ARTICLE IN PRESS

Aquaculture and Fisheries xxx (xxxx) xxx

Contents lists available at ScienceDirect

Aquaculture and Fisheries

journal homepage: www.keaipublishing.com/en/journals/aquaculture-and-fisheries

# Comparing the size selectivity of a novel T90 mesh codend to two conventional codends in the northern shrimp (*Pandalus borealis*) trawl fishery

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ARTICLE INFO

*Keywords:*
Size selectivity
Codend usability
*Pandalus borealis*
Diamond-mesh
T45
T90
Iceland
Lastridge rope

ABSTRACT

The size selectivity and usability of three codends were quantified and compared for the first time in the inshore Northern shrimp (*Pandalus borealis*) trawl fishery of Iceland using the covered codend method: a conventional diamond-mesh codend (T0), conventional square-mesh codend (T45), and a 90° turned mesh codend (T90) constructed of four panels and with shortened lastridge ropes. Fishers, wanting to increase the average-individual size of captured shrimp, had requested the T90 codend to be compared with conventional codends for consideration in the fishery. Results showed that, on average, the T45 and T90 codends had better size selectivity than the T0 codend in terms of releasing individuals smaller than 13 mm carapace length (Minimum References Size; MRS). The T90 codend retained significantly less Northern shrimps between 9 and 19 mm than the T0 codend and between 15 and 19 mm than the T45 codend. No significant difference of size selectivity between T45 and T0 codends was observed. All three codends presented high retention ratios of Northern shrimps above MRS (>63%) for the population encountered. However, the T0 codend was not effective at sorting out small Northern shrimps; at least 86% of Northern shrimps smaller than 13 mm were retained in the T0 codend if encountered. Catches from T45 and T90 codends had a lower proportion of shrimp below MRS. Since discarding of undersized Northern shrimps is prohibited in Iceland and fishers wanted to catch on average larger shrimp, using the novel T90 codend would enable fishers to use their quotas more efficiently.

## 1. Introduction

Discards refer to all biomass that is disposed of at sea off a fishing vessel, and bycatch is the capture of non-targeted species whether disposed of or retained (Alverson, Freeberg, Murawski, & Pope, 1994). Globally, shrimp trawling is associated with high amounts of both bycatch and discards due to their use of small-mesh codends to retain small-bodied target species (Alverson et al., 1994; Howell & Langan, 1992). Additionally, small-mesh codends are not selective for the relatively larger bycatch species (Bayse & He, 2017). Thus, shrimp trawling contributes significantly to ecological impacts of wild fish populations in many parts of the world (e.g. Harrington, Myers, & Rosenberg, 2005).

Northern shrimp (*Pandalus borealis*) is a cold-water pink shrimp that is prevalent throughout the North Atlantic Ocean (Dore & Frimodt, 1987). In Iceland, Northern shrimp mainly occur off the north coast of the country and are highly abundant in shallow inshore coastal fjords (Marine and Freshwater Research Institute (MFRI), 2018a, b). The coastal fjord Ísafjarðardjúp had catches decrease from around 3000 t to 1000 t from 1990 to 2002. Thus, the fishery was subsequently closed in this area from 2003 to 2010 due to low biomass. Fishing started again in 2011 with landings peaking at 1000 t, then gradually decreasing to around 400 t in 2017 (MFRI, 2018b). In Iceland, the minimum reference size (MRS) of Northern shrimp is 13 mm carapace length (CL) in the inshore fishery. The MRS functions as a reference length since discarding

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https://doi.org/10.1016/j.aaf.2020.09.005
Received 28 November 2019; Received in revised form 21 August 2020; Accepted 15 September 2020


Please cite this article as: Haraldur Arnar Einarsson, *Aquaculture and Fisheries*, https://doi.org/10.1016/j.aaf.2020.09.005

of small Northern shrimps has been prohibited in Iceland. If more than 30% of Northern shrimp catch (in number) in a designated area is below the MRS, this fishing ground will be closed.

Mechanical sorting devices, such as grids, are commonly used to reduce bycatch when targeting Northern shrimp (e.g. Grimaldo, 2006; He & Balzano, 2007; Larsen, Herrmann, Sistiaga, Brinkhof, & Santos, 2018); however the use of grids is not mandatory in the coastal fjords of Iceland (Mamie, Leone, Valtýsson, & Ármannsson, 2008). When grids are used in these areas, they often clog with seaweed (ICES, 2016). Clogged grids lead to substantial losses of marketable Northern shrimp and were less effective when the catch rate was high (>1 ton/10 min) which can be common in the coastal fjords (ICES, 2016). Conversely, in the offshore fishery there is a reduced concern of clogging and grids are used. Other differences between the inshore and offshore fisheries include vessel size and fishing depth, where the offshore fishery uses larger vessels and fishes deeper water. Thus, in the absence of using a grid, an alternative method to decrease unwanted catch in a Northern shrimp trawl is to improve the size selectivity of the codend by reducing the catch of small shrimp.

Size selectivity of trawls can be improved in many ways, including altering the codend mesh size, twine size, or mesh orientation (Herrmann, Wienbeck, Moderhak, Stepputtis, & Krag, 2013). Codends are traditionally constructed using diamond netting oriented with its normal direction in-line with the direction of towing, otherwise known as the T0 orientation - oriented 0° in the transversal or towing direction. However, this same netting can be installed in such a way that the netting is rotated 45° (T45) or 90° (T90) in the transversal direction. In contrast to T0 meshes that tend to close under tension, T45 and T90 orientations allow the mesh to remain more open and would improve size selectivity (Herrmann, Priour, & Krag, 2007; Madsen, Herrmann, Frandsen, & Krag, 2012). The open meshes increase the opportunity for escape, which has been particularly effective at increasing the size selectivity for some fish species, especially roundfish (e.g., Bayse, Herrmann, Lenoir, Depestele, Polet, & Verschueren 2016; Tokaç et al., 2014; Wienbeck, Herrmann, Feekings, Stepputtis, & Moderhak, 2014).

T45 mesh codends, also known as square-mesh codends, have been shown to improve the selectivity of several shrimp and prawn fisheries by increasing the mean size of captured target species and decreasing bycatch (Broadhurst et al., 2004; Deval, Bök, Ateş, Ulutürk, & Tosunoğlu, 2009; Karlsen & Larsen, 1989; Sala, Lucchetti, Piccinetti, & Ferretti, 2008). For Northern shrimp, however, T45 codends have produced mixed results. Trials in Iceland and Canada reported significant reductions of undersized Northern shrimps, but also loss of market-size individuals (Hickey, Brothers, & Boulos, 1993, p. 41; Thorsteinsson, 1992). Tests in Greenland found no differences in size-selectivity between T0 and T45 codends (Lehmann, Valdemarsen, & Riget, 1993).

In the Icelandic inshore shrimp fishery, it is mandatory to use a T45 codend if the sorting grid is not installed. However, since discarding is not allowed, a codend that could further improve the size selectivity in this fishery by reducing the capture of undersized Northern shrimp should be considered. Therefore, initiated by a request from local fishers, a four-panel T90 codend with shortened lastridge ropes was designed, tested, and compared to conventional shrimp codends. Previous experience in other fisheries shows that a T90 codend could potentially further improve size selectivity (Bayse et al., 2016; Deval, Özgen, & Özbilgin, 2016; Lomeli, Hamel, Wakefield, & Erickson, 2017). Shortened lastridge ropes allow meshes to stay open along the length of the codend, since the axial component of the drag forces acting on the accumulated catch will be transmitted through the lastridge ropes instead of the mesh bars (Isaksen & Valdemarsen, 1990). Therefore, using shortened lastridge ropes with a T90 codend could prevent stretching the meshes, which reduces mesh opening, as drag forces increase on the codend with increased catch and thereby help to keep the T90 meshes more open during the capture process. Shortened lastridge ropes have been effective at improving the size selectivity of groundfish trawls with T0 codends (Brothers & Boulos, 1994; Hickey et al., 1993, p. 41; Isaksen & Valdemarsen, 1990). However, shortened lastridge ropes are untested in shrimp trawls to the best or our knowledge and specifically not in a T90 mesh codend. Applying the shortened lastridge ropes in a T90 codend may further improve the size selectivity of the shrimp fishery.

