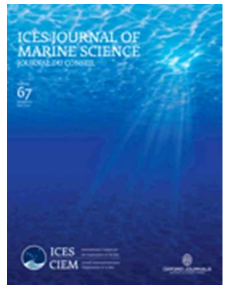

New approach for modelling bell-shaped size selectivity in shrimp trawl fisheries

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New approach for modelling bell-shaped size selectivity in shrimp trawl fisheries

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Abstract

Trawlers targeting shrimps often use a Nordmöre sorting grid ahead of a small mesh codend to avoid bycatch while efficiently catching the target species. However, small fish can pass through the grid and be retained in the codend. This makes the size selection processes in the trawl fishery targeting shrimps complex, and the size-dependent curve for both the shrimp and the bycatch species often exhibits a bell-shaped signature. In this study we developed a new model and a method to estimate this bell-shaped size selection in shrimp fisheries, conducted fishing trials in the Northeast Barents Sea, and applied the new method to quantify the combined size selection of the Nordmöre grid and codend for the deep water shrimp (*Pandalus borealis*) and two bycatch species. The size selectivity for the bycatch showed the expected bell-shaped pattern with low retention probability of very small and larger fish, whereas certain sizes of juveniles had high retention probability. The smallest shrimps were released by the codend, and the Nordmöre grid had high passage probability for all sizes, although it decreased slightly for the largest shrimps.

Keywords: Shrimps; Size selectivity; Nordmöre grid; Bycatch; Trawl fishery.

Introduction

Shrimps are commercially important species, and they are fished all over the world. Although the species and sizes targeted vary, in the majority of shrimp fisheries the selectivity of the gear is based on a grid followed by a size selective codend. This is the case for the deep water shrimp (*Pandalus borealis*) fisheries in the North Atlantic, which have used such selectivity devices since the early 1990s.

Norway was the first country to use sorting grids to avoid bycatch of fish and other marine organisms in shrimp fisheries. The Nordmöre grid, first developed based on a device used to exclude jellyfish, proved to be efficient in excluding bycatch fish species during shrimp trawling (Isaksen et al., 1992). The Nordmöre grid consists of a guiding funnel, a 30–50° sloped grid, and a triangular fish outlet in the upper panel just in front of the grid. It was introduced in the Norwegian shrimp trawl fishery in the Barents Sea in the early 1990s and today is compulsory in several other shrimp fisheries around the world.

All vessels targeting shrimps in Norwegian waters are obliged to use a 19-mm bar spacing Nordmöre grid followed by a codend with a minimum mesh size of 35 mm (Norwegian Directorate of Fisheries, 2011). Thomassen and Ulltang (1975) tested several codend mesh sizes for the northern shrimp fisheries at the end of the 1960s and found that the retention lengths for deep water shrimps were acceptable with the 35-mm mesh size. Despite the many changes (larger gear, larger vessels, faster towing speed, etc.) in the northern shrimp fishery that have occurred since this investigation, the minimum codend mesh size remains at 35 mm. The introduction of the Nordmöre grid eliminated the issue of bycatch of larger sizes of fish because they would not be able to pass through the grid into the trawl codend (Grimaldo and Larsen, 2005; Grimaldo, 2006). However, small-sized fish such as juveniles of various species are still able to pass through the grid and enter the codend together with the targeted shrimps (He and Balzano, 2007, 2013).

Thus, several decades after the introduction of the Nordmöre grid in the shrimp fishery, concerns remain regarding the bycatch risk to juvenile fish. The current regulations of the Northeast Atlantic shrimp fishery allow retention of low numbers of juvenile fish from regulated species. For example, the fishing areas are closed if 10-kg samples of shrimps exceed 8 cod (*Gadus morhua*) or 20 haddock (*Melanogrammus aeglefinus*), 3 redfish (*Sebastes* spp.), and 3 Greenland halibut (*Reinhardtius hippoglossoides*). Additionally, shrimp catches can contain no more than 10% by weight of undersized shrimps (i.e. < 15 mm carapace length) (Norwegian Directorate of Fisheries, 2011). These rather strict bycatch rules have led to frequent closures and openings of several large shrimp fishing grounds in the Northeast Atlantic over the years. The closures can last for weeks or months and cause huge operational problems and increased costs for the fishing fleet (i.e., the distances between potential fishing grounds become greater with increased area closures). Bycatches of juvenile fish and undersized shrimps also cause practical problems when sorting the catch onboard the fishing vessels.

The use of a Nordmöre sorting grid ahead of a small mesh codend makes the size selection processes in the trawl fishery targeting shrimps complex, and the size-dependent curve for both the shrimp and the bycatch species often exhibits a bell-shaped signature. However, a selection model that can properly describe and estimate these bell-shaped signature curves is not available, which implies a challenge to assess size selectivity in trawl fisheries targeting shrimps.

Considering the challenges described above, the aim of the current study was to:

- Develop a new model and a method to estimate bell-shaped size selection in shrimp fisheries using a Nordmöre grid followed by a small mesh size selective codend.

- Quantify in detail the size selection of juveniles of some of the most important fish species frequently caught in the North Atlantic deep water shrimp fishery.
- Quantify the size selectivity for the targeted deep water shrimp of the mandatory selection system consisting of a 19-mm bar spacing Nordmöre grid followed by a 35-mm mesh size diamond mesh codend.

Materials and Methods

Research vessel, study area, and experimental design

The fishing trials were conducted using a selection system composed of a Nordmöre grid followed by a size selective codend. The bar spacing in the Nordmöre grid was measured with a caliper to be 18.8 ± 0.4 mm (mean ± SD) following the procedure described in Wileman et al. (1996). The meshes in the codend were measured to be 33.8 ± 1 mm (mean ± SD) using an ICES gauge following the same procedure.

