have two parameters $L50_{codend}$ and SR_{codend}, whereas the last model have one additional parameter, $1/\delta_{codend}$ that enables an s-shaped curve with asymmetry (Wileman *et al.*, 1996).

For the grid process $r_{grid}(l, \boldsymbol{v}_{grid})$, besides considering the same s-shaped models as for the codend, we also considered the potential situation that only a fraction C of the shrimp will make contact with the grid to be size selected by it. Further, we considered the situation that none of the shrimp did contact the grid. Based on these considerations, we ended considering a total of nine different models for the grid process:

$$r_{grid}(l, \boldsymbol{v}_{grid}) = \begin{cases} logit(l, L50_{grid}, SR_{grid}) \\ probit(l, L50_{grid}, SR_{grid}) \\ gompertz(l, L50_{grid}, SR_{grid}) \\ richard(l, L50_{grid}, SR_{grid}, 1/\delta_{grid}) \\ clogit(l, C_{grid}, L50_{grid}, SR_{grid}) = 1.0 - C_{grid} + C_{grid} \times logit(l, L50_{grid}, SR_{grid}) \\ cprobit(l, C_{grid}, L50_{grid}, SR_{grid}) = 1.0 - C_{grid} + C_{grid} \times probit(l, L50_{grid}, SR_{grid}) \\ cgompertz(l, C_{grid}, L50_{grid}, SR_{grid}) = 1.0 - C_{grid} + C_{grid} \times gompertz(l, L50_{grid}, SR_{grid}) \\ crichard(l, L50_{grid}, SR_{grid}, 1/\delta_{grid}) = 1.0 - C_{grid} + C_{grid} \times richard(l, L50_{grid}, SR_{grid}, 1/\delta_{grid}) \\ 1.0 \end{cases}$$

The last option $crichard(l, L50_{grid}, SR_{grid}, 1/\delta_{grid})$ takes into consideration that the grid might not contribute at all to the size selection process in the test gear. Further, it enables modelling the combined selection process according to the combine sequential size selection processes by a simple s-shaped selection curve. In total, based on the combinations of the potential models for $r_{codend}(l, \boldsymbol{v}_{codend})$ and $r_{grid}(l, \boldsymbol{v}_{grid})$ in $r(l, \boldsymbol{v})$, 36 models were considered to describe the combined size selectivity for SG6M22.