So far, few studies have investigated how T90 mesh codends affect shrimp size selectivity. Deval et al. (2016) reported that a T90 mesh codend significantly increased size-selectivity for four commercial shrimp species in the Eastern Mediterranean. Santos et al. (2018) compared T0, T45, and T90 codends in a predictive size-selectivity study for brown shrimp (*Crangon crangon*). They found that when mesh sizes were smaller than 25 mm, T90 codends had similar size selectivity properties with T45 codends; however, when mesh sizes were larger than 25 mm T90 codends would have better size-selectivity than T45 codends.

The purpose of this study was to quantify and compare the Northern shrimp size-selectivity of three codends used in the Icelandic Northern shrimp fishery: the conventional T0 codend, conventional T45 codend, and the newly designed T90 codend with shortened lastridge ropes. The goal was to improve the size-selection of this fishery by reducing the capture of small Northern shrimps (<13 mm CL), and quantify and compare the usability of the three codends for the inshore fishery.

## 2. Materials and methods

### 2.1. Sea trials

Two sea trials were carried out on commercial fishing grounds in Ísafjarðardjúp, Iceland (Fig. 1). The first trial was from 28 September to October 9, 2016 on the research vessel Bjarni Sæmundsson RE-30 (length 56 m; width 10.6 m; gross tonnage 822 t; engine power 8800 hp maximum of three engines, but only one engine was used during trawling) using an otter trawl, and the second sea trial was carried out from 6 to November 8, 2017 on the commercial Northern shrimp otter trawler Guðbjörg Sigurðardóttir ÍS-508 (length 26.5 m; width 7.0 m; gross tonnage 273 t; engine power 760 hp maximum). For each haul, tow duration, towing speeds, fishing depth, and temperature were recorded. Fishing was carried out 24 h a day and each trawl was hauled back when the catch weight was estimated using trawl-mounted catch sensors to be between 500 kg and 2000 kg.

### 2.2. Gear specifications

The trawl used for all hauls was a standard Northern shrimp bottom trawl (Model 50–1010) used for Northern shrimp stock assessment in shallow-water or inshore areas of Iceland (Jónsdóttir, Bragason, Brynjólfsson, Guðlaugsdóttir, & Skúladóttir, 2017, p. 92). The trawl had 1010 meshes in circumference with a headline length of 24.3 m. Nominal mesh size in circumference was 50 mm. Even though a survey trawl, it is very similar to commercial trawl designs commonly used to capture Northern shrimp in Iceland inshore fishing grounds. No sorting grid was used during sea trials, which is typical for the inshore fishery in this area. The covered codend method was used to enable estimating codend size selectivity (Wileman, Ferro, Fonteyne, & Millar, 1996). The cover was made of 10 mm knotless netting. Flexible kites were mounted on the cover net to expand the cover and avoid masking the codend (Grimaldo, Larsen, Sistiaga, Madsen, & Breen, 2009). For sea trials, the trawl and rigging of fishing gears were identical, using the exact same warp, doors, and trawl in each trial (gear components were moved from the first vessel to the second); the only change was the codend.

All codends (Fig. 2) were constructed of similar netting (42 mm nominal mesh size measured knot-to-knot, polyethylene material). The T0 and T45 mesh codends were made of single 2.5 mm diameter mesh in a two-panel configuration. The T0 codend was 100 meshes in circumference, and the T45 codend was 100 bars in circumference. The stretched length of the T0 and T45 codends was 12.6 m, and the lastridge

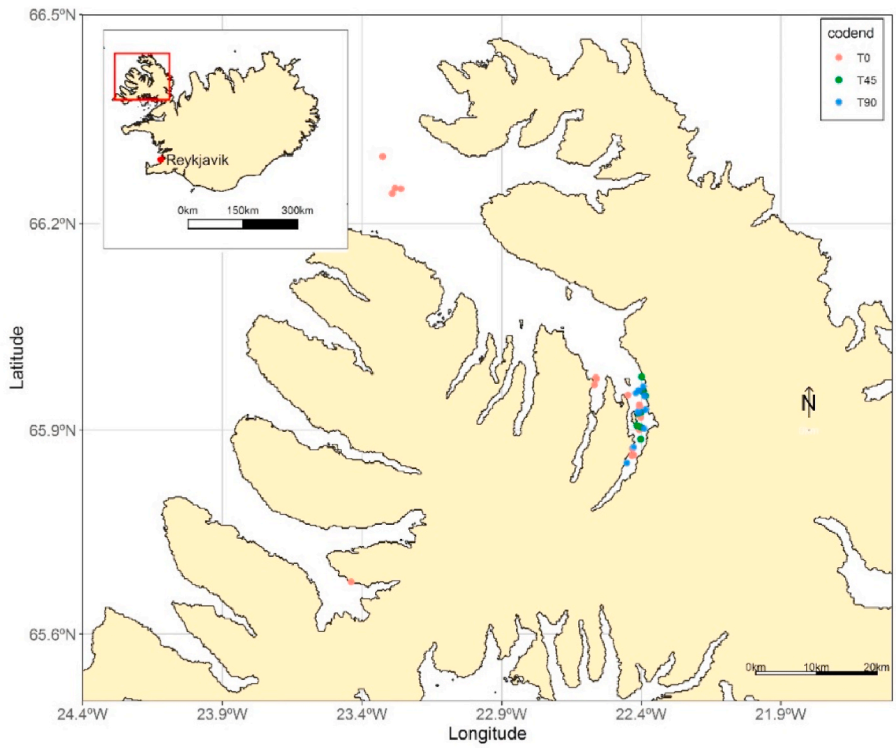


**Fig. 1.** Location of the fishing trials: red points show towing start positions with T0 codend; green points with T45 codend; blue points with T90 codend. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

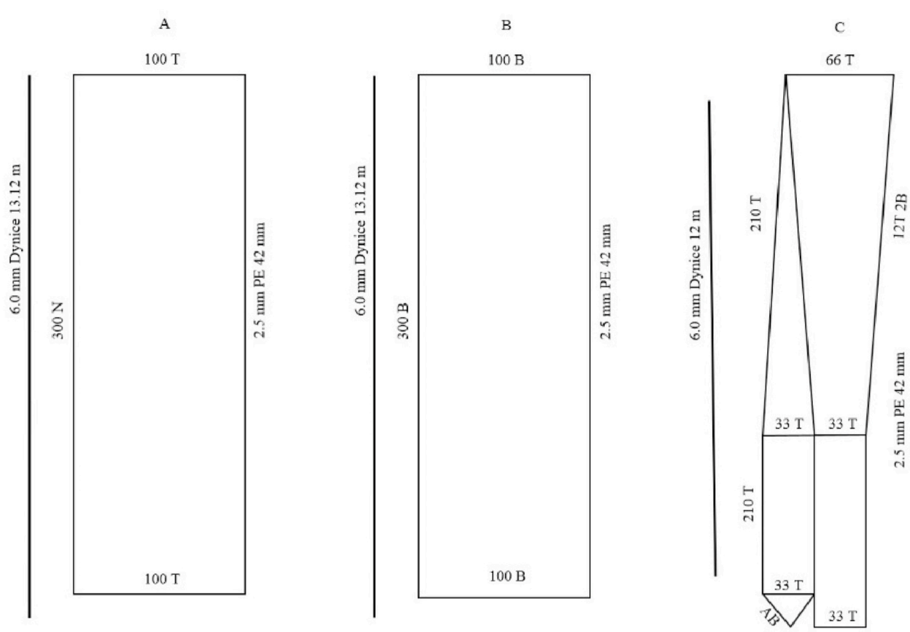


**Fig. 2.** Schematic diagram of (A) T0, (B) T45 and (C) T90 codend.

ropes were longer (4%) than the stretched length. The T90 mesh codend was made of single 2.5 mm diameter mesh in a four-panel configuration with shortened lastridge ropes (Fig. 2). Stretched length of the T90 codend was 14.7 m, and the lastridge ropes were shorter (18%) than the stretched length. Meshes were measured with the OMEGA gauge following procedures described by Fonteyne (2005) prior to sea trials. The average mesh size for the T0 codend was 39.7 mm with a standard deviation (SD) of 0.8, T45 codend was 33.3 mm with a SD of 1.0, and the T90 codend was 36.3 mm with a SD of 1.0.

### 2.3. Size-selectivity analysis

Total Northern shrimp catch from the codend and cover were separated and weighed. Random subsampling was applied by weight. To improve the accuracy of selectivity estimation, we measured approximately 500 individuals in the subsample from both compartments, codend and cover to the nearest 0.5 mm using an electronic digital calliper (ABSOLUTE Coolant Proof Caliper Series 500, Aurora, Illinois, USA) connected to a laptop.