In order to independently assess the contribution of the grid and the codend to the overall selectivity of the gear, the shrimps and fish released by the grid and the codend could be collected separately using two independent covers: one over the opening of the grid and the other one over the codend. Such double cover setups have been used previously to collect selectivity data in fish fishery studies (e.g., Sistiaga et al., 2010). However, the meshes in a shrimp codend are already small, which increases the risk that the cover with even smaller mesh size will affect the selectivity in the codend. This is mainly related to the substantial reduction in water flow created by the small meshes that would have to be used over a shrimp codend and to the risk of a masking effect. In addition, using two covers makes the whole gear setup more complicated (e.g., the covers can become entangled). Therefore, we used two different experimental setups during the sea trials. In the test haul setup, we fished with a Nordmöre grid followed by a selective codend. In those hauls a small-meshed cover (mesh size 16.4 ± 0.5 mm (mean ± SD)) collected fish and shrimps escaping from the opening in front of the Nordmöre grid and no cover was used over the codend (Fig. 1). In the control haul setup, the codend contained a small-meshed inner net (mesh size 18.5 ± 0.9 mm (mean ± SD)) installed with a low hanging ratio to prevent fish and shrimps from escaping through the codend. In this setup, the fish and shrimps that escaped in front of the Nordmöre grid were collected in a small-meshed cover (mesh size 18.9 ± 1.2 mm (mean ± SD)) (Fig. 1). Test and control hauls were conducted in the same fishing area during the same cruise.

The catch data from these groups of hauls were applied together to estimate the size selectivity for deep water shrimps and for the investigated bycatch species for the combined size selection system consisting of a Nordmöre grid and a size selective codend. For test hauls, the catch was collected in the test grid cover (GT) and in the test codend (CT), whereas for control hauls, the catch was collected in the control grid cover (GC) and in the blinded codend (CC). For each haul, the catches in the compartments GT and CT for test hauls and GC and CC for control hauls were sorted by species, length measured, and sorted into 1-cm wide length groups for fish and 1-mm wide length groups for shrimps. Thus, the catch data consisted of count numbers (*n*) representing the number of individuals of the different species collected in each of the compartments. The total length of the fish was measured using a measuring board, and the carapace length of the shrimps was measured using a caliper.

FIG. 1

The fishing trials were performed on board the research trawler (R/V) "Helmer Hanssen" (63.8 m LOA and 4080 HP) from 16 to 28 February, 2016. The fishing grounds chosen for the tests were located in the north of the Barents Sea (i.e. the Central bank, east of Hopen Island). The fishing trials were carried out using two identical Campelen 1800# trawls built entirely of 80–40 mm meshes in the wings and belly (2 mm polyethylene (PE) twine). Two trawls were used so that during the fishing operation test and control hauls could be efficiently and easily alternated. Thyboron T2 ($6.5m^2$ and 2200 kg) trawl doors were used, and an 8-m long rope was linked between the warps 80 m in front of the doors, which kept the distance between the doors at 48–52 m during the tows. The Campelen trawl has a 19.2 m fishing line and is believed to work at its optimal wingspread (ca. 15 m) and height (ca. 6.5 m) when the door distance is kept in this range. We used 40 m double sweeps and a 19.2 m long rockhopper gear built of three sections with 46 cm rubber discs.

Both trawls were equipped with 4-panel Nordmöre grid sections that are equivalent in dimensions and construction to the 2-panel standard Nordmöre grid section used by the Norwegian coastal fleet targeting shrimp. The Nordmöre grid in such a section is made of stainless steel and is 1510 mm high and 1330 mm wide. The grid in both sections used was mounted so that it would maintain an angle of 45 ± 2.5° while fishing.

Model for size selection

The size selection system consists of two main parts:

i) The first part is a Nordmöre grid, which the fish and shrimps must pass through to enter the codend. If they do not pass through this grid they are released during this first part of the selection process. To pass through the grid, two conditions need to be fulfilled: a) they need to contact the grid and b) morphologically they must be able to pass through the grid, which is dependent on their size and orientation when they come in contact with the grid.

ii) The second part is a codend that collects the fish and shrimps that pass through the grid. The codend is also size selective, and its size selection is the second part of the combined selection process.

Thus, for a fish or deep water shrimp to be retained in the codend ($r_{combined}(l)$), it must be retained by the first process ($r_{grid}(l)$), meaning passing through the grid, and also by the second process ($r_{codend}(l)$), meaning being held in the codend. Therefore, the combined size selection of the process can be modeled by:

$$r_{combined}(l) = r_{grid}(l) \times r_{codend}(l) \quad (1)$$

where l denotes the length of the fish or the length of the shrimp carapace. This system can be defined as a sequential dual selection system. It is a dual system because it consists of two processes and it is sequential because the second process follows the first.

The next step is to model each of the two size selection processes individually. For the first process, we need to consider that some fish or shrimps might not contact (see Larsen et al., 2016 for the explanation of contact in this context) the Nordmöre grid at all or that they might do so with such a poor orientation that they have no length-dependent chance of passing though the grid. This is modeled by the length-independent parameter C_{grid}. C_{grid} has a value in the range 0.0 to1.0, where 1.0 means that every individual of the species contacts the grid in a way that gives it a length-dependent chance of passing through the grid. For an individual contacting the grid with sufficiently good orientation to give it a length-dependent chance of passing through grid ($rcontact_{grid}(l)$), the following logit model was used:

$$rcontact_{grid}(l, L50_{grid}, SR_{grid}) = 1.0 - logit(l, L50_{grid}, SR_{grid}) \quad (2)$$

Model (2) considers that the probability of being able to pass through the grid is length dependent and will decrease for larger individuals. $L50_{grid}$ denotes the length of fish or shrimp with 50% probability of being retained, and SR_{grid} (selection range) describes the difference in length between fish or shrimp with 75% and 25% probability of being retained, respectively.

