Size selectivity and catch efficiency of diamond-mesh codends in demersal trawl fishery for conger pike (*Muraenesox cinereus*) of the South China Sea

Bingzhong Yang[a, b*], Bent Herrmann[c, d, c], Lei Yan[a, b], Jie Li[a, b], Teng Wang[a, b]

[a] South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Guangzhou 510300, China

[b] Key Laboratory of Open-Sea Fishery Development, Ministry of Agriculture and Rural Affairs, Guangzhou 510300, China

[c] SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, 9850, Hirtshals, Denmark

[d] University of Tromsø, Breivika, N-9037 Tromsø, Norway

[e] DTU Aqua, Technical University of Denmark, Hirtshals, Denmark

* Corresponding author. South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Guangzhou 510300, China.
E-mail address: yangbingzhong@scsfri.ac.cn (B. Yang).

has been listed as one of the major fish species with depleted stock status (FAO, 2009). A decade passed, the situation is still serious. One indicator is that the annual landing of this species was far higher than its maximum sustainable yield (MSY). According to Zhang et al., 2017), the MYS of conger pike should be 11.8×10^4 t in the SCS, however the actual landing in 2018 was 16.41×10^4 t (MARA, 2019) in the specific area, demonstrating that the fishery resource of this species has still being overexploited.

Like most of other traditionally important demersal fish species, the depletion of stock status for conger pike in the SCS can be contributed to a number of factors. Among them, indiscriminate and intense fishing of juvenile fish is the largest challenge (FAO, 2009; Szuwalsk et al., 2017; Zhang et al., 2020). Several studies have demonstrated that capturing of undersized conger pike is a serious problem. For instance, catch composition survey of shrimp trawl fishery had been conducted in 2006 and 2012 in the SCS, respectively; the results were the identical, showing that 100% of the conger pike captured by demersal trawl were juvenile (Yang et al., 2008; Yang et al., 2014). Recently, Zhang et al. (2020) conducted a nationwide field survey of fishing gears targeting fish species in China. Their results showed that in total 68.75% of landed conger pike were undersized, regardless fishing gears, from most fishing grounds of China.

Issues of catching juvenile fish can be related to the exploitation pattern of the fishery, which is mainly depended on the size selectivity of the fishing gears used and on the extent to which particular size classes are targeted (Wileman et al., 1996; Vasilakopoulos et al., 2011). In the SCS, the captured of juvenile conger pike is believed to associate with poor size selectivity of the trawl net used, especially in the codend. Due to small mesh size used in the codend (often 25 mm or even less), and most codends are diamond-mesh, substantial number of juvenile fish species, including conger pike, would be retained when they are abundant in the fishing grounds. The minimum mesh size (MMS) regulation, in which all trawl fishing in the SCS should have a MMS of 39 mm in the codend, was firstly implemented in 2004. Later in 2013, this regulation was updated to two sizes (25 and 40 mm): trawl targeting shrimp subjected to a MMS of 25 mm, and fish-directed trawl required a MMS of 40 mm in the codend (Shen and Heino, 2014). These regulations were promulgated and implemented by China’s central government (the Ministry of Agriculture and Rural Affairs), aimed to protect fishery resources, especially to prevent juvenile fish from overfishing. Their enforcement and effectiveness, however, are widely doubted and criticized (Shen and Heino, 2014; Cao et al., 2017; Zhang et al., 2020). Despite the existence of the MMS regulations, some fishermen still tend to use small mesh size to maintain their catches as most traditional fisheries resources have been depleted (Liang and Pauly, 2017; Zhang et al., 2020). Low compliance of the MMS regulations can be due to lack of knowledge about the selective properties of trawl, especially in the codend where most size selection takes place (Glass, 2000). For one thing, these regulations were based on studied finished in the 1980s (Shen and Heino, 2014); for the other, they are not fully tested and evaluated after implementation. From the perspective of fishermen, they worry that the catch losses would be great when using the codends with legal mesh sizes. Specifically, there is no study or literature addresses size selection of diamond-mesh codend for conger pike in the SCS.

At present, there is no minimum landing size (MLS) of conger pike officially legislated to supplement the MMS regulations in the SCS. The fishing fleets can land any size of conger pike, and that is why most vessels tend to use small mesh sizes in the codend. However, substantial differences in market prices among different sizes of conger pike, in terms of weight, have driven fishermen prefer to capture larger ones. For instance, an individual of conger pike, whose weight is larger than 250 g, can be sold at a price of 18 yuan/kg, while the bigger ones, which weigh more than 1000 g, will have a price of 42 yuan/kg. By comparison, smaller conger pike, with a weight less than 250 g, will be categorized as feed-grad fish which have a price of only 2 yuan/kg. As a result, catching conger pike with weight less than 250 g would provide little economic income for the fishermen. Moreover, handling these juvenile conger pike is still time-consuming and manpower demanded onboard the fishing fleets. For this consideration, fishermen have desire to improve the size selectivity of their fishing gears. Additionally, catching juvenile fish can have negative impacts on fishery recruitment and biodiversity of the marine ecosystems (Szuwalski et al., 2017). Thus, improving size selection of trawl codend for conger pike is highly relevant in both the protection of fishery resource and convenience of fishermen.

In order to improve size selection of trawl codend, there are a lot of gear modification can be made (Kennelly and Broadhurst, 2021). Past experiences and accomplishments of selectivity studies for some well-known fish species have demonstrated that the size selection of diamond-mesh codend can be improved by simply increasing its mesh size (Fryer et al., 2016; O'Neill et al., 2020). These positive outcomes raise concern about how the size selection of diamond-mesh codends for conger pike will be affected be mesh sizes and if the exploitation pattern of towed gears for this specific fish can be improved by increasing mesh sizes in the codends.

To address the issues mention above, the main objective of this study was to investigate the size selectivity and catch efficiency of diamond-mesh codends for conger pike in demersal trawl fishery of the SCS. We tested six diamond-mesh codends with different mesh sizes, from 25 to 54 mm, and paid special attention to two legal codends, with 25 and 40 mm mesh size, respectively. We intended to address the following research questions:

1) To what extent is the size selectivity of the legal diamond-mesh codends satisfactory for conger pike?

2) Can the size selectivity and exploitation pattern of diamond-mesh codends for conger pike be improved by increasing the mesh sizes?

2. Materials and Methods

2.1. Sea trials

Sea trials were carried out onboard a commercial trawler, named "Guibeiyu 96899" (length: 38 m, engine power: 280 kW), in October 2019. The fishing ground located in the Beibu Gulf of the northern South China Sea (Fig. 1), which is a traditional fishing ground for demersal trawl fishery. Towed duration and speed were kept mainly at 2 h and 3.5 knots, which is the level for commercial demersal trawl fisheries. During the sea trials, the experimental fishing was conducted day and night continually, which was the same as the commercial fishing.

2.2. Fishing gear and experimental set-up

The fishing vessel equipped with a double-rigged trawl system, in which two identical trawls could be hauled and retrieved by the same vessel simultaneously and separately (Fig. 2). We used the trawl components of the vessel except for the codends. The trawls all had a fishing circumference of 860 meshes, with a mesh size of 45 mm, and a total stretched length of ~33 m. The mesh size was 45 mm in the wings and 30 mm in the extension. Two identical sets of trawl doors, made of wood and steel with a dimension of 1.90×0.83 m (length × width), were used to spread the gears. During commercial fishing, these double-rigged trawls would have a vertical net opening of ~1.5 m, and a wingspread of about 15 m.