The retention of Northern shrimp was considered independent and with a binominal distribution. The proportion of Northern shrimp of length $l$ retained in the codend is modelled and averaged over hauls with the function $r_{av}(l,\boldsymbol{v})$, where $\boldsymbol{v}$ is a vector representing two or more size selection parameters to be estimated (Herrmann, Sistiaga, Nielsen, & Larsen, 2012). This would provide information about the average consequences for the size selection process of applying different codends in the fishery. Therefore, it was assumed that the size selective performance of a specific codend for all the individual hauls conducted within a trial was representative of how the codend would perform in a commercial fishery (Millar, 1993; Sistiaga, Herrmann, Grimaldo, & Larsen, 2010).

Size selection was estimated by minimizing expression (1) with respect to parameters $\boldsymbol{v}$, which is equivalent to maximizing the likelihood for the observed data in form of the length-dependent number of Northern shrimp retained in the codend versus those escaping to the cover:

$$-\sum_{j=1}^{m}\sum_{l}\left\{\frac{nR_{jl}}{qR_j}\times ln(r_{av}(l,\boldsymbol{v}))+\frac{nE_{jl}}{qE_j}\times ln(1.0-r_{av}(l,\boldsymbol{v}))\right\} \quad (1)$$

where the outer summation is over the $m$ hauls conducted with the specific codend in the specific sea trial and the inner over length classes $l$. $nR_{jl}$ and $nE_{jl}$ are the number of shrimp length measured in codend and cover in haul $j$ belonging to length class $l$. $qR_j$ and $qE_j$ are the sampling factors for the fraction of the Northern shrimp length measured in the codend and cover, respectively.

Four basic selectivity models were tested to describe $r_{av}(l,\boldsymbol{v})$ for each codend: Logit, Probit, Gompertz, and Richard (Eq. (2)), which assume that all individuals entering the codend are subjected to the same size selection process (Wileman et al., 1996). Additional models (Eq. (2)) were also considered to estimate the codend size selection: CLogit, DLogit, TLogit and Poly4 (for details see Cheng, Einarsson, Bayse, Herrmann, & Winger, 2019).

$$r_{av}(l,\boldsymbol{v})=\begin{cases} Logit(l,\boldsymbol{v}) \\ Probit(l,\boldsymbol{v}) \\ Gompertz(l,\boldsymbol{v}) \\ Richard(l,\boldsymbol{v}) \\ CLogit(l,\ C,\ \boldsymbol{v})=\ 1.0\ -\ C\ +\ C\ \times\ Logit(l,\ \boldsymbol{v}) \\ DLogit(l,C_1,\boldsymbol{v})=C_1\times Logit(l,\boldsymbol{v}_1)+(1.0-C_1)\times Logit(l,\boldsymbol{v}_2) \\ TLogit(l,C,\boldsymbol{v})=C_1\times Logit(l,\boldsymbol{v}_1)+C_2\times Logit(l,\boldsymbol{v}_2)+(1.0-C_1-C_2)\times Logit(l,\boldsymbol{v}_3) \\ Poly4(l,\boldsymbol{v})=\dfrac{exp\left(v_0+\ v_1\ \times\ \dfrac{l}{100}+v_2\times\dfrac{l^2}{100^2}+v_3\ \times\ \dfrac{l^3}{100^3}+v_4\ \times\ \dfrac{l^4}{100^4}\right)}{1.0+exp\left(v_0+\ v_1\ \times\ \dfrac{l}{100}+v_2\times\dfrac{l^2}{100^2}+v_3\ \times\ \dfrac{l^3}{100^3}+v_4\ \times\ \dfrac{l^4}{100^4}\right)} \end{cases} \quad (2)$$

How well the models fit the data was inspected using the goodness-of-fit procedure described by Wileman et al. (1996). Where the $p$-value represented the likelihood to obtain at least as big a discrepancy between the fitted model and the observed data by coincidence, and should not be $< 0.05$. If a poor statistical fit was observed ($p$-value $< 0.05$), the residuals were inspected to determine whether the poor result was due to structural problems when modelling the experimental data using the different selection curves or if it was due to overdispersion in the data (Wileman et al., 1996). The most appropriate model for each codend was selected based on Akaike information criterion (AIC) values, where the selected model had the lowest AIC (Akaike, 1974). Once a size selection model was selected for the specific codend, uncertainty in the estimated size selection curve and parameters was obtained using a double bootstrapping technique with 1000 bootstrap repetitions to provide Efron 95% percentile confidence intervals (CIs; Efron & Tibshirani, 1986; Herrmann et al., 2012; Millar, 1993). This technique accounts for both within and between haul variation in size selection (Fryer, 1991).

Length-dependent selectivity between codends was compared with Delta curves ($\Delta r(l)$) estimated as:

$$\Delta r(l)=r_e(l)-r_c(l) \quad (3)$$

where $r_e(l)$ is the size selectivity of the experimental codend (T90 or T45), and $r_c(l)$ is the selectivity of the control (baseline) codend (T45 or T0). The 95% CIs for Delta curves were estimated based on the bootstrap population of results for the individual codend which was compared by the double bootstrap method described above. For details on this procedure consult Herrmann, Krag, and Krafft (2018). Significant differences in size selection between codends was obtained if the 95% CIs for Delta curves had length classes that did not overlap 0.0.

### 2.4. Cumulative catch curve

The population structure $nPop_l$ was generated using original datasets from this study by pooling data over all hauls (Northern shrimp in the cover + Northern shrimp in the codend) in the same season and same area independent of codend used. $nPop_l$ represents the total number of individuals entering the codend belonging to length class $l$. For each population, uncertainties (95% CIs) were obtained based on a double bootstrap method. This considered both the between-haul variability in the structure of the population entering the codend and within-haul variability due to limited numbers of Northern shrimps entering the codend in that specific haul, as well as the effect of subsampling. Specifically, the double bootstrap procedure accounted for between-haul variability by selecting hauls $h$ with replacement from the $h$ number of hauls from the dataset. Within-haul uncertainty was accounted for by resampling with replacement the Northern shrimp length-measured, followed by raising the numbers according to the subsampling ratios within each compartment (cover and codend). The number resampled for each compartment in this inner bootstrap loop equalled the total number of individuals length-measured in the respective compartment in the selected haul. 1000 bootstrap repetitions were conducted and used to calculate the 95% CIs for the population $nPop_l$.

Using the size-selection curves predicted for each codend, and applying them to $nPop_l$, we obtained simulated accumulated catch curves that quantifies the proportion of the catch consisting of shrimp with CL not exceeding a specific size $L$:

$$CDF\_nCatch(L) = \sum_{l=0}^{L} \{r_{codend}(l) \times nPop_l\} \tag{4}$$

Ideally, a good codend would catch more commercial sized than undersized individuals regardless of the population structure fished. Because *CDF_nCatch(L)* expresses the proportion of the catch up to a certain length, the rate at L = MRS denotes the proportion of undersized catch for a given population scenario fished by the specific codend.

For each *CDF_nCatch(L),* we estimated 95% CIs based on the bootstrap sets for $r_{codend}(l)$ and $nPop_l$ using the approach described by Herrmann et al. (2018). Specifically, this was obtained by the procedure described below. Because the bootstrap sets for $r_{codend}(l)$ and $nPop_l$ were obtained independently, a new bootstrap set of results for *CDF_nCatch(L)* was created using:

$$CDF\_nCatch(L)_i = \sum_{l=0}^{L} \{r_{codend}(l)_i \times nPop_{li}\} \tag{5}$$

where $i$ denotes the bootstrap repetition index (Herrmann et al., 2018). In Eq. (5) the 1000 bootstrap sets generated from the original datasets were multiplied to obtain the new bootstrap set for *CDF_nCatch(L)*. Based on this bootstrap set, 95% CIs for *CDF_nCatch(L)* were obtained.