Based on the above, the following model was used for the size selection in the first process ($r_1(l)$):

$$r_{grid}(l, C_{grid}, L50_{grid}, SR_{grid}) = C_{grid} \times \left(1.0 - logit(l, L50_{grid}, SR_{grid})\right) \quad (3)$$

The escape probability through the outlet in front of the Nordmöre grid was therefore modeled by:

$$e_{grid}(l, C_{grid}, L50_{grid}, SR_{grid}) = 1.0 - r_{grid}(l, C_{grid}, L50_{grid}, SR_{grid}) = 1.0 - C_{grid} + C_{grid} \times logit(l, L50_{grid}, SR_{grid}) \qquad (4)$$

For the second process (i.e., codend size selection), we assumed that the retention probability can be modeled by a logit model (see Wileman et al. 1996 for further information about the logit model):

$$r_{codend}(l, L50_{codend}, SR_{codend}) = logit(l, L50_{codend}, SR_{codend}) \qquad (5)$$

Thus, by inserting (3) and (5) into (1) we arrived at the following combined size selection model:

$$r_{combined}(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}) = C_{grid} \times \left(1.0 - logit(l, L50_{grid}, SR_{grid})\right) \times logit(l, L50_{codend}, SR_{codend}) \qquad (6)$$

Model (6) is a so-called structural model because it is based on modeling the individual processes expected to be involved in the combined size selection in the system. One advantage of applying a structural model compared to an empirical-based model is that once the values of the parameters in the model are estimated, they can be applied to investigate not only the combined processes in the system but also the individual processes. In this context, each of the model parameter values obtained can be directly interpreted.

In the case of model (6), five parameters need to be estimated to be able to describe the size selection in the system: C_{grid}, $L50_{grid}$, SR_{grid}, $L50_{codend,}$ and SR_{codend}. C_{grid} loosely models the contact probability with the grid for modes of orientation that result in a length-dependent probability for an individual to pass through the grid. If all individuals contact the grid with a reasonable mode of contact, then the value for C_{grid} should be 1.0. However, this is not necessarily the case, as some individuals may escape through the escape outlet in front of the Nordmöre grid (Fig. 1) without contacting the grid first. Other individuals may be so poorly orientated when they meet the grid that the probability of them passing through will be similar to those not contacting the grid, which will also be reflected in the value of C_{grid}. Thus, $L50_{grid}$ and SR_{grid} are respectively the L50 and SR values for individuals contacting the grid with a reasonable mode of orientation. $L50_{codend}$ and SR_{codend} are the L50 and SR values for the codend selection (Fig. 1). As different species have different morphology and behavior, values of the parameters C_{grid}, $L50_{grid}$, SR_{grid}, $L50_{codend}$, and SR_{codend} for the same combined system will be species specific. Therefore, the analysis was applied separately for the different fish species and for the deep water shrimps.

Data analysis and parameter estimation

Catch data were collected in two groups. One of the groups consisted of control hauls obtained by summing compartments GC and CC (Fig. 1). Together, they sampled the size and species composition of fish entering the selective parts of the trawl (Nordmöre grid and codend), and in this respect the control hauls can be paired with the test hauls so that a paired-gear estimation method can be used (Wileman et al., 1996). However, compared to the standard paired-gear method in which none of the selective parts of the system uses covers to collect fish or shrimps escapees, our test hauls are special because they use a cover (GT) to collect fish and shrimps escaping ahead of the Nordmöre grid. Therefore, our experimental data collection design represents a combination of the paired and covered data collection and estimation methods (Wileman et al., 1996).

To estimate the average size selection of the test setup with pooled data, we paired them with the pooled control hauls. Based on this approach, the experimental data in the analysis were treated like three compartment data. Fish or shrimp caught were observed in GT, GC, or (GC + CC). For the estimation based on the size selection model established in section 2.2, we needed to express the probabilities that fish or shrimps of a specific length l would be observed in each of these three compartments conditioned they were caught. The probability that the fish or shrimps would enter the selection section in one of the test hauls and in one of the control hauls was modeled by the split factor, SP, as is traditionally done for paired-gear data analysis (Wileman et al., 1996). This means that the probability that a fish or shrimp will enter the test haul is SP, whereas the probability of them entering the control haul is $1.0 - SP$. All fish or shrimps entering the control haul are retained because both the cover over the grid outlet and the blinded codend retain all potential escapees. For a fish or shrimp entering one of the hauls included in the analysis (test or control), the probability that it will be retained in the cover in front of the Nordmöre grid in one of the test hauls would, based on equation (4), be $SP \times e_{grid}(l, C_{grid}, L50_{grid}, SR_{grid})$. For a fish or shrimp entering one of the hauls included in the analysis, the probability that it will be retained in the codend of a test haul would, based on equation (6), be

$SP \times r_{combined}(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend})$. Considering this, the probability γ that a fish or shrimp entering one of the test or control hauls will be observed in one of the three compartments (GT, GC, or GC+CC) can be expressed as:

$$\gamma(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}, SP) =$$
$$SP \times e_{grid}(l, C_{grid}, L50_{grid}, SR_{grid}) +$$
$$SP \times r_{combined}(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}) + 1.0 - SP \qquad (7)$$

