Reducing catch efficiency of rabbitfish (*Siganus oramin*) in a shrimp beam trawl fishery of the South China Sea

Bingzhong Yang[a, b*], Bent Herrmann[c, d, e], Zhaohai Cheng[f, g]

[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

[f] School of Resources and Environmental Engineering, Wuhan University of Technology, 122 Luoshi Road, Wuhan,Hubei, China

[g] School of Environmental Science and Engineering, Hubei Polytechnic University, 16 Guilinbei Road, Huangshi, Hubei, China

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

Abstract

The bycatch of unwanted fish species is a main concern in shrimp beam trawl fishery of the South China Sea. This study evaluated the effect of using combined square-mesh and diamond-mesh codends (CSDM codends) on catch efficiency of a shrimp trawl fishery with the catch comparison and catch ratio approach. The trouser trawl method was applied using the commercial 22-mm diamond mesh codend (D22) as the baseline. The target species, greasyback shrimp (*Metapenaeus ensis*), and main fish bycatch rabbitfish (*Siganus oramin*) were chosen as the referred species. The results demonstrated that there was no significant change for the target species but a significant reduction on the unwanted fish bycatch when the CSDM codends were used. Compared with the D22 codend, the CSDM codends would reduce the catch efficiency of greasyback shrimp by less than 18% on average, and the reduction was not statistically significant; whereas catch efficiency of rabbitfish would be significantly reduced by more than 45% and the reduction was length-dependent. The results also showed that the catch efficiency of fish bycatch would reduce as the mesh sizes of the diamond-section of the tested codends increased. These promising results demonstrate that the CSDM codends have a potential to be applied to fishery management for mitigating fish bycatch in the shrimp fishery of the studied area.

Keywords: catch efficiency, codend, greasyback shrimp, *Metapenaeus ensis*, bycatch, reduction, rabbitfish, *Siganus oramin*

Introduction

Shrimp fishery is of great social-economic importance in the South China Sea (SCS). In 2018, a total of 250 474 t of shrimp capture production was reported, accounting for 8.1% of the total marine capture production in the SCS (Chinese Fishery Statistical Yearbook, 2019). Moreover, as most of the traditional fish resources have been overexploited, the shrimp fishery is ever-increasingly important. To target shrimp species, beam trawl is one of the most widely used fishing gear in China. Fishing vessels, which conduct shrimp beam trawl fishing, are widely distributed in coastal areas of the SCS. It has been estimated that there were more than 600 shrimp beam trawlers operated in the fishing grounds of Guangdong province (Yang et al., 2015). Shrimp beam trawl is often operated along inshore areas with a water depth about 6-30 m, and one fishing vessel can haul several trawl-nets, often 2-12 nets, depending on the size of the vessel (total length 10-20 m) and its engine power (30-95 kW) (Yang, 2002; Yang, 2007).

Similar to other shrimp fisheries around the world, the major challenge is to address the issue of unwanted bycatch for the shrimp beam trawl fishery in the SCS (Broadhurst, 2000; Eayrs, 2007; Larsen et al., 2018). Some previous studies have demonstrated that shrimp beam trawling induced a serious bycatch problem due to small mesh size of codend used and the overlapping of shrimp, fish and organisms in the fishing grounds of the SCS (Yang et al., 2015; Yang et al., 2017a). These studies showed that greasyback shrimp *Metapenaeus ensis* was the target species and fish species, in which rabbitfish *Siganus oramin* was the most important one, were the main bycatch for the shrimp trawl fishery in the SCS (Yang et al., 2017a). Greasyback shrimp is an important species, which widely distributed along the SCS. It serves as the basis of the economic income for the fishermen of shrimp beam trawl. Until now, there is no minimum landing size (MLS) for greasyback shrimp in the SCS. However, some scientific studies used its first matured length, 80 mm total length, as the minimum conservation reference size (MCRS) (Yang et al., 2017b). Rabbitfish was recorded as one of the most abundant fish bycatch species. Although this species is not subjected to any bycatch quota, MLS and any other management regulations, fishermen dislike it and desire to get rid of it. Rabbitfish is very low-valued, especially the small-sized individuals, often used as fish feed in aquaculture (Zhang et al., 2020); for the other, it is manpower demanding and time-consuming to handle this unwanted species. Moreover, the fins of this fish are poisonous

(Chen et al., 2016), they may hurt fishermen during the handling process onboard. Thus, releasing rabbitfish, especially in the hauling period, will be a great benefit for the fishermen in the SCS.