### 2.5. Estimation of usability indicators

Using the size-selection curves predicted for each codend and applying them to the population $nPop_l$, we obtained simulated catches, $r_{codend}(l) \times nPop_l$. These were then summarized by calculating three different indicators ($nP-$, $nP+$, *nRatio*, and *dnRatio*), for each of the $nPop_l$ separately (Eq. (4)). $nP-$ and $nP+$ estimate the retention efficiency of the catch below and above MRS; *nRatio* represents the landings ratio of catch below to above MRS; *dnRatio* calculates the discard ratio

**Table 1**
Operational conditions for all hauls during sea trials in 2016 and 2017.

| Codend | Haul ID | Date | Sample number | | Sampling ratio | | Towing duration (min) | Maximum towing depth (m) |
|---|---|---|---|---|---|---|---|---|
| | | | Codend | Cover | Codend | Cover | | |
| T0 | | | | | | | | |
| | 1 | September 28, 2016 | 597 | 592 | 0.0012 | 0.0107 | 74 | 63 |
| | 2 | October 02, 2016 | 608 | 642 | 0.0246 | 0.2407 | 72 | 120 |
| | 3 | October 03, 2016 | 601 | 599 | 0.0944 | 0.3147 | 58 | 106 |
| | 4 | October 03, 2016 | 608 | 624 | 0.0189 | 0.1350 | 50 | 71 |
| | 5 | October 04, 2016 | 605 | 643 | 0.0145 | 0.2072 | 47 | 69 |
| | 6 | October 04, 2016 | 621 | 622 | 0.0118 | 0.0588 | 30 | 59 |
| | 7 | October 04, 2016 | 628 | 596 | 0.0015 | 0.0256 | 47 | 71 |
| | 8 | October 04, 2016 | 610 | 625 | 0.0095 | 0.0592 | 41 | 68 |
| | 9 | October 05, 2016 | 621 | 614 | 0.0241 | 0.1175 | 44 | 71 |
| | 10 | October 05, 2016 | 597 | 611 | 0.0176 | 0.2221 | 29 | 68 |
| | 11 | October 05, 2016 | 616 | 597 | 0.0179 | 0.1605 | 29 | 67 |
| | 12 | October 06, 2016 | 609 | 603 | 0.0240 | 0.1549 | 44 | 71 |
| | 13 | October 06, 2016 | 611 | 608 | 0.0076 | 0.2845 | 38 | 63 |
| | 14 | October 07, 2016 | 605 | 603 | 0.0041 | 0.0736 | 30 | 65 |
| | 15 | October 07, 2016 | 599 | 599 | 0.0010 | 0.0195 | 58 | 49 |
| | 16 | October 08, 2016 | 620 | 610 | 0.0526 | 0.2410 | 29 | 114 |
| | 17 | October 08, 2016 | 621 | 605 | 0.0656 | 0.2721 | 60 | 111 |
| | 18 | October 09, 2016 | 613 | 603 | 0.0074 | 0.0945 | 29 | 76 |
| | 19 | October 09, 2016 | 625 | 609 | 0.0075 | 0.0577 | 58 | 59 |
| T45 | | | | | | | | |
| | 20 | November 06, 2017 | 600 | 599 | 0.0102 | 0.1261 | 26 | 53 |
| | 21 | November 06, 2017 | 603 | 599 | 0.0010 | 0.0721 | 30 | 47 |
| | 22 | November 06, 2017 | 606 | 605 | 0.0063 | 0.0127 | 19 | 64 |
| | 23 | November 06, 2017 | 604 | 606 | 0.0016 | 0.1035 | 27 | 66 |
| | 24 | November 07, 2017 | 604 | 606 | 0.0127 | 0.0558 | 18 | 63 |
| | 25 | November 07, 2017 | 611 | 604 | 0.1529 | 0.1330 | 14 | 67 |
| | 26 | November 07, 2017 | 608 | 603 | 0.1516 | 0.3247 | 14 | 52 |
| | 27 | November 07, 2017 | 605 | 619 | 0.0259 | 0.2325 | 14 | 42 |
| | 28 | November 07, 2017 | 607 | 603 | 0.0072 | 0.1106 | 13 | 67 |
| T90 | | | | | | | | |
| | 29 | November 07, 2017 | 223 | 609 | 0.5000 | 0.3537 | 14 | 61 |
| | 30 | November 07, 2017 | 603 | 605 | 0.0045 | 0.0321 | 15 | 43 |
| | 31 | November 07, 2017 | 366 | 606 | 0.5000 | 0.3801 | 15 | 61 |
| | 32 | November 08, 2017 | 603 | 605 | 0.0066 | 0.0340 | 22 | 58 |
| | 33 | November 08, 2017 | 569 | 601 | 0.0064 | 0.0247 | 19 | 65 |
| | 34 | November 08, 2017 | 603 | 601 | 0.0378 | 0.0836 | 19 | 60 |
| | 35 | November 08, 2017 | 604 | 606 | 0.0836 | 0.0816 | 26 | 61 |
| | 36 | November 08, 2017 | 606 | 605 | 0.0212 | 0.0172 | 37 | 65 |
| | 37 | November 08, 2017 | 607 | 604 | 0.0182 | 0.0143 | 27 | 72 |
| | 38 | November 08, 2017 | 605 | 606 | 0.0044 | 0.0152 | 12 | 54 |

assuming all the individuals below and above MRS are either discarded or retained. Ideally for a target species, $nP-$, *nRatio* and *dnRatio* should be low (close to 0), while $nP+$ should be high (close to 100), i.e., all individuals over MRS that enter the codend are retained. The indicators were estimated by:

$$\begin{cases} nP- = 100 \times \dfrac{\sum_{l<MRS}\{r_{codend}(l) \times nPop_l\}}{\sum_{l<MRS}\{nPop_l\}} \\ nP+ = 100 \times \dfrac{\sum_{l>MRS}\{r_{codend}(l) \times nPop_l\}}{\sum_{l>MRS}\{nPop_l\}} \\ nRatio = \dfrac{\sum_{l<MRS}\{r_{codend}(l) \times nPop_l\}}{\sum_{l>MRS}\{r_{codend}(l) \times nPop_l\}} \\ dnRatio = 100 \times \dfrac{\sum_{l<MRS}\{r_{codend}(l) \times nPop_l\}}{\sum_{l}\{r_{codend}(l) \times nPop_l\}} \end{cases} \quad (6)$$

All indicators ($nP-$, $nP+$, *nRatio*, and *dnRatio*) were estimated with uncertainties for each codend and population scenario, using the bootstrap set for $r_{codend}(l)$ and $nPop_l$. Specifically based on Herrmann et al. (2018), the bootstrap set for calculating indicator values were obtained based on each bootstrap repetition result applying $r_{codend}(l)$ and $nPop_l$ simultaneously in Eq. (4). Finally, based on the resulting bootstrap set, 95% CIs were obtained for each of the indicators. All the analyses above were conducted with the software SELNET (Herrmann et al., 2012).

## 3. Results

### 3.1. Fishing operations and catch data

A total of 38 hauls were carried out during two sea trials: 19 hauls with T0 codend, 9 hauls with T45, and 10 hauls with T90 (Table 1). The first trial evaluated the T0 codend at 19 stations at water depths of 49–120 m, and an average towing duration of 46 min (29–74 min) (Table 1). The second trial consisted of 9 hauls for the T45 and 10 hauls for the T90 codend. For hauls that fished the T45 codend, average towing duration was 19 min (ranged from 13 to 30 min), and towing depths ranged from 42 to 67 m. For T90 codend hauls, towing duration averaged 21 min (ranged 12–37 min), towing depths varied from 43 to 72 m (Table 1). Northern shrimp was the predominantly captured species, therefore it was the only species analysed. Measurements of CL were recorded for a total of 45,549 Northern shrimp. Two shrimp were removed from the T90 data set. These individuals were much smaller (<10 mm) than the other shrimp captured, and each was the only observation in their length class. Keeping these individuals in the data set produced high retention values for very small shrimp, which is unrealistic.

### 3.2. Size selectivity

For each codend, the eight models (Eq. (2)) were fitted to the collected data. Table 2 presents the AIC values for the fit of each model; the model with lowest AIC value was selected as the best one for each codend. For the T0 and T45 codends, the best model was DLogit for the T90 codend, the best model was Poly4. Selected model fit statistics were presented in Table 3. The *p*-values were <0.05 for each model selected. However, the deviation between experimental rates and the fitted curve did not show any systematic patterns. Therefore, it was assumed that the low *p*-value was due to overdispersion from subsampling given the large catches of shrimp, and that each model could be applied to describe size selection.

**Table 3**
Selected model fit statistics for each codend.

| Codend | T0 | T45 | T90 |
|---|---|---|---|
| Model | DLogit | DLogit | Poly4 |
| DOF | 39 | 29 | 26 |
| Deviance | 536.4 | 102.5 | 63.6 |
| *p*-value | <0.001 | <0.001 | <0.001 |

Size selectivity results for the T0 codend are presented in Fig. 3. According to the selectivity curve, the T0 codend indicated high retention probability (average retention > 85%) for all sizes of shrimp. However, for sizes below MRS confidence bands were wide due to a low number of observations at these length classes. These results indicate that the T0 codend generally was not very size selective.