Based on equation (7) and the considerations above, the probabilities p_{GT}, p_{CT}, and p_{GC+CC} that a fish or shrimp observed in the catch will be found in compartment GT, CT, or GC+CC, respectively, can be expressed by:

$$p_{GT}(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}, SP) = \frac{SP \times e_{grid}(l, C_{grid}, L50_{grid}, SR_{grid})}{\gamma(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}, SP)}$$

$$p_{CT}(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}, SP) = \frac{SP \times r_{combined}(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend})}{\gamma(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}, SP)}$$

$$p_{GC+CC}(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}, SP) = \frac{1.0 - SP}{\gamma(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}, SP)}$$

(8)

By using equation (8), the values for the parameters in the selection model (6) can be estimated from the collected experimental data by minimizing the following function with respect to $C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}$, and SP:

$$-\sum_l \left\{ \sum_{i=1}^{a} \left[\frac{nGT_{li}}{qGT_i} \times ln\left(p_{GT}(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}, SP)\right) \right] + \sum_{i=1}^{a} \left[\frac{nCT_{li}}{qCT_i} \times ln\left(p_{CT}(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}, SP)\right) \right] + \sum_{j=1}^{b} \left[\left(\frac{nGC_{lj}}{qGC_j} + \frac{nCC_{lj}}{qCC_j} \right) \times ln\left(p_{GC+CC}(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}, SP)\right) \right] \right\} \quad (9)$$

where the outer summation is over length classes *l* in the experimental data and the inner summation is over experimental fishing hauls *i* (from *1* to *a*) and *j* (from *1* to *b*) with, respectively, the test and control setup. nGT_{li}, nCT_{li}, nGC_{lj}, and $nCC_{lj}$are the number of fish or shrimps length measured of length class *l* in haul *i* and *j* in the respective compartment, with qGT_i, qCT_i, qGC_j, and qCC_j being the corresponding sampling factors (i.e., the fraction of the catch that was length measured). Minimizing (9) with respect to the parameters in it is the same as maximizing the likelihood for the observed experimental data, assuming that the formulated model (8) describes the experimental data sufficiently well. The observed experimental data sharing rates among the three compartments of the data, which model (8) is expected to describe, are given by:

$$p_{GT_l} = \frac{\frac{nGT_l}{qGT}}{\frac{nGT_l}{qGT}+\frac{nCT_l}{qCT}+\frac{nGC_l}{qGC}+\frac{nCC_l}{qCC}}$$
$$p_{CT_l} = \frac{\frac{nCT_l}{qCT}}{\frac{nGT_l}{qGT}+\frac{nCT_l}{qCT}+\frac{nGC_l}{qGC}+\frac{nCC_l}{qCC}} \quad (10)$$
$$p_{GC+CC_l} = \frac{\frac{nGC_l}{qGC}+\frac{nCC_l}{qCC}}{\frac{nGT_l}{qGT}+\frac{nCT_l}{qCT}+\frac{nGC_l}{qGC}+\frac{nCC_l}{qCC}}$$

Due to the experimental procedure followed, there was no obvious way to pair the data from the individual test and control hauls. Hence, to estimate the mean selectivity parameters for the experimental gear, the raised length frequency data of the corresponding test hauls were combined and compared with the combined data from the control hauls as formulated in function (9). The confidence limits for the parameters and curves for the size selection model were estimated using a double bootstrapping method that accounts for the uncertainty resulting from this unpaired nature of the data collection. For this, we adopted and further generalized the method for estimating uncertainty in size selectivity based on unpaired trawl data described by Sistiaga et al. (2016). This procedure accounts for between-haul variation (Fryer, 1991) by selecting *a* hauls with replacement from the test hauls and *b* hauls with replacement from the control hauls during each bootstrap loop. Within-haul variability is accounted for by randomly selecting fish with replacement from each of the selected hauls for each compartment separately, where the number selected from each compartment in each haul is the same as the number sampled in that compartment in that haul. These data are then raised and combined as described above, and the selectivity parameters are again estimated. The additional uncertainty in the estimation caused by subsampling is automatically accounted for by raising the data after the re-sampling (Eigaard et al., 2012). We performed 1000 bootstrap repetitions to calculate the Efron 95% confidence limits (Efron, 1982; Chernick, 2007) for the selection parameters.

The model’s ability to describe the experimental data sufficiently well was evaluated based on the p-value, model deviance versus degrees of freedom (DOF), inspection of how the model curve reflects the length-based trend in the data, and inspection of residual plots for model deviation (Wileman et al., 1996). The analysis was carried out using the software SELNET (Herrmann et al., 2012, 2013ab), which implements the models and the bootstrap method described above.

Results

Collected data

We conducted 16 hauls during the trial, including 8 test hauls (Table 1) and 8 control hauls (Table 2). The number of shrimps length measured during the cruise was of 4405 individuals. Of the fish bycatch species, we measured 8773 American plaice (*Hippoglossoides platessoides*) and 4439 redfish (*Sebastes* spp.).