Six diamond-mesh codends with different mesh sizes, 25 to 54 mm (termed as D25-D54; Fig. 2 and Table 1), were designed and tested. All the tested codends were designed based on the dimension of the commercial codend, which had circumference of 220 meshes with 25 mm size and a total stretched length of 4.8 m. Measurements of mesh sizes (mesh openings) were conducted according to the protocol described in Wileman et al. (1996). Except for the mesh sizes, the tested codends were identical to the commercial one in twine material, diameter, and stretched dimension (both in circumference and length). However, to neutralize the potential bias of the circumference to the experiment, the mesh number reduced as the mesh sizes increased for the tested codends. The covered codend method was applied in our experiments. The dimension of the cover was 1.5 times of the tested codend, following the recommendation of Wileman et al. (1996). Detailed information about the tested codends and the covers was listed in Table 1 and Fig. 2. In order to avoid the masking effect, flexible kites made of waterproof canvas (He, 2007; Grimaldo et al., 2009) were equipped in the front, middle and back part (potential catch accumulation zone of codend) of the cover, 12 kites in total. Before the formal experiments, two underwater video recording systems (GoPro HERO4 BLACK Edition) were used to check whether the cover would mask the tested codend.

As the fishing vessel was able to haul two trawls simultaneously, we arranged three pairwised tests: D25 vs. D30, D35 vs. D40 and D45 vs.D54, to explore how the mesh size would impact the size selection of the codends. The codends used were the only change, two at a time attached to the same trawls. To remove the potential bias, we made sure that fishing procedure of the two trawls was conducted simultaneously.

After the haul-back process, catches from each compartment, codend and cover, were processed separately for each tested codend. All catch of conger pike were sorted, subsampled (if needed), and frozen for length and weight measurement in the laboratory.

2.3. Estimation of size selectivity

Estimation of size selectivity of each codend for conger pike was conducted separately using the software SELNET (Herrmann et al., 2012). For each tested codend, the experimental design enabled to analyze catch data as binominal data, whereby conger pike was either retained by the codend or cover. The catch proportion (probability), of a given fish with length *l* by a specific codend in haul *j* was expressed as $r_j(l)$. The value of $r_j(l)$ can be calculated by the catch number of the codend and the total number. For the same codend, however, the value of $r_j(l)$ would be expected to vary between hauls (Fryer, 1991). In the present study, our main interest was the length-dependent values of $r\ (l)$ averaged over hauls, because this would provide information about outcomes for size selection process of using a specific codend in the fishery. Thus, it was assumed that size selective performance of the tested codend in the experiment was representative of how the codend would perform in a commercial fishery (Millar, 1993; Sistiaga et al., 2010; Herrmann et al., 2016).

We used $r_{av}(l)$ to represent the estimation of the average size selection by pooling data from all hauls (Herrmann et al., 2012). Different parametric models were tested and compared for $r_{av}(l)$, where *v* is a vector consisting of the parameters of the model. The purpose of this analysis is to estimate the values of parameter *v* that make experimental data (averaged over hauls) most likely to be observed, by assuming that the model is able to describe the data sufficiently well. Thus, expression (1) was minimized the respect to parameter *v*, which was equivalent to maximizing the likelihood for the observed data in form of the length-dependent number of fish caught by the codend (nR_{jl}) versus those escaping to the cover (nE_{jl}):

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

Where the outer summation is over the *m* hauls conducted, while the inner summation is over length class *l*; qR_j and qE_j are the sub-sampling factors for the fraction of the fish length measured in the codend and cover, respectively.

Four commonly used models, Logit, Probit, Gompertz and Richards, were chosen as candidates to describe $r_{av}(l)$ (Wileman et al., 1996). The first three models can be fully presented by two selective parameters L50 (50% retention length) and SR =L75-L25. For the Richards model, an additional parameter, $1/\delta$, is required to describe the asymmetry of the curve. Detailed information about these models can be found in Wileman et al. (1996).

Each of the candidate models was fitted in (1), and then selection of the best model was conducted by comparing their AIC values. The model with the lowest AIC values is regarded as the best one (Akaike, 1974). The ability of a model to describe the data sufficiently well can be evaluated by inspecting the corresponding *p*-value, which expresses the likelihood of obtaining at least as big a discrepancy between the fitted model and the observed experimental data as would be expected by coincidence. For the fitted model to be a candidate to model the size selection data, the *p*-value should not be less than 0.05 (Wileman et al., 1996). In case of a poor statistical fit (p-value < 0.05), the residuals would be inspected to determine whether the result was due to structural problems when modelling the experimental data using the different models or if it was due to overdispersion in the data (Wileman et al., 1996).

After the specific size selection model was identified for a given codend, a double bootstrapping technique was applied to estimate the confidence intervals (CIs) for the size selection curves and parameters, by taking both within- and between-haul variation into account (Millar, 1993; Herrmann et al., 2012). A “pooled” set of data was analyzed using the identified selection model, then 1000 bootstrap repetitions was conducted to estimate the Efron percentile 95% CIs for the selection curve and its parameters (Herrmann et al., 2012).

2.4. Estimation of exploitation pattern indicators

In order to test and compare how these codends with different mesh sizes perform under the same fishery population of conger pike, a specific scenario of population, $nPop_l$, was generated by pooling data over all hauls (Melli et al., 2019; Einarsson et al., 2021). Applying the size selection curves predicted in section 2.3, four exploitation pattern indicators, *nP-*, *nP+*, *nRatio*, and *dnRatio* (Eq. 2), were calculated for each codend with a minimum conservation reference size (MCRS). Additionally, as it is mentioned in the introduction section that the market-price for conger pike is often expressed as weight, and the fishermen's main concern is how the proportion of weight retained will be impacted by applying the selective codends, we calculated two additional ratios, *wP-* and *wP+* (Eq. 2), by converting the number of conger pike per length class into weights, using a length-weight relationship, $w(l)=a\times l^b$ (Melli et al., 2019).These indicators directly depend on the size structure on the fish population encountered during the experimental fishing, and can provide additional information for the evaluation of the exploitation patter for the tested codends. Specifically, as there is no official MLS and MCRS regulation for the studied species, we estimated a Market Reference Size (MRS) based on the length-weight relationship from our data, using the minimum market-demand weight, 250 g, as a starting point. Meanwhile, the coefficients of length-weight relationship, *a* and *b*, were obtained at that process.

$$
\begin{aligned}
nP- &= 100 \times \frac{\sum_{l<MRS}\{r_{codend}(l)\times nPop_l\}}{\sum_{l<MCRS}\{nPop_l\}} \\
nP+ &= 100 \times \frac{\sum_{l\geq MRS}\{r_{codend}(l)\times nPop_l\}}{\sum_{l\geq MRS}\{nPop_l\}} \\
nRatio &= \frac{\sum_{l<MRS}\{r_{codend}(l)\times nPop_l\}}{\sum_{l\geq MRS}\{r_{codend}(l)\times nPop_l\}} \\
dnRatio &= 100 \times \frac{\sum_{l<MRS}\{r_{codend}(l)\times nPop_l\}}{\sum_{l}\{r_{codend}(l)\times nPop_l\}} \quad (2) \\
wP- &= 100 \times \frac{\sum_{l<MRS}\{a\times l^b\times r_{codend}(l)\times nPop_l\}}{\sum_{l<MRS}\{a\times l^b\times nPop_l\}} \\
wP+ &= 100 \times \frac{\sum_{l\geq MRS}\{a\times l^b\times r_{codend}(l)\times nPop_l\}}{\sum_{l\geq MRS}\{a\times l^b\times nPop_l\}}
\end{aligned}
$$

where $r_{codend}(l)$ is the size selection curve obtained for the specific codend, while $nPop_l$ represents the size structure of conger pike entering the codends in terms of individuals with length class l, a and b are coefficients of length-weight relationship for conger pike. *nP-* and *nP+* are the percentage of retained fish below and above the MRS (in number), respectively, taking the size structure of the population encountered into account. It would be preferable to have an *nP-* value close to 0 and an *nP+* value close to 100. *nRatio* is the landing ratio between captured fish below and above the MRS. The *dnRatio* is the percentage of fish individuals below the MRS retained by the codend. Both *nRatio* and *dnRatio* should be as low as possible. *wP-* and *wP+* are ratios similar to *nP-* and *nP+*, but in weight proportion. The double bootstrapping approach was applied to estimate the Efron percentile 95% CIs for the indicator values, taking both within- and between-haul variation into consideration (Herrmann et al., 2012; Herrmann et al., 2018; Melli et al., 2019; Einarsson., 2021).