The selectivity curve of the T45 codend showed high average retention probability for catch above MRS, > 70%, and increased to >90% for catch above 17 mm (Fig. 3). Catches <17 mm suffered from low confidence; however, the model followed the experimental rates well until lengths <12 mm. Catches below 12 mm, do not follow a clear trend and it is difficult to determine what the data indicate within the large CIs. Very few Northern shrimps were captured below 10 mm in the codend and cover, which accounts for the large CIs.

The T90 codend had a much more gradual increase in retention probability as length increased when compared to the T0 and T45 codend (Fig. 3). Retention probability gradually increased from 10 cm to full retention.

Codends were directly compared with Delta curves (Fig. 3). The Delta plot comparing T0 and T45 codends contained 0.0 throughout, which shows no significant difference in size selectivity between codends. However, the model indicated that the T0 codend retained more Northern shrimp below 17 mm, which gradually increased toward zero, as did the CIs. When comparing the T0 and T90 codend, significantly less individuals were retained at lengths between 9 and 19 mm (Fig. 3). This shows that using the T90 codend significantly reduces the catch of undersized and market-sized Northern shrimp. Size selectivity between the T90 and T45 codend was significantly different for market-sized Northern shrimps at lengths between 14 and 22 mm. Few Northern shrimp were captured below 10 mm for both of these codends, rendering results for these lengths inconclusive.

### 3.3. Cumulative catch curve

The estimated population structure was significantly different between years (Fig. 4). In 2016, observed lengths were shifted to the left of 2017, where 2016 had a mode at 16 mm, 2017 was bimodal with a mode of corresponding size to 2016 at 19 mm, and a relatively smaller mode at

**Table 2**
Akaike's information criterion (AIC) for each model fit per codend. The selected model is highlighted in bold.

| Codend | Model | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Logit | Probit | Gompertz | Richard | DLogit | TLogit | CLogit | Poly4 |
| T0 | 1,632,066 | 1,631,556 | 1,632,171 | 1,626,596 | **1,617,175** | 1,618,452 | 1,618,446 | 1,618,223 |
| T45 | 539,720 | 537,239 | 541,775 | 535,847 | **535,361** | 535,367 | 535,481 | 535,542 |
| T90 | 714,498 | 713,750 | 717,409 | 713,055 | 713,000 | 713,006 | 713,011 | **712,893** |

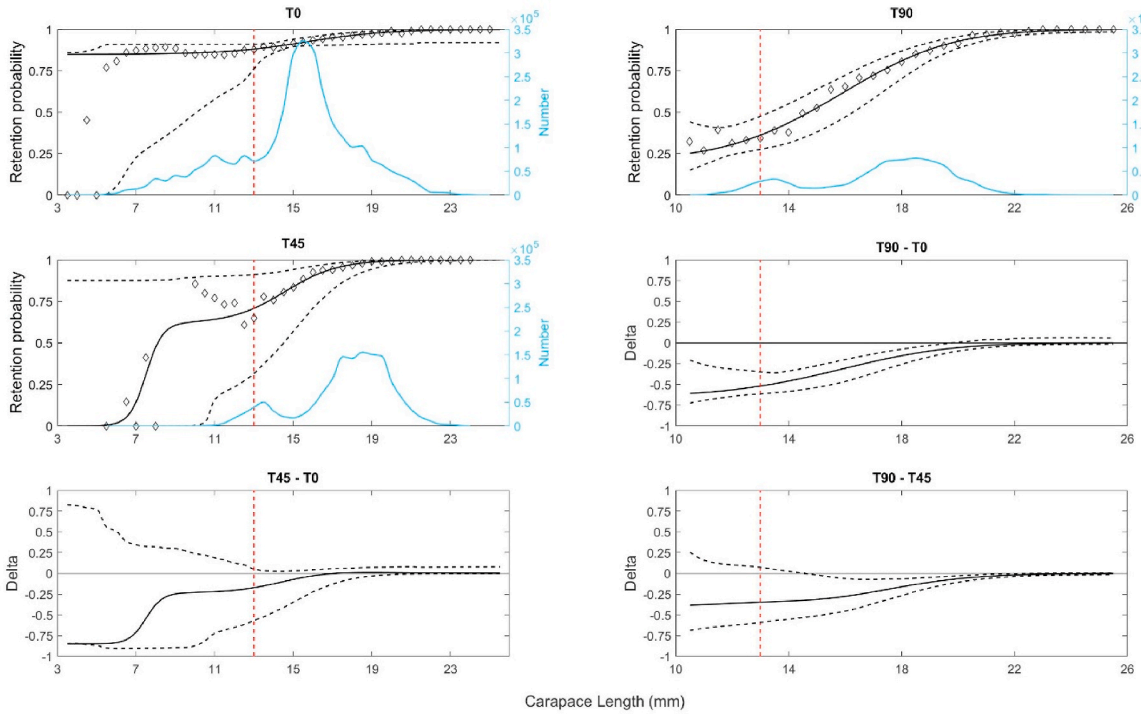


**Fig. 3.** Size selection curve for each codend and corresponding Delta curves: Diamond symbols represent the experiment rates of certain length class; thick black curve indicates the fitted size selection curves; stipple curves describe the 95% confidence limits for the fitted selectivity curves; blue curves shows the size distribution of the population encountered during sea trials; vertical stipple line represents the MRS for Northern shrimps; Delta curves show pairwise comparison of each codend selectivity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

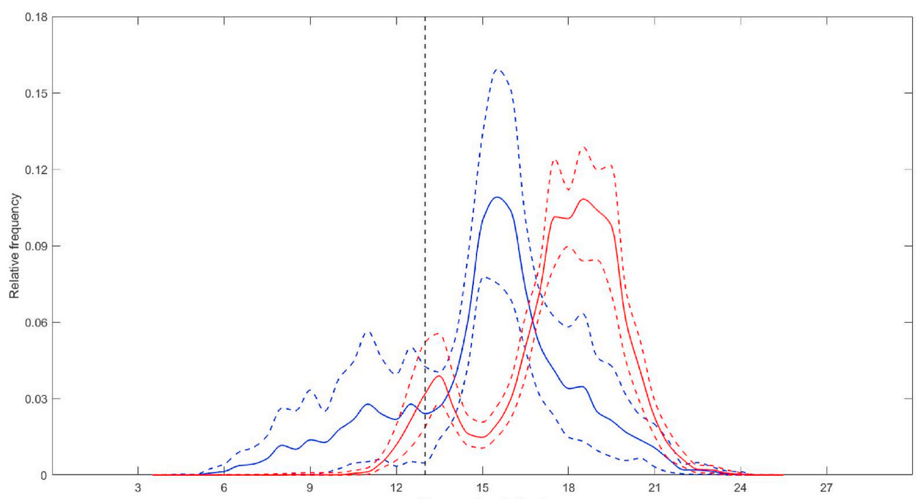


**Fig. 4.** Estimated average population from all hauls at the same fishing area and season. Blue line represents data from sea trials conducted in year 2016; Red line shows data from sea trials did in year 2017; Vertical stipple line represents the MRS for Northern shrimps; Red and blue stipple lines show 95% Efron CIs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

14 mm. Additionally, more smaller individuals <11 mm entered the codend in 2016. In terms of significant differences, 2016 had higher proportions from 10 to 11 mm and 14–17 mm, and 2017 had higher frequencies from 17 to 21 mm).