TABLE 1

TABLE 2

Size selectivity for shrimps

The model used reflected the pattern observed in the experimental data well (Fig. 2). Thus, although the p-value observed in the fit statistics was low, we are confident that the model used represents the data adequately. All shrimps were estimated to make contact with the Nordmöre grid, and most of them passed through it. However, the grid passage probability was estimated to decrease slightly with increasing shrimp size. The codend selectivity showed size-dependent release for shrimps with carapace length < 23 mm, with only about 20% of the shrimps with carapace length of 15 mm being retained by the codend. $L50_{codend}$ was estimated to be 17.72 mm, and SR_{codend} was estimated to be 3.63 mm (Table 3). $L50_{grid}$ was 49.2 mm, which at first glance could seem meaningless because it is above the size range for this species of shrimp (Table 3). However, this value is expected to be above a biologically meaningful value and confirms that most of the shrimps can pass through the grid except for the slight decrease for large shrimps. The combined selectivity for the grid and codend exhibited a slightly bell-shaped signature, with few shrimps < 15 mm being retained, a maximum retention rate for shrimps with carapace length of 25 mm, and a slight decrease for shrimps above this size.

FIG. 2

TABLE 3

Size selectivity for American plaice

The model used reflected the pattern observed in the experimental data well (Fig. 3). Despite the p-value being < 0.05, the model used represents the data adequately and therefore we are confident about the performance of the model. All American plaice were estimated to make contact with the Nordmöre grid, and most of them passed through it. The grid passage probability was very high for American plaice up to 12 cm long, followed by a monotonous decrease and then very low passage probability for fish > 30 cm long. The codend only showed low size selectivity for American plaice with an $L50_{codend}$ value of 6.84 cm, thus all American plaice > 10 cm long that entered the codend were retained in it (Table 3). The combined selectivity for the grid and codend showed a clear bell-shaped signature, with a high retention probability for American place ~10 cm long (ca. 90% retention). Retention of individuals < 5 cm long was practically 0 and retention of fish in the range of 10 to 30 cm decreased, with really low retention rates for fish > 30 cm long. In the range of 6 to 23 cm, retention probability for American plaice for the gear was > 25%, meaning that this gear would not be adequate in areas where the numbers of American plaice within this range are high.

FIG. 3

Size selectivity for redfish

For redfish, the model used represented the experimental data well up to l = 22 cm (Fig. 4). Because fish above this size are outside the selective range of the gear, the model adequately describes the size selection process in the gear. This upper limit is regarded as a consequence of unequal entry of bigger redfish into the test and control gears. The combined size selection showed a clear bell-shaped signature, with > 60% of redfish around 12 cm long being retained by the gear but < 25% of redfish < 9 cm and > 15 cm long being retained. The grid passage probability was high (> 80%) for redfish < 12 cm long, and it decreased monotonously, with no redfish > 20 cm entering the codend. The codend size selection showed that none of the redfish > 14 cm would be released by the codend and that $L50_2$ and SR_2 were 9.8 cm and 1.7 cm, respectively (Table 3).

FIG. 4

Discussion

The bell-shaped size selection data resulting from the grid and codend configuration used in this study were based on a new model and estimation method that is an extension of the unpaired method described in Sistiaga et al. (2016). This new approach models the observed data summed over hauls for a group of test and controls hauls, and it combines a structural dual sequenced size selection model with unpaired data collection for groups of test and control hauls. This model effectively described the length-dependent sharing of the observed catch between the test codend, the test grid cover, and the control gear for all species investigated. In addition to enabling estimation of the combined size selection for the Nordmöre grid followed by the diamond mesh codend, this method enabled estimation of the size selection for each of the selection devices individually because the structural model explicitly described the selectivity processes in each of the devices. Structural size selection models have previously been developed and applied to describe size selection in other trawl fisheries. This includes models for fish sorting grids in combination with codends in finfish fisheries (Sistiaga et al., 2010; Herrmann et al., 2013a), square mesh panels in combination with selective codends (Zuur et al., 2001; O'Neill et al., 2006; Alzorriz et al., 2016), double grid sorting devices (Larsen et al., 2016: Sistiaga et al., 2016), and excluding grids combined with a selective codend (Brčić et al., 2015; Stepputtis et al., 2015; Lövgren et al., 2016). Excluding grids combined with a selective codend result in the same bell-shaped selection pattern as the Nordmöre grid followed by a size selective codend. However, our study is the first time such a modelling process has been applied to a shrimp trawl fishery and the first time that a sequential model with two compartment data collection in test and control gears have been used. Our method is more complex than the methods previously applied, but it is necessary due to the practical problems that would have resulted from using a small mesh cover over the test codend.

The new method and model presented herein offer new possibilities for studying size selectivity in other shrimp fisheries. In particular, our approach enables detailed mapping of which sizes of bycatch species would have especially high risk of being caught if they are abundant in the shrimp fishing grounds.

In this study, we demonstrated the ability of the new model to represent bell-shaped selectivity data in detail for shrimp and two fish bycatch species: American plaice and redfish. For the juvenile bycatch species, our results demonstrated very high and length-dependent grid passage probability. Thus, in conjunction with the small-meshed diamond mesh codend used in the shrimp fishery, the gear has high catch risk for certain size ranges of these bycatch species. The use of the combined bycatch reducing and size selective system consisting of the Nordmöre grid and 35 mm codend mesh is well established in the Northeast Atlantic shrimp fishery. However, the data from our study clearly show that fish within a limited size range and undersized shrimps retained in the 35-mm codend will continue to be a problem for the northern shrimp fleet. If fish bycatch reduction and size selectivity of shrimp are to be improved, the next research goal should be to address the mesh selection process in front of or aft of the Nordmöre grid section, including the codend. On board the fishing vessels, crew members seek simple and practical solutions to improve species separation in order to reduce production (i.e., cleaning and grading the shrimp catches). From this point of view, sorting devices based on flexible mesh panels are preferred.