2.5 Delta selectivity

Length-dependent size selection between codends with different mesh sizes was compared with delta curves, $\Delta r(l)$ in the values was estimated by:

$$\Delta r(l) = r_B(l) - r_A(l) \quad (3)$$

Where $r_A(l)$ is the size selection for codend A with a small mesh size, and $r_B(l)$ represents the size selection curve for codend B with a relatively larger mesh size. Efron 95% percentile CIs for $\Delta r(l)$ could be obtained based on two bootstrap populations of results for both $r_A(l)$ and $r_B(l)$. As they were obtained independently, a new bootstrap population of results was created for $\Delta r(l)$ by:

$$\Delta r(l)_i = r_B(l)_i - r_A(l)_i \quad i \in [1 \ldots 1000] \quad (4)$$

where i is the bootstrap repetition index. As the bootstrap re-sampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on (4), by using the two independently generated bootstrap files (Herrmann et al., 2018; Herrmann et al., 2019).

3. Results

3.1. Experimental data

We conducted 46 valid hauls for the six different codends during the sea trials, in which towing duration was mainly 2 h, with a range of 118 to 156 min, and subsampling ratios varied from 0.25 to 1.0 (Table 2). Conger pike was present in all hauls, and in total 593 individuals were length measured and weighted. The length of the studied fish ranged from 5.0 to 26.6 cm, with an average of 14.2 cm; while the weight was in the range of 3.7 to 344.9 g, averaged at 74.9 g. Based on the 593 pairwised data of length (L) and weight (W), we estimated the length-weight relationship, the equation: $W = 0.0129 \times L^{3.175}$($R^2$=0.956), for the specific species (Fig. 3). According to this equation, we approximately calculated that the length of a conger pike weighted 250 g was 22.4 cm. This value was used as the MRS to estimate the exploitation pattern indicators in our study. The estimated population structure showed that most conger pike had a length below the estimated MRS (Fig. 4).

3.2. Size selectivity of conger pike

Based on the lowest AIC value (Table 3), the Logit model was selected as the best one for the tested codends except the D30 codend, whose best model was the Probit. Specifically, both the Logit and Probit model resulted lowest and equal AIC value, for the D54 codend, we chose the former one. All selected models fitted well with the experimental data, as their *p*-values were larger than 0.05 except the D45 codend (Table 4). As the model used reflected the main trend in the experimental data well (Fig. 5(e)), we considered the low *p*-value of the D45 codend to be a consequence of over-dispersion in the experimental data.

The number of conger pike caught by the tested codends decreased as the mesh sizes increased (Fig. 5). For instance, the D25 codend caught relatively more fish comparing with the D54 codend. The retention curves also reflected a similar fishing pattern. In general, the retention probability curves showed a tendency of becoming more flat as the mesh sizes increased. As the mesh sizes of codends enlarged, the retention rate of conger pike individuals above MRS decreased, while CIs for the retention curves increased (Fig. 5). For the three codends with smaller mesh sizes, D25, D30 and D35, the estimated retention rate for conger pike's at MRS would be above 50% while it for the three other codends D40, D45 and D54 would be lower than 50% and decreasing with mesh size. The retention probability of fish at the MRS length was relatively high for the D25, D30 and D35 codend, all above 88%, indicating high fishing risk for undersized fish; while the retention probability dropped to 42.94% for the D40 codend, and smaller values for the D45 and D54 codend (Fig. 5).

In general, the exploitation pattern indicators showed that applying codends with larger mesh sizes would reduce the catch efficiency for both commercial-sized and undersized fish. For instance, the D25 codend retained 54.31% (CI: 41.52-66.45%) of individuals under the MRS (*nP-*); by comparison *nP-* ratio would drop to 9.61% (CI: 3.45-16.40%) for the D40 codend, and less than 6% for the D45 and D54 codend, respectively (Table 4). Using codends with large mesh sizes, however, might compromise decreasing catch efficiency for fish above the MRS. As three codends with smaller mesh sizes, the D25, D30 and D35 codend, retained most fish above the MRS (*nP+* > 92%), while the D40 codend retained 50.93% of fish above the target size, and the relative value for the D54 codend was 6.15%, indicating a low fishing efficiency for commercial-sized fish. The additional indicators when lengths were converted into weights, *wP-* and *wP+*, reflected a similar trend to *nP-* and *nP+*, respectively. Very high discarded ratios (*dnRatio*) were obtained, all larger than 83%, for the tested codends.

3.3. Delta selectivity

Results of delta selectivity curves showed that applying codends with larger mesh sizes would reduce retention probability for the studied species, the bigger difference between the mesh sizes the lower delta probability could be obtained, and most of these differences were statistically significant for fish at some specific length range (Fig. 6 and Fig. 7). For instance, compared with the D25 codend, the D30 and D35 codend would have significant lower retention probability for fish with length ranged from 12.6 to 20.1 cm (Fig. 6a), and 11.6 to 26.8 cm (Fig. 6b), respectively. There was no significant difference of selectivity between the D30 and D35 codend. For fish with length above 12 cm, the D40 codend would have significant lower retention probability than the D25 codend (Fig. 6d); while a significant effect was obtained for fish with length range of 14.9 to 21.2 cm in the D40 vs. D30 comparison (Fig. 6e). The selectivity of the D40 codend did not significantly differ from that of the D35 codend. Compared with the D25, D30 and D35 codend, the D45 codend significantly had lower retention probability for fish larger the following length: 11.9 cm (Fig. 7a), 14.5 cm (Fig. 7b) and 18.2 cm (Fig. 7c), respectively. No significant difference was obtained between the D40 and D45 codend. In the three pairwised comparisons D54 vs. D25, D54 vs. D30 and D54 vs. D35, significant differences were obtained for fish with length above the following value: 12.2 cm (Fig. 7e), 15 cm (Fig. 7f), and 18.7 cm (Fig. 7g), respectively. There was no significant difference of selectivity for the two pairwised comparisons, D54 vs. D40 and D54 vs. D45.

4. Discussion

Among several technical controls, the MMS regulation is the most important one used by fisheries management in China. To the best of our knowledge, this was the first time two diamond mesh codends with legal mesh sizes, 25 and 40 mm, were tested in respect of size selectivity for conger pike in the SCS. In addition, we tested four alternative diamond mesh codends with different mesh sizes, from 30 to 54 mm. In general, our results demonstrate that the retention rate of conger pike's would decrease while the catch efficiency decrease with the increment of mesh sizes in codends.

Firstly, our results showed that selective properties of the D25 codend were insufficient to protect juvenile fish for the studied species. Retention risks were high for conger pike well below the MRS value and the retention probability for fish with a length of MRS was 100%. Further, the exploitation pattern indicators showed that the D25 codend would retain a large proportion of conger pike below the MRS, more than 54% of conger pike below the MRS was retained, and 93.88% (CI: 89.25-96.97%) of conger pike retained by the codend would have to be discarded.

Second, our results demonstrated that a simple and effective modification to release undersized conger pike would be just increasing the mesh sizes in the codend. For instance, when the mesh sizes of codends enlarged from 25 to 35 mm, and the retention probability at the MRS length was dropped from 100% to 88.58%, meaning that juvenile conger pike had larger chance to escape from the codends when mesh sizes increased. When it came to the other legal codend, D40, the problem of capturing juvenile fish was significantly mitigated. The retention probability at the MRS length was < 43%; while less than 10% of the conger pike sized below MRS was retained. However, the loss of commercial-sized fish for the D40 codend was considerable, as about 50% fish above the MRS would escape from it. Additionally, CIs in both selective parameters and exploitation pattern indicators of the D40 codend were wider compared to codends with smaller mesh sizes, indicating that there might be some uncertainty in the selective properties for this legal codend. When the mesh sizes further increased to 45 and 54 mm, the retention probability of conger pike became relatively low, especially for the D54 codend very few fish was retained. Similarly, CIs of estimated parameters were still wide. These results demonstrate that increasing mesh sizes is a simple way to improve codend selectivity for conger pike. This approach, however, is not a panacea. When the mesh size increase to 40 mm, uncertainty might be given rise to selective properties of the diamond-mesh codends.