Figs. 5 and 6 illustrate the cumulative capture proportions between the different codends for 2016 and 2017, respectively. Following the population estimates from Fig. 4, cumulative capture proportions were shifted to the left for 2016 due to smaller Northern shrimp being present on fishing grounds. In 2016, the T0 codend trended higher catches at lengths of 7–21 mm versus both the T45 and T90 codend, however a significant difference was only observed between 12 and 21 mm for the T90 codend; no significant difference was observed between the T0 and T45 codend (Fig. 5). The T45 codend trended higher catches from 11 to 21 mm when compared to the T90 codend, but these differences were not significantly different. Generally, similar results were observed in 2017, the T0 codend indicated higher catches from 11 to 22 mm when compared to the T45 and T90 codends, but there were no significant differences between the T0 and T45 codends; the T0 codend caught significantly more Northern shrimp from 11 to 22 mm (Fig. 6). There were no significant differences between the T45 and T90 codends,

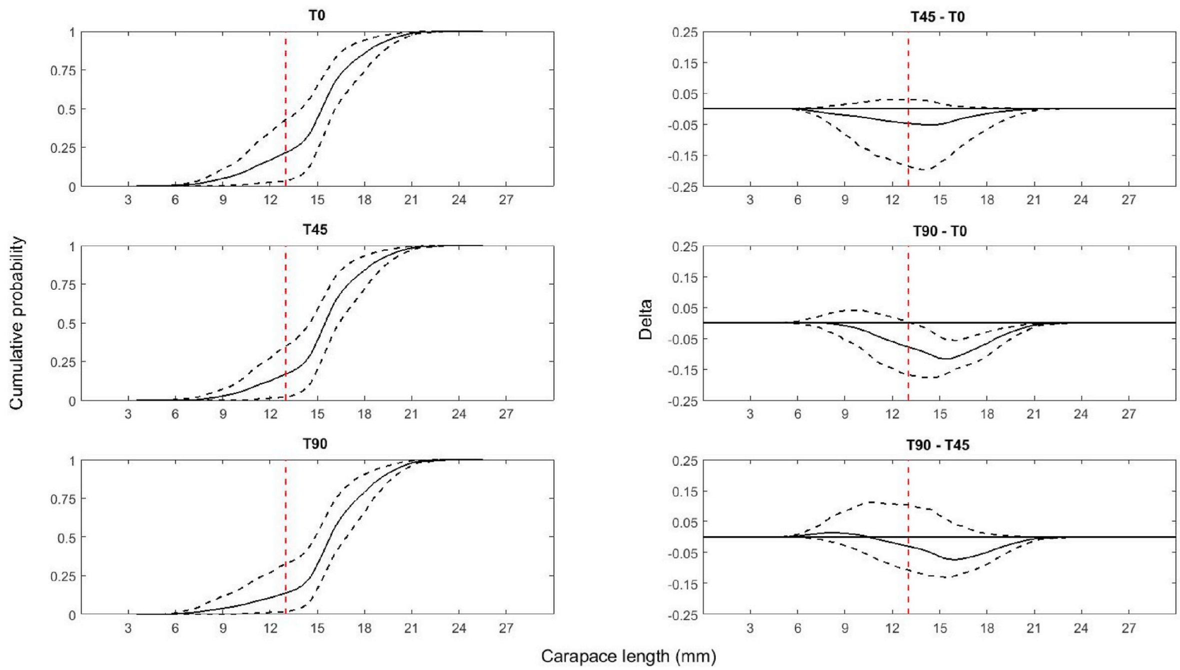


**Fig. 5.** Cumulative catch curve based on estimated average population in year 2016 (first column) and corresponding Delta curves (last column): thick black curve indicates the cumulative proportion of catch retained in each codend; stipple curves describe the 95% Efron CIs; vertical stipple line represents the MRS; Delta curves show pairwise comparison of cumulative capture populations.

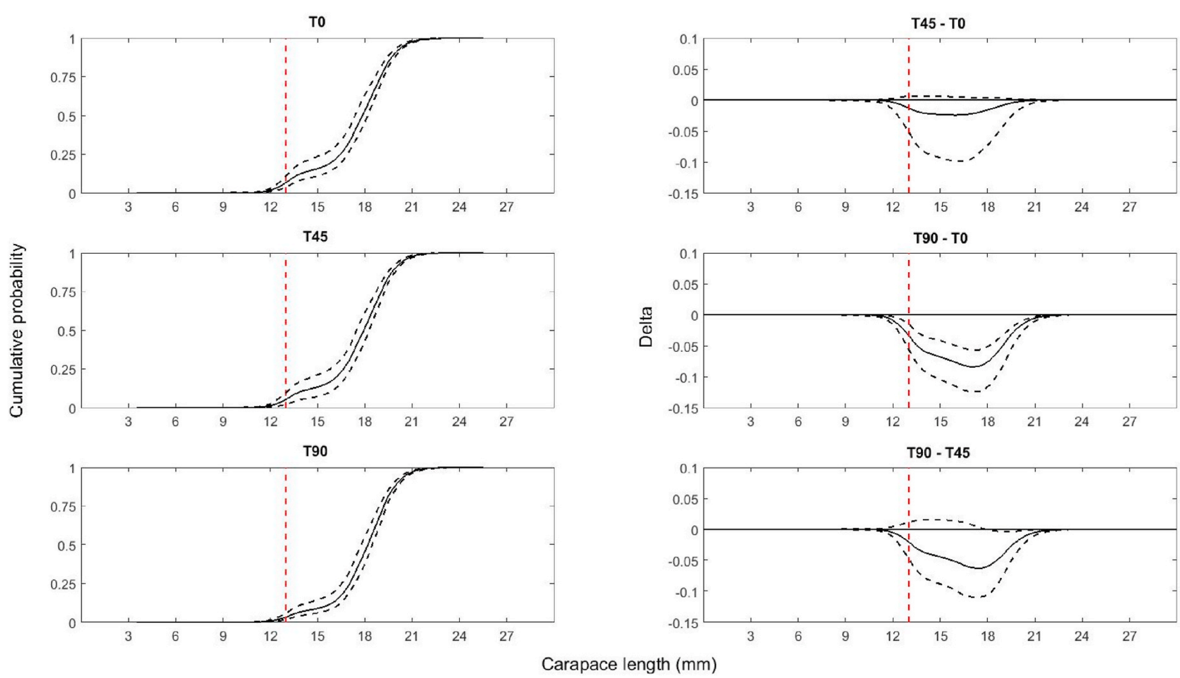


**Fig. 6.** Cumulative catch curve based on estimated average population in year 2017 (first column) and corresponding Delta curves (last column): thick black curve indicates the cumulative proportion of catch retained in each codend; stipple curves describe the 95% Efron CIs; vertical stipple line represents the MRS; Delta curves show pairwise comparison of cumulative capture populations.

however the T45 codend did indicate higher catches from 12 to 21 mm (Fig. 6). For both years, cumulative capture proportions for individuals over 21 mm were around 100% for all the codends; and the results of the $\Delta r(l)$ function was approximately 0.0.

### 3.4. Usability indicators

Table 4 shows the usability indicators for each codend based on the average population size structure observed in 2016 and 2017. Both indicators *nP*- and *nP*+ were similar for each codend in between 2016 and 2017. The T0 codend had high retention of undersized and marketable catch (>86%). The T45 codend also had high retention of market-sized Northern shrimp (>89%), but indicated lower catches of undersized Northern shrimp (<60%), however these differences were not significantly different from the T0 codend. The T90 codend had lower values for each indicator (<33% and <77%, for *nP*- and *nP* + , respectively).

**Table 4**
Usability indicators (*nP-*, *nP +* , and *dnRatio* in percent) for each codend based on different year-population scenarios.

| Year | 2016 | | | 2017 | | |
|---|---|---|---|---|---|---|
| Codend | T0 | T45 | T90 | T0 | T45 | T90 |
| *nP-* | 86.2 (52.5–91.0) | 59.5 (17.3–88.0) | 34.6 (17.7–49.8) | 87.2 (65.4–91.1) | 67.2 (24.4–90.0) | 33.0 (24.6–43.9) |
| *nP+* | 93.3 (90.6–95.7) | 89.0 (68.5–96.2) | 63.9 (51.8–76.1) | 95.6 (92.9–98.4) | 94.1 (82.4–97.9) | 77.1 (65.9–83.3) |
| *nRatio* | 0.24 (0.02–0.64) | 0.17 (0.02–0.46) | 0.14 (0.01–0.47) | 0.04 (0.01–0.06) | 0.03 (0.01–0.06) | 0.02 (0.01–0.03) |
| *dnRatio* | 19.3 (2.3–39.1) | 14.7 (1.5–31.7) | 12.3 (1.3–32.2) | 3.7 (1.69–6.09) | 2.9 (0.94–5.35) | 1.8 (0.81–3.27) |

Each indicator between T0 and T90 were significantly different, but none were between T45 and T90, typically due to T45 having large CIs.

The *nRatios* of Northern shrimp below and above MRS were similar for the codends within each year (Table 4). However, *nRatio* was 6–7 times as high for 2016, which reflects the size distribution difference between years. For each year, the T90 codend had the lowest *nRatio*, followed by the T45, and the T0 codend. The difference between *nRatios* was not significant for each comparison.