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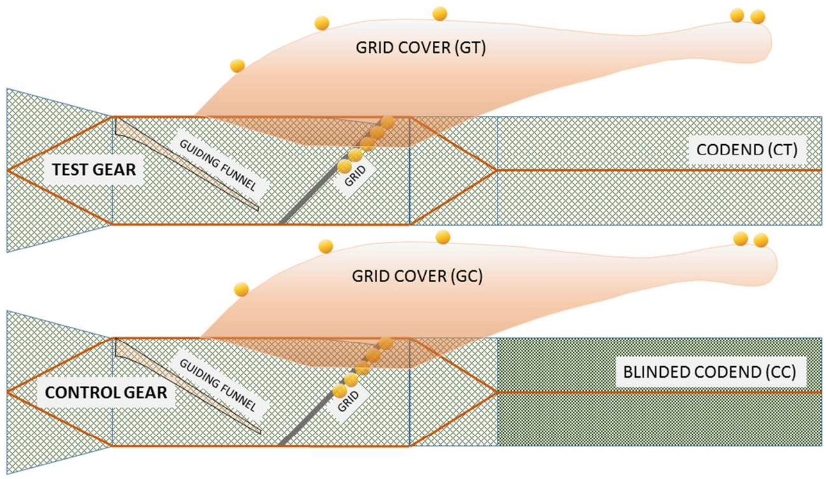

Fig. 1: Experimental design: with separate group of hauls with test gear (top) and control gear (bottom).

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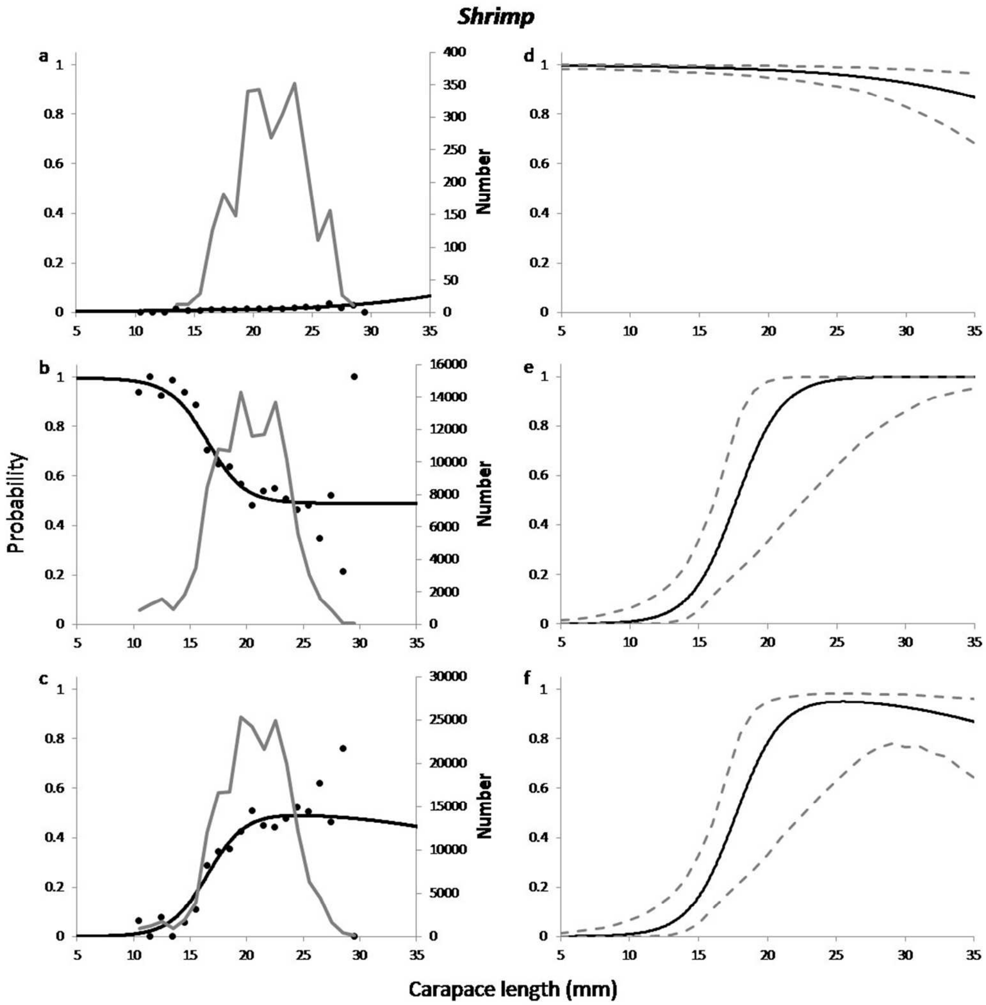

Fig. 2: Size selectivity plots for shrimps. The left column shows the fit of the selection model (8) to the experimental catch sharing rates (10). Plot "a" shows the length dependent share of shrimps found in the grid cover of the test gear, plot "b" shows the length dependent length of shrimps found in the control gear, and plot "c" shows the length dependent share of shrimps observed in the codend of the test gear. The plots in the right column show the selectivity curves for the test gear with plot "d" showing the length dependent grid passage probability (4), plot "e" showing the length dependent codend selectivity in the test gear (5), and plot "f" showing the combined size selectivity of the Nordmöre grid and the codend for the test gear (6).