Previous studies have demonstrated that fish behaviour and fish shape are important factors affecting size selectivity (Wileman et al., 1996; Harada et al., 2007; Herrmann et al., 2009; He, 2010; Tokai et al., 2019). In our study, conger pike has a snake-like body, and its cylindrical body shape may facilitate escaped activity from the codend meshes. Liang et al. (1999) reported that conger pike was capable to pass through a codend mesh which was smaller than its body girth of (body-girth/mesh-perimeter was 1.056). Jiang and Hu (1992) also reported that conger pike had a special ability to escape from the codend mesh, not only by using its head but also with tail to escape firstly from the mesh, sometime even tried to bite the mesh to escape. We did not measure data of body girth for conger pike retained in the experiment. By comparison selectivity of codends with different mesh sizes, however, the retention probability generally decreased as the mesh sizes increased. This result might be related to the special behaviour and body shape of this specific species.

It is widely aware that only implementing MMS regulations is not enough to protect juvenile fish. Other supplemented regulations, such as minimum landing size (MLS), should be formulated and enforced to match with the MMS regulations (Suuronen et al., 2007). At present, there is no official MLS regulation for conger pike in the SCS. Under that circumstance, some literature used length at first maturity of conger pike as a MRS, the value was 340 mm, to estimate fishing rate of undersized fish (Yang et al., 2008; Yang et al., 2014). However, considering that this previously used the MRS was based on survey data in the 1990s, we estimated a new MRS based on the length and weight relationship by taking the market-demanded value into account. As the length-weight curve showed a very clear tendency, we believed that our method would be a better choice to estimate the exploitation pattern indicators. Additionally, it is highly relevant that a formal MLS regulation should be formulated for conger pike in the SCS as soon as possible.

To improve selective properties of a given diamond mesh codend, mesh size is one of the most important design features (Wileman et al., 1996). Our study solely investigated the effect of mesh sizes on size selection of diamond mesh codend for conger pike. Other factors, such as the number of open meshes around the codend circumference, twine diameter, mesh shape and extension length, had been previously reported to have impact on size selectivity of trawl codends (Reeves et al., 1992; Fryer et al., 2016; O'Neill et al., 2020; Robert et al., 2020). Future research work should take the influence of the design features mentioned above into account.

Based on the results, we recommend some implications and suggestions for management and governance issues to obtain a sustainable development of demersal trawl fishery for conger pike in the SCS. First of all, the 25-mm MMS regulation in shrimp trawl fishery of SCS is insufficient to protect juvenile conger pike. Second, the 40-mm MMS regulation for fish targeted trawl fishery should be maintained for a period until a better modification is made to have good compromise in releasing undersized conger pike and retaining a commercial-sized one. Third, an official MLS or MCRS regulation should be formulated for conger pike to supplement the MMS regulations in the SCS.

5. Conclusions

By testing, comparing and evaluating size selective properties of six diamond-mesh codends with different mesh sizes, main conclusions can be drawn as below:

1) Size selectivity and exploitation pattern of diamond-mesh codends targeting conger pike could be improved by applying larger mesh sizes.
2) The D25 codend performed poorly at releasing undersized conger pike. The implication for fishery management is that the trawl fleets targeting shrimp species, which follow the MMS regulation of 25-mm mesh size in codends, should change fishing dynamics (e.g.

fishing period and grounds) or modifying the gear configuration, using other selective devices (e.g. sorting grid), when juvenile conger pike is abundant in the fishing grounds.

3) Using the D40 codend would significantly reduce the retention probability of juvenile conger pike, however, at the cost of losing some commercial-sized one.

Acknowledgements

We would like to thank the captain and crews of commercial vessels "*Guibeiyu 96899*" for their cooperation in sea trials. We also thank Mr. Roger B. Larsen from the Arctic University of Norway UIT for providing the approach of doing underwater recordings with GoPro (Hero4) and a lot of useful information about that. This work was funded by National Key R&D Program of China (2020YFD0901205), Central Public-interest Scientific Institution Basal Research Fund, South China Sea Fisheries Research Institute, CAFS (NO. 2020YJ01), and financial support of Ministry of Agriculture and Rural Affair "Standard and management regime of fishing gears in the South China Sea".

References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Autom. Control. https://doi.org/10.1109/TAC.1974.1100705.

Cao, L., Chen, Y., Dong, S., Hanson, A., Huang, B., Leadbitter, D., Little, D.C., Pikitch, E.K., Qiu, Y., Sadovy de Mitcheson, Y., Sumaila, U.R., Williams, M., Xue, G., Ye, Y., Zhang, W., Zhou, Y., Zhuang, P., Naylor, R.L., 2017. Opportunity for marine fisheries reform in China. PNAS 114, 435-442. https ://doi.org/10.1073/pnas.16165 83114

Chen, G., Liang P., Guan S., Yu J., Li N., 2016. Pictures of marine fishes in the South China Sea. Science Press, Beijing. (in Chinese)

Einarsson, H.A., Cheng, Z., Bayse, S.M., Herrmann, B., Winger, P.D., 2021. Comparing the size selectivity of a novel T90 mesh codend to two conventional codends in the northern shrimp (*Pandalus borealis*) trawl fishery. Aquaculture and Fisheries (in Press) https://doi.org/10.1016/j.aaf.2020.09.005

FAO, 2009. Report of the second Workshop on the Assessment of Fishery Stock Status in South and Southeast Asia. http://epub.sub.uni-hamburg.de/epub/volltexte/2012/16717/pdf/i1663e00.pdf

Fryer, R.J., 1991. A model of between-haul variation in selectivity. ICES J. Mar. Sci. 48, 281-290.

Fryer, R.J., O'Neill, F.G., Edridge, A., 2016. A meta-analysis of haddock size-selection data. Fish Fish. 17, 358-374. DOI: 10.1111/faf.12107.

Glass, G.W., 2000. Conversation of fish stocks through bycatch reduction: a review. Northeast. Nat. 7, 395-410. doi:10.2307/3858520.

Grimaldo, E., Larsen, R.B., Sistiaga, M., Madesen, N., Breen, M., 2009. Selectivity and escape percentage during three phases of the towing process for codends fitted with different selection systems. Fish. Res. 95, 198-205.

Harada, M., Tokai, T., Kimura, M., Hu, F., Shimizu, T., 2007. Size selectivity of escape holes in conger tube traps for inshore hagfish *Eptatretus burger* and white-spotted conger *conger myriaster* in Tokyo Bay. Fish. Sci. 73, 477-488.

He, P., 2007. Selectivity of large mesh trawl codends in the Gulf of Maine: I. Comparison of square and diamond mesh. Fish. Res. 83, 44-59.

He, P., 2010. Behavior of marine fishes: capture processes and conservation challenges. Wiley-Blackwell, Oxford, UK.

Herrmann, B., Krag, L.A., Frandsen, R.P., Madsen, N., Lundgren, B., Stæhr, K.J., 2009. Prediction of selectivity from morphological conditions: Methodology and a case study on cod (*Gadus morhua*). Fish. Res. 97, 59-71.

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the Size Selectivity of Redfish (*Sebastes* spp.) in North Atlantic Trawl Codends. J. Northwest Atl. Fish. Sci. 44, 1-13. https://doi.org/10.2960/J.v44.m680

Herrmann, B., Krag, L.A., Feekings, J., Noack, T., 2016. Understanding and Predicting Size Selection in Diamond-Mesh Cod Ends for Danish Seining: A Study Based on Sea Trials and Computer Simulations. Mar. Coast. Fish. 8, 277-291.

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

Herrmann, B., Sitiaga, M., Larsen, R.B., Brinkhof, J., 2019. Effect of three different codend designs on the size selectivity of juvenile cod in the Barents Sea shrimp trawl fishery. Fish. Res. 219, 1-8.