All the codends had low discard ratios (*dnRatio* in number) and were below the management threshold of 30% for both year-population scenarios (Table 4). For 2016 population, the *dnRatio* was higher across each codend when compared to 2017, and no significant difference was observed between any codend. The T0 codend had the highest *dnRatio* (19.3%), followed by the T45 (14.7%), and the T90 codend (12.3%). For the 2017 population, *dnRatios* of the codends were much smaller than those of 2016, *dnRatio* $<$ 3.7% for each codend with no significant difference between codends.

## 4. Discussion

This research investigated the size selectivity and usability of two conventional (T0 and T45) and one novel (T90) codend used to capture Northern shrimp in Icelandic waters. Size selectivity curves of the three codends were estimated and compared. Compared to the T45 and T0 codends, the T90 codend presented better size selection performance in terms of releasing undersized catch; the difference was significant for catch at certain length ranges between the T90 and T0 (9–19 mm) but not between the T45 and T0. Likely, the meshes of the T90 codend were able to remain more open than the conventional codends, which led to the reduced capture of small shrimp. Differences between the codends, including mesh orientation, panel design, and lastridge rope length likely improved mesh opening.

In terms of releasing juvenile or undersized Northern shrimp, the T90 codend should be considered for the sustainability of the fishery. However, using the T90 codend may be economically ambivalent for fishers in Iceland. Due to the ban on discarding of undersized catch, a T90 codend can increase catch efficiency of limited quotas, effectively increasing average catch size. However, the reduction of undersized catch has to be considered in the context of losing marketable-sized shrimp from 13 to 19 mm, which would be an economical loss. Furthermore, at the conclusion of this research, the fishery switched from a T45 codend to the novel T90, with the main consideration being the increase in average-individual size as a perceived economical benefit.

CIs of each curve for individuals under 11 mm were very wide and became wider as CL decreased (Fig. 3). This is attributed to the limited number of small individuals retained in the codend and cover, resulting in few data defining the left tail of the curve. This can also be validated from the size distribution of the population (Fig. 3); numbers of the individuals (CL $<$ 11 mm) retained in each gear only accounted for a small proportion of all the catch. There are two possible explanations for this situation: there were very few individuals below 11 mm in the populations at the fishing locations, or alternatively these small individuals were present but escaped through the cover net. The wide CIs affected the estimation accuracy of the selectivity making the selectivity within that length range uncertain.

When undersized Northern shrimps were present in the encountered population, few could escape from the T0 codend into the cover (>86% retention), and the T45 also displayed high undersized retention (>60%). These results show that the T0 and T45 codends were not very effective at sorting out undersized Northern shrimps, if present in the fished population. By comparison, the T90 codend was much more effective at releasing small Northern shrimps (<35% retention); however, market-sized catch was significantly reduced. When considering 2016 results, the T90 codend would retain about 64 Northern shrimps (in number) above MRS when there were 100 Northern shrimps at this length range in the codend and cover (Table 4). The same indicator for the T0 and T45 codends was above 89. Thus, fishing vessels may experience an economic loss if they use the T90 codend instead of T0 or T45 codends. However, according to the Icelandic fishery regulations, discarding of undersized catch is prohibited, and the undersized catch was counted as a part of the landing quota. Therefore, with a T90 codend fishers in Iceland could potentially make the most effective use of their quota by increasing the value of their quota, while having a cleaner fishery in terms of undersized Northern shrimp catch.

The above scenario is context dependent. When considering the fished population, the T90 codend produced these results for 2016 when many small Northern shrimp were present in the fishery – *nRatio* and *dnRatio* was at its highest (0.24 and 19.3%, respectively for the T0 codend). However, in 2017 few relatively small Northern shrimps were present, and *nRatios* and *dnRatios* dropped across all codends and had very similar, and very low values (<0.04 and 4%, respectively). *dnRatio* of each codend (<30%) demonstrated that using the codends tested would not lead to the fishing area closure according to Iceland fishing regulations. In terms of decreasing the discard ratio, there was no significant difference for applying the T0, T45 or T90 codend in the Northern shrimp fisheries, however both *nRatio* and *dnRatio* indicated less discard for the T45 codend compared to the T0 and less discard for the T90 when compared to the T45. In this scenario, the T90 codend was not the most effective codend in terms of effective quota use. The T0 or T45 codend would have been more effective, since they captured more large market-sized Northern shrimp and all codends captured similar amounts of undersized Northern shrimp.

Mesh orientation likely was not the only factor contributing to the observed differences in size selectivity in this study. The nominal mesh size of the three codends was the same, but measured mesh sizes were slightly different. Additionally, the T0 and T45 codends were in a two-panel configuration while the T90 codend was in a four-panel configuration and had shortened lastridge ropes. Due to these differences in design and construction, these results should be viewed as differences between codends. Future work should investigate how each of these changes individually affects the size selectivity of Northern shrimp.

Thorsteinsson (1992) reported that changing from T0 to T45 codend effectively reduced the catch of undersized Northern shrimp, which is not consistent with our results, nor the results of Lehmann et al. (1993) and Hickey et al. (1993, p. 41). Our results indicated that the T45 codend decreased the undersized catch compared to the T0 codend, however the difference was not significant and had wide confidence intervals (Fig. 3). Of note, the methods of each of these studies differ from ours, and each other, where we used the covered codend method. Thorsteinsson (1992), Hickey et al. (1993, p. 41) and Lehmann et al. (1993) used the paired gear method. Other differences include analytical methods (selectivity models with confidence intervals), materials (mesh size, twine diameter), and fishing grounds. However, when fished populations were similar between studies, similar results were observed. Our results were fished on similar population sizes when compared to Lehmann et al. (1993) and Hickey et al. (1993, p. 41), which also observed no difference between codends. Interestingly, Thorsteinsson (1992) only observed large differences in length distributions at small sizes (11–13 mm), sizes where each of the other mentioned studies had low catches, and at larger sizes (>15 mm) Thorsteinsson's (1992) results were similar to the other studies – no difference between codends. Perhaps a T45 codend does reduce these sizes of Northern shrimp, however we were unable to determine this from our study, and future work should be done to address this. Since the sea trials were carried out in different years, the uncertainties between the trials may affect the comparison of the codend selectivity results. Although the statistic analysis applied in the paper addressed the issue of between-year variation, the potential difference in the variability of the collected selectivity data caused by the experimental design can not be ignored.

In conclusion, this study demonstrated differences in the size selectivity and usability of three codends targeting Northern shrimp in Icelandic inshore waters. The T0 and T45 codends performed poorly at releasing Northern shrimp below the MRS. The T90 codend released significantly more undersized Northern shrimp, but at the cost of losing some Northern shrimp above MRS. Additionally, these results were very context dependent. In 2016, when many small Northern shrimps were in the fishery, the T90 codend was the best choice in terms of size selectivity, efficient quota use, and conservation of resources. In 2017, it could be argued that there was no real difference between fishing any of the codends, in terms of avoiding undersized Northern shrimp, since few small Northern shrimps were in the fished population. Perhaps using the codend with the least selectivity would be better in terms of efficiency and conserving fuel use. As is often the case in fisheries management, there is rarely a simple solution that works in every case, and size selectivity is ultimately dependent on the fished population.

## Acknowledgements

This project was funded by Marine and Freshwater Research Institute (Iceland). We would like to thank the staff from MFRI. Thanks are also extended to crew of the research vessel Bjarni Sæmundsson RE-30 and crew of the commercial shrimp trawler Guðbjörg Sigurðardóttir ÍS-508.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aaf.2020.09.005.

## References

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control, 19*, 716–723.

Alverson, D. L., Freeberg, M. H., Murawski, S. A., & Pope, J. G. (1994). *A global assessment of fisheries bycatch and discards*. Rome: FAO.

Bayse, S. M., & He, P. (2017). Technical conservation measures in new england small-mesh trawl fisheries: Current status and future prospects. *Ocean & Coastal Management, 135*, 93–102.

Bayse, S. M., Herrmann, B., Lenoir, H., Depestele, J., Polet, H., Vanderperren, E., et al. (2016). Could a T90 mesh codend improve selectivity in the Belgian beam trawl fishery? *Fisheries Research, 174*, 201–209.

Broadhurst, M. K., Millar, R. B., Kennelly, S. J., Macbeth, W. G., Young, D. J., & Gray, C. A. (2004). Selectivity of conventional diamond-and novel square-mesh codends in an Australian estuarine penaeid-trawl fishery. *Fisheries Research, 67*, 183–194.