305x308mm (96 x 96 DPI)

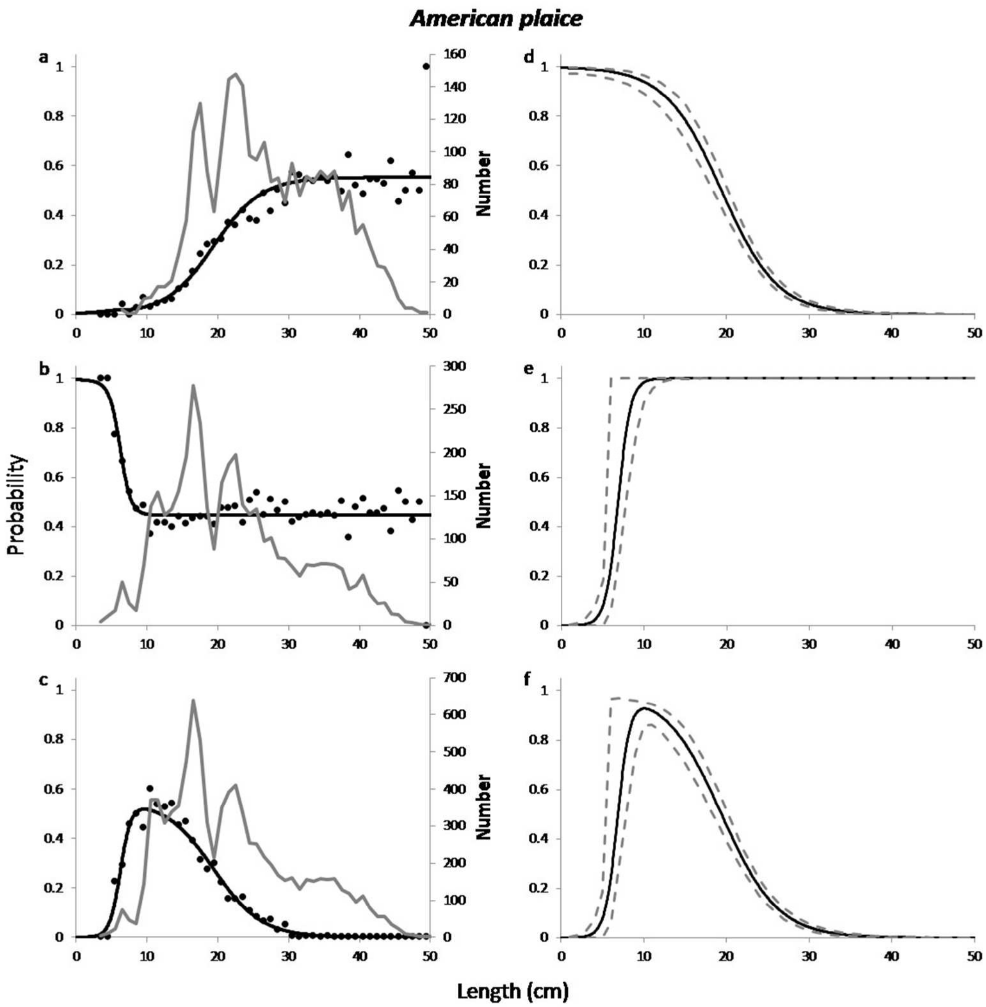

Fig. 3: Size selectivity plots for American plaice. The left column shows the fit of the selection model (8) to the experimental catch sharing rates (10). Plot "a" shows the length dependent share of American plaice found in the grid cover of the test gear, plot "b" shows the length dependent length of American plaice found in the control gear, and plot "c" shows the length dependent share of American plaice observed in the codend of the test gear. The plots in the right column show the selectivity curves for the test gear with plot "d" showing the length dependent grid passage probability (4), plot "e" showing the length dependent codend selectivity in the test gear (5), and plot "f" showing the combined size selectivity of the Nordmöre grid and the codend for the test gear (6).

305x308mm (96 x 96 DPI)