Jiang, S., Hu, Y., 1992. Designs and fishing technology of beam trawl for conger pike. China Fish. 4, 34-35. (in Chinese)

Kennelly, S.J., Broadhurst, M.K., 2021. A review of bycatch reduction in demersal fish trawls . Rev. Fish. Biol. 31, 289-318. https://doi.org/10.1007/s11160-021-09644-0

Liang, C., Pauly, D., 2017. Growth and mortality of exploited fishes in China's coastal seas and their uses for yield-per-recruit analyses. J. Appl. Ichth. 33, 746-756. http://doi.org/10.1111/jai.13379

Liang, Z., Horikawa, H., Tokimura, M., Tokai, T., 1999. Effect of Cross-sectional Shape of Fish Body on Mesh Selectivity of Trawl Codend. Nippon Suisan Gakkaishi 65, 441-447. (in Japanese with an English abstract)

MARA, 2019. China fishery yearbook 2019. China Agriculture Press, Beijing, China. (in Chinese)

Melli, V., Herrmann, B., Karlsen, J.D., Feekings, J.P., Krag, L.A., 2019. Predicting optimal combination of by-catch reduction devices in trawl gears: A meta-analytical approach. Fish Fish. 00, 1-17. https://doi.org/10.1111/faf.12428

Millar, R.B., 1993. Incorporation of between-haul variation using bootstrapping and nonparametric estimation of selection curves. Fish. Bull. 91, 564-572.

O'Neill, F.G., Fryer, R.J., Frandsen, R.P., Herrmann, B., Madsen, N., Mieske, B., 2020. A meta-analysis of plaice size-selection data in otter trawl codends. Fish. Res. 227, 105558.

Reeves, S.A., Armstrong, D.W., Fryer, R.J., Coull, K.A., 1992. The effect of mesh size, cod-end extension length and cod-end diameter on the selectivity of Scottish trawls and seines. ICES J. Mar. Sci. 49, 279-288.

Robert, M., Morandeau, F., Scavinner, M., Fiche, M., Larnaud, P., 2020. Toward elimination of unwanted catches using a 100 mm T90 extension and codend in demersal mixed fisheries. PLoS ONE 15 (7): e0235368. https://doi.org/10.1371/journal.pone.0235368

Shen, G., Heino, M., 2014. An overview of marine fisheries management in China. Mar. Pol. 44, 265-272.

Sistiaga, M., Herrmann, B., Grimaldo, E., Larsen, R.B., 2010. Assessment of dual selection in grid based selectivity systems. Fish. Res. 105, 187-199.

Suuronen, P., Tschernij, V., Jounela, P., Valentinsson, D., Larsson, P.O., 2007. Factors affecting rule compliance with mesh size regulations in the Baltic cod trawl fishery. ICES J. Mar. Sci. 64, 1603-1606.

Szuwalski, C.S., Burgess, M.G., Costello, C., Gaines, S.D., 2017. High fishery catches through trophic cascades in China. PNAS 114, 717-721.

Tokai, T., Shiode, D., Sakai, T., Yoda, M., 2019. Codend selectivity in the East China Sea of a trawl net with the legal minimum mesh size. Fish. Sci. 85, 19-32.

Vasilakopoulos, P., O’Neill, F.G., Marshall, C., 2011. Misspent youth: does catching immature fish affect fisheries sustainability. ICES J. Mar.Sci. 68, 1525-1534.

Wileman, D., Ferro, R.S.T., Fonteyne, R., Millar, R.B., 1996. Manual of Methods of Measuring the Selectivity of Towed Fishing Gear. ICES Coop. Res. Rep. 215.

Yang, B., Yang, L., Tan, Y., Zhang, P., Yan, L., 2014. Analysis and assessment of by-catch composition of shrimp beam trawl in coastal sea of Zhanjiang. Mar. Sci. 38, 65-70. (in Chinese with an English abstract)

Yang, L., Zhang, X., Tan, Y., Zhang, P., 2008. Analysis of the catch composition of small shrimp-beam-trawl net in shallow waters of Pearl River Estuary, China . South China Fish. Sci. 4, 70-77. (in Chinese with an English abstract)

Zhang, K., Liao, B., Xu, Y., Zhang, J., Qiu, Y., Chen, Z., 2017. Assessment for allowable catch of fishery resources in the South China Sea. Haiyang Xuebao 39, 25-33. (in Chinese with an English abstract)

Zhang, W., Liu, M., Sadovy de Mitcheson, Y., Cao, L., Leadbitter, D., Newton, R., Little, D. C., Li, S., Yang, Y., Chen, X., Zhou, W., 2020. Fishing for feed in China: Facts, impacts and implications. Fish Fish. 21, 47-62. https ://doi.org/10.1111/faf.12414

Lists of Figures

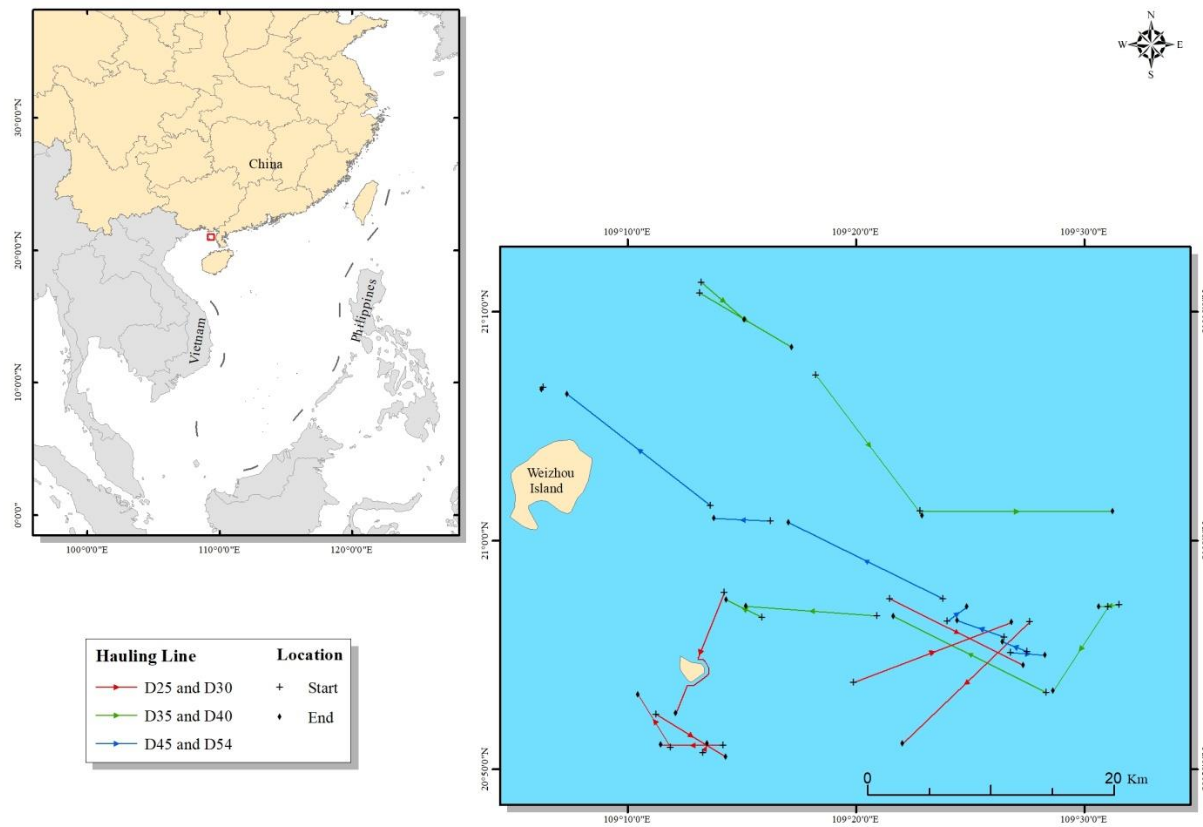

Fig. 1. Location of sea trials: the colorful lines represent hauling lines (red lines represent the D25 and D30 codend, purple lines represent the D35 and D40 codend, and green lines represent the D45 and D54 codend, respectively).