Brothers, G., & Boulos, D. L. (1994). *Experiments with lastridge rope hanging ratios*. Montpellier, France: ICES-FAO working group on fishing technology and fish behaviour. April 25-26, 1994.

Cheng, Z., Einarsson, H. A., Bayse, S. M., Herrmann, B., & Winger, P. D. (2019). Comparing size selectivity of traditional and knotless diamond-mesh codends in the Iceland redfish (*Sebastes spp.*) fishery. *Fisheries Research, 216*, 138–144.

Deval, M. C., Bök, T., Ateş, C., Ulutürk, T., & Tosunoğlu, Z. (2009). Comparison of the size selectivity of diamond (PA) and square (PE) mesh codends for deepwater crustacean species in the Antalya Bay, eastern Mediterranean. *Journal of Applied Ichthyology, 25*, 372–380.

Deval, M. C., Özgen, G., & Özbilgin, H. (2016). Selectivity of 50 mm T0 and T90 codends for commercial shrimp species in the Turkish deepwater trawl fishery, Eastern Mediterranean. *Journal of Applied Ichthyology, 32*, 1041–1057.

Dore, I., & Frimodt, C. (1987). *An illustrated guide to shrimp of the world*. Huntington, NY: Osprey Books.

Efron, B., & Tibshirani, R. (1986). Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. *Statistical Science, 1*, 54–75.

Fonteyne, R. (2005). *Protocol for the use of an objective mesh gauge for scientific purposes*. Copenhagen, Denmark: International Council for the Exploration of the Sea.

Fryer, R. J. (1991). A model of between-haul variation in selectivity. *ICES Journal of Marine Science, 48*, 281–290.

Grimaldo, E. (2006). The effects of grid angle on a modified Nordmøre-grid in the Nordic Shrimp Fishery. *Fisheries Research, 77*, 53–59.

Grimaldo, E., Larsen, R. B., Sistiaga, M., Madsen, N., & Breen, M. (2009). Selectivity and escape percentages during three phases of the towing process for codends fitted with different selection systems. *Fisheries Research, 95*, 198–205.

Harrington, J. M., Myers, R. A., & Rosenberg, A. A. (2005). Wasted fishery resources: Discarded bycatch in the USA. *Fish and Fisheries, 6*, 350–361.

He, P., & Balzano, V. (2007). Reducing the catch of small shrimps in the Gulf of Maine pink shrimp fishery with a size-sorting grid device. *ICES Journal of Marine Science, 64*, 1551–1557.

Herrmann, B., Krag, L. A., & Krafft, B. A. (2018). Size selection of Antarctic krill (*Euphausia superba*) in a commercial codend and trawl body. *Fisheries Research, 207*, 49–54.

Herrmann, B., Priour, D., & Krag, L. A. (2007). Simulation-based study of the combined effect on cod-end size selection of turning meshes by 90 and reducing the number of meshes in the circumference for round fish. *Fisheries Research, 84*, 222–232.

Herrmann, B., Sistiaga, M., Nielsen, K. N., & Larsen, R. B. (2012). Understanding the size selectivity of redfish (*Sebastes spp.*) in North Atlantic trawl codends. *Journal of Northwest Atlantic Fishery Science, 44*, 1–13.

Herrmann, B., Wienbeck, H., Moderhak, W., Stepputtis, D., & Krag, L. A. (2013). The influence of twine thickness, twine number and netting orientation on codend selectivity. *Fisheries Research, 145*, 22–36.

Hickey, W. M., Brothers, G., & Boulos, D. L. (1993). *By-catch reduction in the northern shrimp fishery*. Canadian Technical Report of Fisheries and Aquatic Sciences, 1964.

Howell, W. H., & Langan, R. (1992). Discarding of commercial groundfish species in the Gulf of Maine shrimp fishery. *North American Journal of Fisheries Management, 12*, 568–580.

ICES. (2016). *Report of the working group on fishing technology and fish behaviour (WGFTFB), 25-29 april 2016, merida, Mexico* (Vol. 22, p. 183). ICES. C.M. 2016/SSGIEOM.

Isaksen, B., & Valdemarsen, J. W. (1990). Codend with short lastridge ropes to improve size selectivity in fish trawls. *ICES Fish Capture Committee CM 1990/B, 46*, 8.

Jónsdóttir, I. G., Bragason, G. S., Brynjólfsson, S. H., Guðlaugsdóttir, A. K., & Skúladóttir, U. (2017). *Yfirlit yfir rækjurannsóknir við Ísland, 1988-2015. Northern shrimp research in Icelandic waters, 1988-2015. HV2017-007*.

Karlsen, L., & Larsen, R. (1989). Progress in the selective shrimp trawl development in Norway. *Proceedings of the world symposium on fishing gear and fishing vessel design (p30–38*. St. John's: Marine Institute.

Larsen, R. B., Herrmann, B., Sistiaga, M., Brinkhof, J., & Santos, J. (2018). Catch and release patterns for target and bycatch species in the Northeast Atlantic deep-water shrimp fishery: Effect of using a sieve panel and a Nordmøre grid. *PloS One, 13*, Article e0209621.

Lehmann, K., Valdemarsen, J. W., & Riget, F. (1993). Selectivity in shrimp trawl codends tested in a fishery in Greenland. *ICES Marine Science Symposia, 196*, 80–85.

Lomeli, M. J., Hamel, O. S., Wakefield, W. W., & Erickson, D. L. (2017). Improving catch utilization in the US West Coast groundfish bottom trawl fishery: An evaluation of T90-mesh and diamond-mesh cod ends. *Marine and Coastal Fisheries, 9*, 149–160.

Madsen, N., Herrmann, B., Frandsen, R. P., & Krag, L. A. (2012). Comparing selectivity of a standard and turned mesh T90 codend during towing and haul-back. *Aquatic Living Resources, 25*, 231–240.

Mamie, J. C. J., Leone, S., Valtýsson, H.þ., & Ármannsson, H. (2008). Stock assessment of shrimp *Pandalus borealis* (KRØYER 1838). In *Skjálfandi bay northern Iceland* (Vol. 43). United Nations University Fisheries Training Program.

Marine and Freshwater Research Institute (MFRI). (2018a). Assessment reports 2018, offshore northern shrimp. https://www.hafogvatn.is/static/extras/images/stofnmat_uthafsraekja_taekniskyrsla_2018_v1836543.pdf. Assessed 03 Januaral 2019.

Marine and Freshwater Research Institute (MFRI). (2018b). Assessment reports 2018, shrimp in Ísafjarðardjúp. https://www.hafogvatn.is/static/extras/images/Stofnmat_innfjar%C3%B0arr%C3%A6kja_isafjardardjup_20181102481.pdf. Assessed 03 Januaral 2019.

Millar, R. B. (1993). Incorporation of between-haul variation using bootstrapping and nonparametric estimation of selection curves. *Fishery Bulletin, 91*, 564–572.

Sala, A., Lucchetti, A., Piccinetti, C., & Ferretti, M. (2008). Size selection by diamond-and square-mesh codends in multi-species Mediterranean demersal trawl fisheries. *Fisheries Research, 93*, 8–21.

Santos, J., Herrmann, B., Stepputtis, D., Günther, C., Limmer, B., Mieske, B., et al. (2018). Predictive framework for codend size selection of brown shrimp (*Crangon crangon*) in the North Sea beam-trawl fishery. *PloS One, 13*, Article e0200464.

Sistiaga, M., Herrmann, B., Grimaldo, E., & Larsen, R. B. (2010). Assessment of dual selection in grid based selectivity systems. *Fisheries Research, 105*, 187–199.

Thorsteinsson, G. (1992). The use of square mesh codends in the Icelandic shrimp (*Pandalus borealis*) fishery. *Fisheries Research, 13*, 255–266.

Tokaç, A., Herrmann, B., Aydın, C., Kaykac, H., Ünlüler, A., & Gökçe, G. (2014). Predictive models and comparison of the selectivity of standard (T0) and turned mesh (T90) codends for three species in the Eastern Mediterranean. *Fisheries Research, 150*, 76–88.

Wienbeck, H., Herrmann, B., Feekings, J. P., Stepputtis, D., & Moderhak, W. (2014). A comparative analysis of legislated and modified Baltic Sea trawl codends for simultaneously improving the size selection of cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*). *Fisheries Research, 150*, 28–37.

Wileman, D. A., Ferro, R. S. T., Fonteyne, R., & Millar, R. B. (1996). Manual of methods of measuring the selectivity of towed fishing gears. *ICES Cooperative Research Report, 215*, 126.