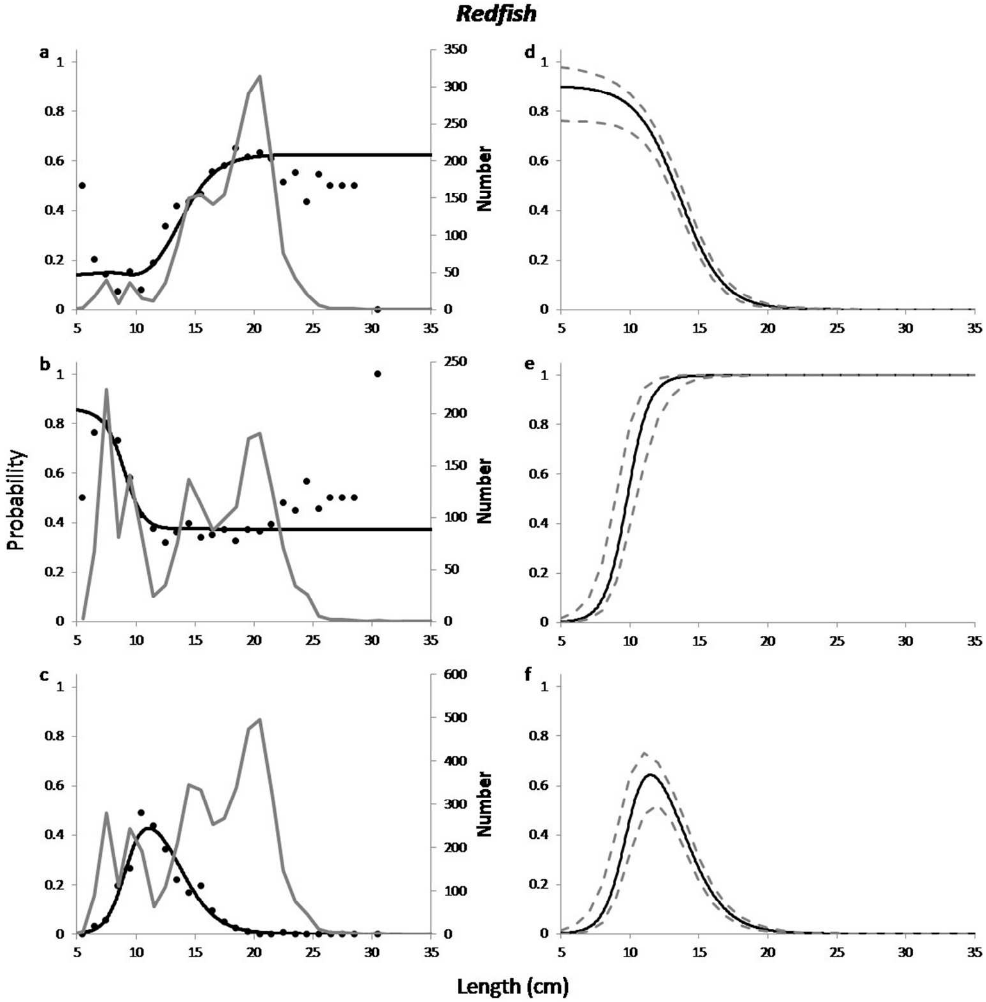

Fig. 4: Size selectivity plots for redfish. The left column shows the fit of the selection model (8) to the experimental catch sharing rates (10). Plot "a" shows the length dependent share of redfish found in the grid cover of the test gear, plot "b" shows the length dependent length of redfish found in the control gear, and plot "c" shows the length dependent share of redfish observed in the codend of the test gear. The plots in the right column show the selectivity curves for the test gear with plot "d" showing the length dependent grid passage probability (4), plot "e" showing the length dependent codend selectivity in the test gear (5), and plot "f" showing the combined size selectivity of the Nordmöre grid and the codend for the test gear (6).

305x308mm (96 x 96 DPI)

TABLES

Table 1: Overview of the fish and shrimp length measured in the test hauls carried out during the trials. The values in brackets represent the sampling factors. For the fish species there was no subsampling.

Haul Nr	Trawling time (min)	Depth (m)	*Shrimp*		*American Plaice*		*Redfish*		*Cod*		*Haddock*	
			GT (% measured)	CT (% measured)	GT	CT	GT	CT	GT	CT	GT	CT
9	60	268	150 (63.13%)	150 (1.34%)	391	283	211	42	38	14	19	18
10	62	265	123 (31.72%)	146 (0.94%)	444	347	392	65	46	9	27	54
11	64	268	98 (66.77%)	134 (1.05%)	482	402	494	108	114	22	63	135
12	62	265	7 (100%)	121 (2.10%)	283	309	211	47	29	13	12	23
13	63	274	21 (100%)	141 (1.76%)	239	212	354	91	26	22	23	26
14	60	256	50 (100%)	161 (2.67%)	256	202	98	33	25	7	56	52
15	63	252	75 (80.61%)	146 (1.08%)	230	320	135	82	117	23	40	133
16	66	269	140 (8.18%)	167 (1.78%)	298	120	142	24	38	9	32	10

Table 2: Overview of the fish and shrimp length measured in the control hauls carried out during the trials. The values in brackets represent the sampling factors. For the fish species there was no subsampling.

Haul Nr	Trawling time (min)	Depth (m)	*Shrimp*		*American Plaice*		*Redfish*		*Cod*		*Haddock*	
			GC	CC	GC	CC	GC	CC	GC	CC	GC	CC
1	60	268	123 (72.31%)	160 (1.63%)	208	177	56	36	21	11	13	23
2	61	257	120 (58.14%)	153 (1.95%)	238	182	143	37	17	8	20	10
3	60	278	163 (7.47%)	173 (1.16%)	438	187	404	169	58	9	112	113
4	60	271	108 (9.60%)	171 (1.20%)	265	156	184	86	12	7	36	38
5	63	266	144 (40.54)	160 (1.91%)	321	121	108	20	28	9	22	15
6	61	271	169 (100%)	175 (2.02%)	206	150	68	34	8	12	10	12
7	60	271	208 (22.74)	169 (1.02%)	391	287	187	94	12	12	52	42
8	63	272	189 (21.12)	190 (0.73%)	327	301	164	120	18	12	33	72

Table 3: Size selectivity parameters and fit statistics results for shrimps, American plaice and redfish based on fitting the model (8) to the experimental data. Values in () are 95% confidence limits.

	Shrimps	American Plaice	Redfish
C_{grid}	1.00 (0.98 - 1.00)	1.00 (0.97 - 1.00)	0.90 (0.75 - 0-99)
$L50_{grid}$ (mm)	49.17 (37.16 - 68.57)	19.40 (18.41 - 20.20)	13.61 (13.06 - 14.28)
SR_{grid} (mm)	16.52 (8.02 - 27.82)	7.47 (6.44 - 8.61)	3.46 (2.93 - 3.97)
$L50_{codend}$ (mm)	17.72 - (16.10 - 22.59)	6.84 (5.46 - 7.68)	9.78 (8.85 - 10.45)
SR_{codend} (mm)	3.63 (1.79 - 9.45)	1.66 (0.10 - 2.66)	1.74 (1.33 - 2.60)
SP	0.51 (0.42 - 0.70)	0.55 (0.49 - 0.61)	0.63 (0.51 - 0.74)
DOF	34	90	54
Deviance	175.66	118.38	101.91
p-value	<0.0001	0.0241	0.0001