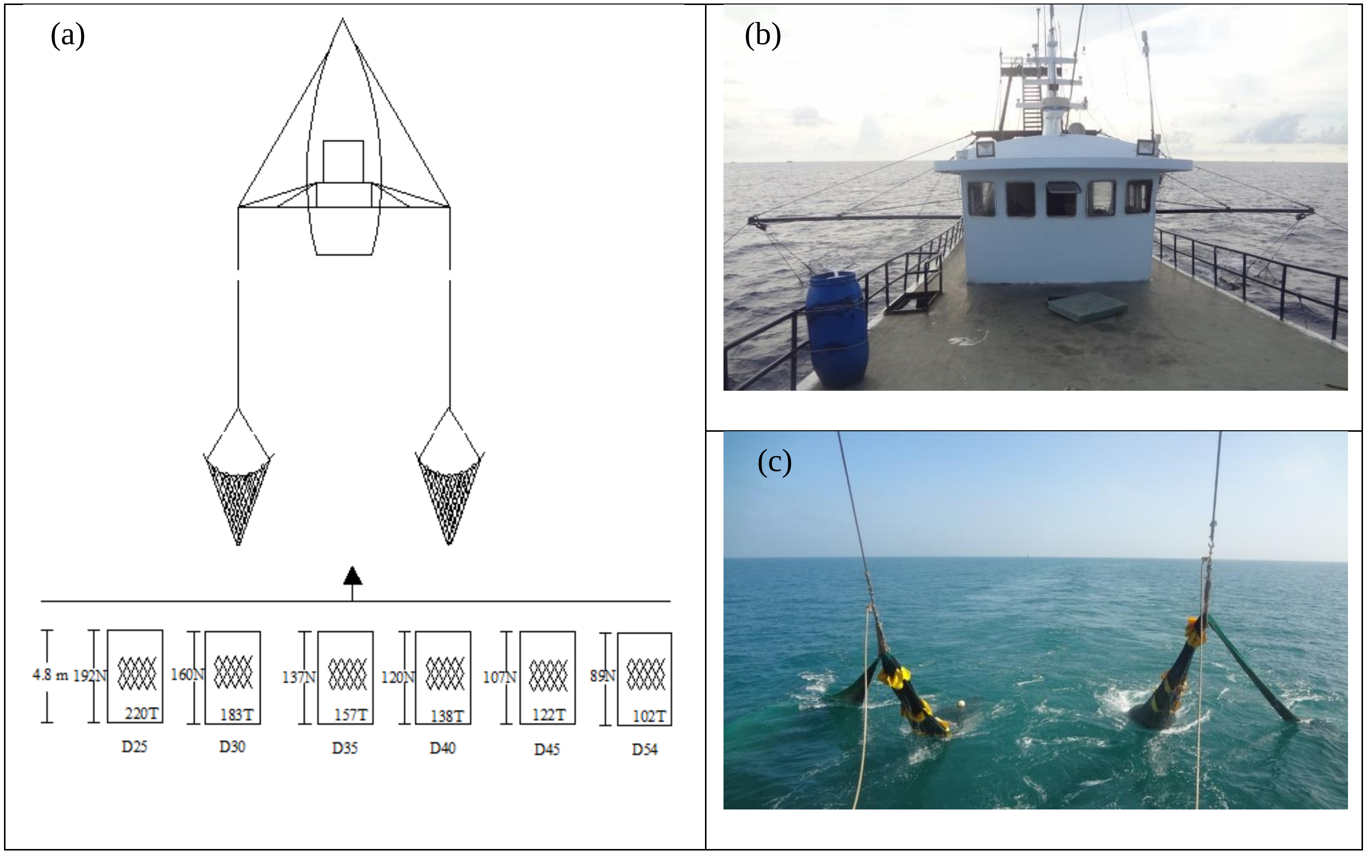

Fig. 2. Schematic view of the fishing gear configuration tested in the experiments. (a): the fishing vessel and specification of the tested codends, (b): the vessel towing two trawls simultaneously, and (c): the haul-back process of the tested codends.

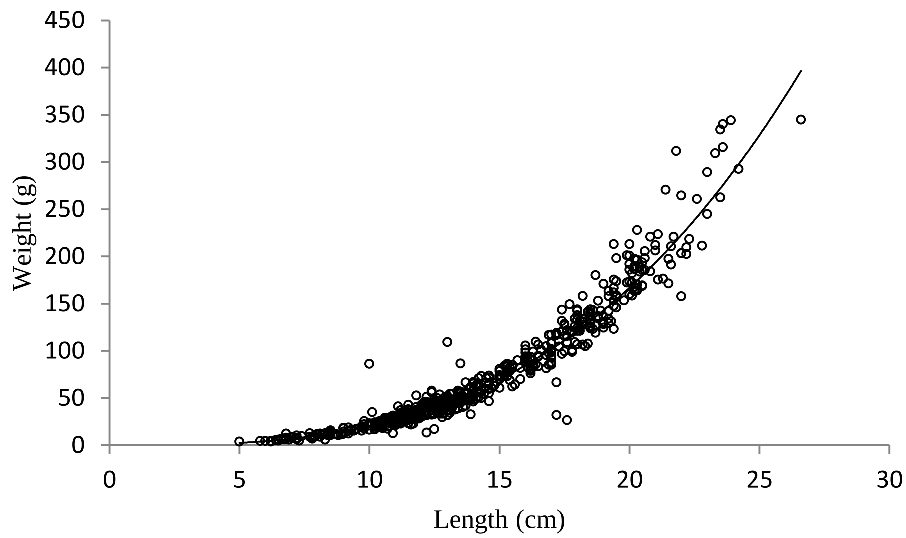

Fig. 3. The length-weight relationship curve of conger pike based on the experimental data.

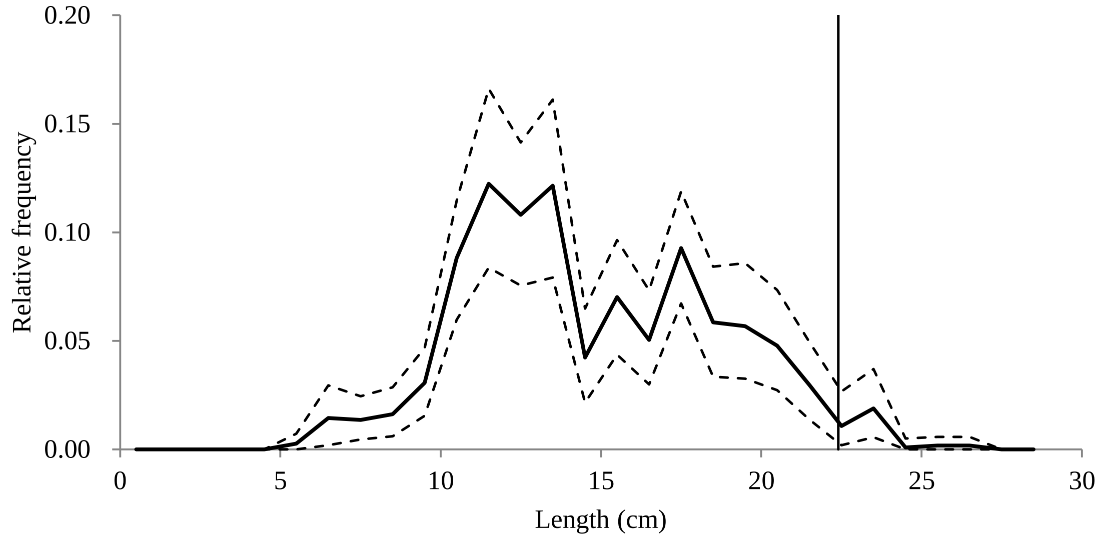

Fig. 4. Estimated average population from all hauls during the sea trials. Stipple lines show the 95% Efron confidence intervals, and the vertical line represents the MRS (Market Reference Size) of conger pike.

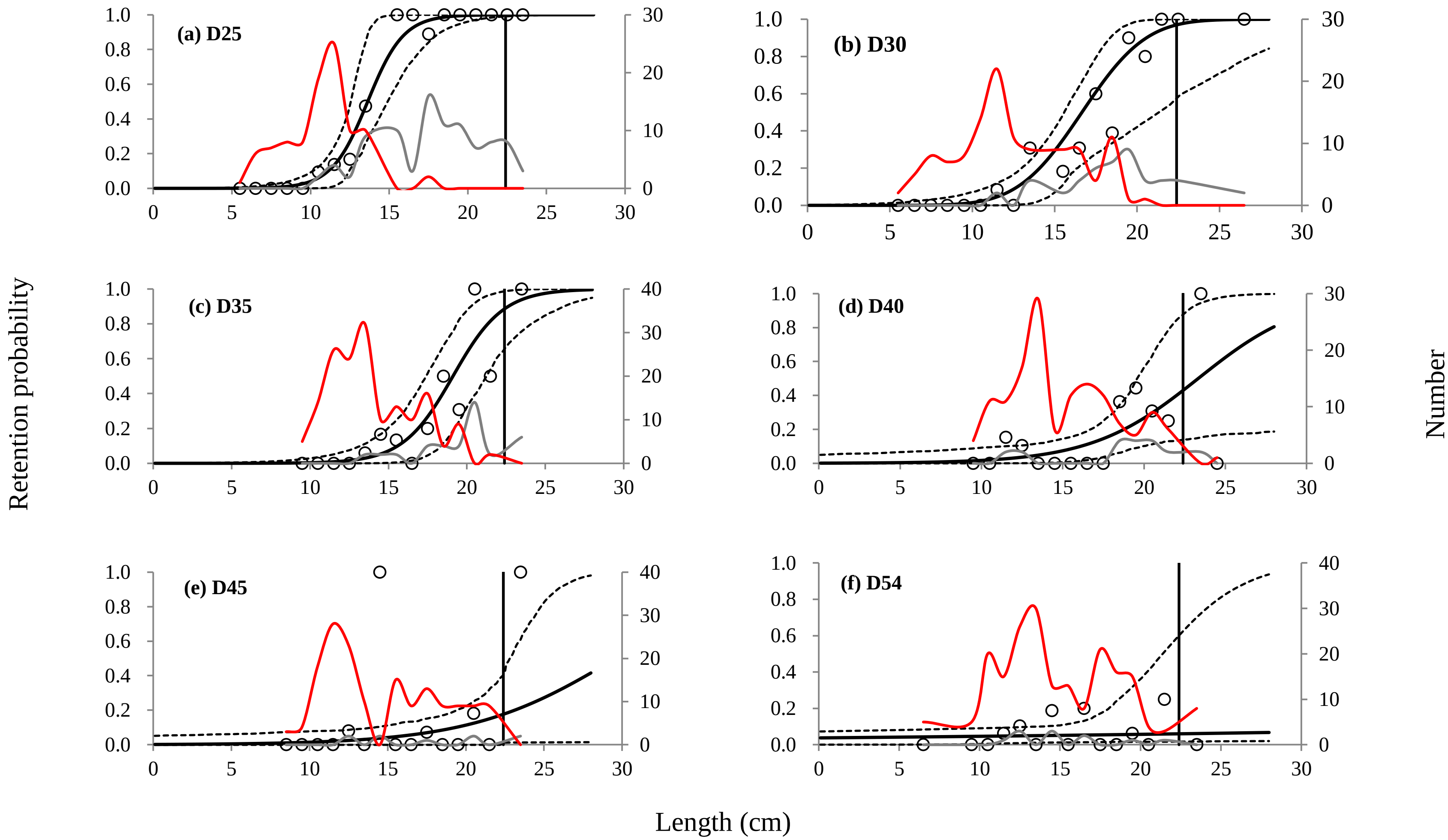

Fig. 5. Experimental catch proportion and fitted selection curves. Circle marks represent experimental catch proportion. Red curves represent the size distribution of fish caught by the cover, grey curves represent the one caught by the tested codend. Stippled curves describe the 95% confidence intervals for the fitted selection curves. Vertical lines represent the MRS (Market Reference Size) of conger pike.

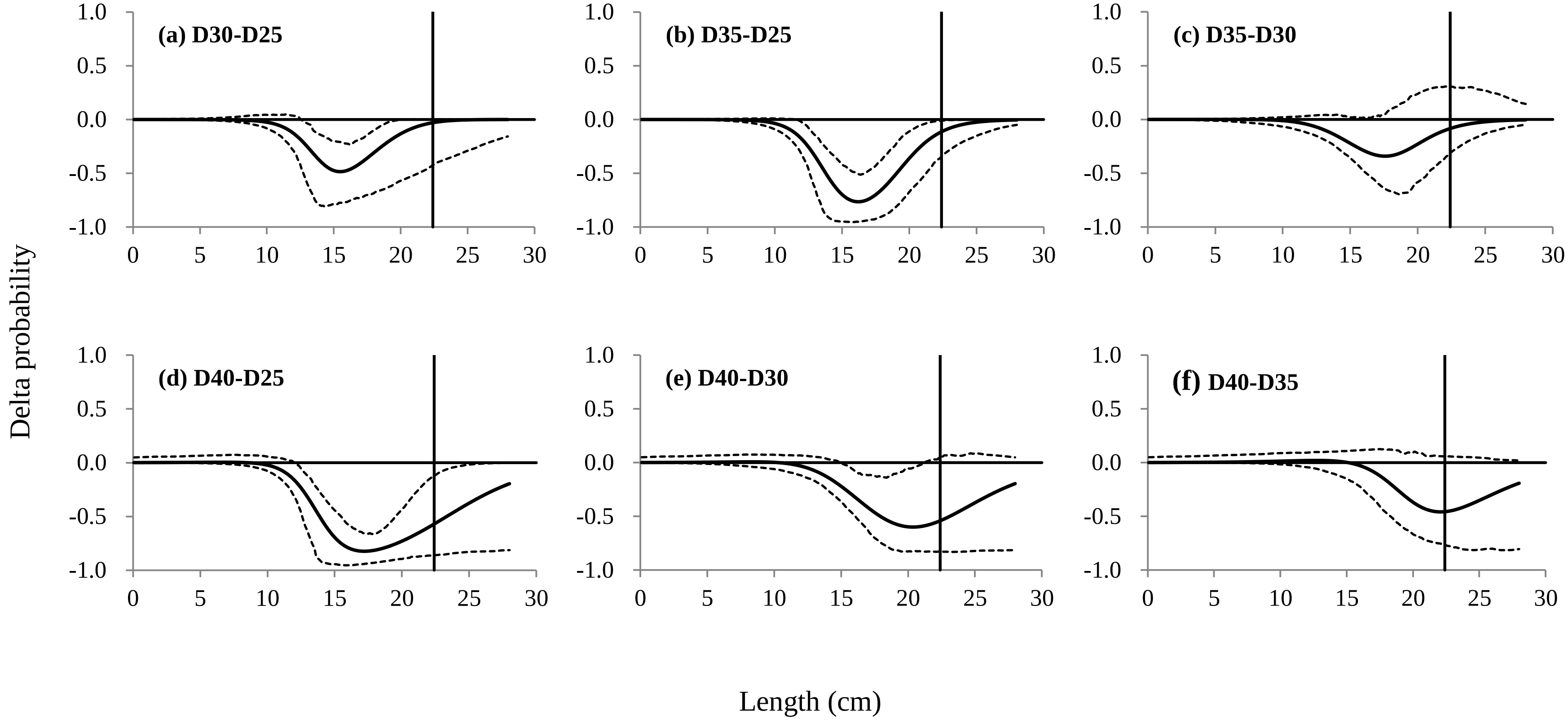

Fig. 6. Delta selectivity curves between four tested codends, the D25, D30, D35 and D40 codend. The solid black curves represent the delta selectivity for each comparison, and the stippled curves represent the 95% confidence intervals. Vertical lines represent the MRS (Market Reference Size) of conger pike.

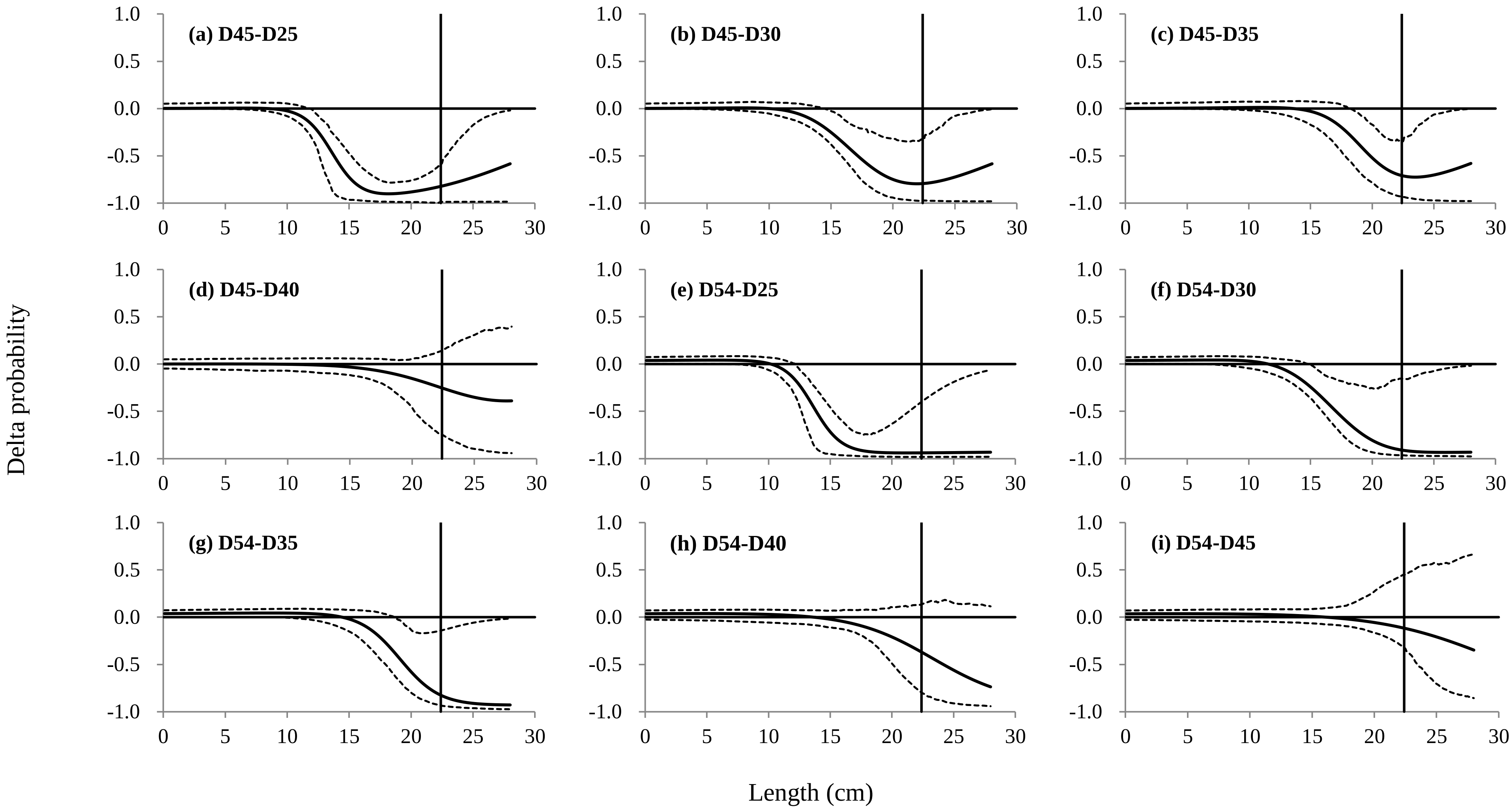

Fig. 7. Delta selectivity curves between six tested codends, the D25, D30, D35, D40, D45 and D54 codend. The solid black curves represent the delta selectivity for each comparison, and the stippled curves represent the 95% confidence intervals. Vertical lines represent the MRS (Market Reference Size) of conger pike.

Lists of Tables

Table 1. Overview of specification of the tested codends. SD represents standard errors.

codend	mesh opening±SD	twine diameter±SD	mesh number in length	mesh number in circumference
D25	25.91±1.05	1.40±0.36	220	192
D30	29.74±0.70	1.24±0.11	183	160
D35	35.70±1.14	1.31±0.10	157	137
D40	40.40±0.85	1.36±0.17	138	120
D45	44.28±0.66	1.24±0.09	122	107
D54	54.54±0.86	1.26±0.09	102	89
cover	12.51±0.78	1.18±0.10	550	480

Table 2. Catch data overview from the sea trials.

	Codend					
data specification	D25	D30	D35	D40	D45	D54
No. of hauls	8	8	8	8	7	7
Duration range (min)	118-156	118-156	128-153	128-153	120-128	120-128
No. in codend	39	22	20	10	5	8
No. in cover	96	119	98	76	51	49
Sub-sampling factor in codend	0.33-0.50	0.33-0.50	0.33-0.50	0.50-0.50	0.50-1.00	0.50-1.00
Sub-sampling factor in cover	1.00-1.00	0.50-1.00	0.33-1.00	0.25-1.00	0.25-0.33	0.20-0.33
Length range (cm)	5.0-23.5	5.8-26.6	9.2-23.5	9.8-24.2	8.4-23.6	6.7-23.9
Weight range (g)	3.7-334.2	3.8-344.9	14.9-309.3	22.1-315.8	11.2-340.2	6.7-344.0

Table 3. Akaike's information criterion (AIC) of each model for the tested codends. Selected model in bold.

codend	Models			
	Logit	Probit	Gompertz	Richards
D25	**98.65**	99.10	100.74	100.60
D30	122.83	**122.25**	123.86	124.64
D35	**119.30**	119.78	122.93	120.22
D40	**107.53**	108.29	109.28	109.34
D45	**68.63**	68.84	68.98	70.38
D54	**90.57**	90.57	90.66	92.56

Table 4. Selective parameters, fit statistics and exploitation pattern indicators obtained for the tested codends.

	Codends					
Parameters	D25	D30	D35	D40	D45	D54
model	Logit	Probit	Logit	Logit	Logit	Logit
L50	13.63 (12.56-14.90)	16.66 (15.57-21.32)	19.11 (17.40-21.28)	23.34 (19.56-53.10)	29.59 (22.82-191.48)	147.48 (21.39-195.29)
SR	2.51 (0.86-3.74)	4.12 (2.06-9.69)	3.52 (1.83-5.73)	7.24 (2.57-35.24)	10.26 (2.48-100.00)	100.00 (4.86-100.00)
nP_{-}	54.31 (41.52-66.45)	32.21 (17.34-41.11)	16.78 (6.71-28.81)	9.61 (3.45-16.40)	4.83 (0.00-11.23)	5.11 (1.29-12.49)
nP_{+}	99.98 (99.45-100.00)	98.41 (63.56-100.00)	92.98 (73.48-99.35)	50.93 (15.19-93.30)	21.47 (1.39-60.53)	6.15 (1.77-67.61)
nRatio	15.34 (8.31-32.02)	9.24 (4.67-19.61)	5.10 (1.87-11.01)	5.32 (1.50-20.75)	6.36 (0.00-33.59)	23.46 (3.79-44.39)
dnRatio	93.88 (89.25-96.97)	90.24 (82.35-95.15)	83.60 (65.15-91.67)	84.20 (60.05-95.40)	86.41 (0.00-97.11)	95.91 (79.13-97.80)
wP_{-}	79.63 (67.81-88.17)	55.29 (28.35-66.96)	33.65 (15.70-50.60)	16.46 (6.99-30.23)	7.54 (0.00-15.44)	5.40 (1.43-20.72)
wP_{+}	99.98 (99.47-100.00)	98.52 (64.49-100.00)	93.37 (74.56-99.41)	52.00 (15.20-93.64)	22.06 (1.39-62.20)	6.17 (1.78-68.48)
p-value	0.9644	0.8438	0.0831	0.0558	0.0320	0.177
deviance	7.41	9.61	19.23	21.97	23.91	17.51
DOF	16	15	12	13	13	13

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.