To reduce the bycatch species, one technical measure is to improve selectivity through modifications of fishing gears (Broadhurst, 2000; Melli et al., 2019). Considering the fact that the codend, currently used by commercial fishing in the SCS, is diamond mesh, with small size of 18-22 mm, the simplest way to improve selectivity might be increasing the mesh size. This method seemed, however, to have little effect, as Yang et al. (2018b) demonstrated that the size selectivity of codend was hardly changed when mesh size increased from 18 mm to 30 mm. There is also another concern about the loss of target shrimp if the mesh sizes of codend further increase. To release fish bycatch, the Nordmøre grid and square mesh panel (SMP) have been proved to be successful in many fisheries (Graham et al., 2003; Herrmann et al., 2015; Larsen et al., 2017; Larsen et al., 2018). Compared with the Nordmøre grid, the SMP is more easy to install and have less impact on the fishing operation. The SMP is often used in the extension of a trawl, and the release effect largely depends on its position to the codline (Graham et al., 2003; Herrmann et al., 2015). Inspired by these literatures, Yang et al. (2017b) initially modified a codend by using two pieces of SMP to construct a combined square mesh and diamond mesh codend (CSDM), and tested it with the covered codend method. The result indicated that the novel CSDM codend had good selective properties for both shrimp and fish bycatch species. A latter test further proved that using 35 mm as the mesh size of the square-mesh section would be a good choice (Yang et al., 2018a; Yang et al., 2018b). These studies have showed that the CSDM codend had potential to address the bycatch issue in shrimp beam trawl fishery of the SCS. However, before it can be fully applied to the commercial fishery and management regulation, there are still some questions need to be addressed. For instance, will the catch efficiency change when the CSDM codend is used, compare to the present codend. From the perspective of fishermen, their largest concern is if the shrimp catch, which can be quantified by catch efficiency, will dramatically lose when the CSDM codend is used. The previous selectivity studies mentioned above focused on the selective parameters for some special species, shrimp or/and fish. None of the articles analyze the catch efficiency of shrimp bean trawl for greasyback shrimp and rabbitfish simultaneously. Additionally, using the covered codend method required a small mesh cover to retain the escapees. The existence of the cover net would make the fishing process, to some extent, different from the commercial fishing. These differences might have effect on the evaluation of the CSDM codend. Thus, the catch efficiency of the CSDM codend needs to be further tested and evaluated, especially using a sampling method close to the commercial fishing to compare with the present codend used.

To explore the concerns and questions mentioned above, we investigated the catch efficiency of the CSDM codends with a catch comparison and catch ratio analysis using the trouser trawl method. We estimated the catch efficiency of three CSDM codend designs, with the same mesh size of the square-mesh section (35 mm) but different mesh sizes in the diamond-mesh section (25, 30 and 35 mm) compared with the commercially used codend. Our study intends to address the following research questions:

1) Would the catch efficiency of the shrimp beam trawl for greasyback shrimp and rabbitfish change if the CSDM codends are used compare to the commercial codend?

2) If the catch efficiency would change, are these changes length-dependent for the target shrimp and fish bycatch?

3) How will the changes from the mesh sizes in the diamond-mesh section of the CSDM affect the fishing efficiency?

2. Materials and Methods

2.1 Sea trials

Sea trials were conducted on board the commercial fishing vessel "Yueyangdong 12081" (overall length 21 m; gross tonnage 42 t; engine power 98 kW) in September 2017. All the tows were carried out on the fishing grounds of the northern SCS (Fig. 1). Fishing time and locations were determined by the captain, and all hauls were carried out following the regular routine of commercial fishing.

2.2 Experimental design of fishing gears

To facilitate the trouser trawl data sampling, a trawl-net was constructed using the net used in the commercial fishing as the basis. We made sure that the construction of the net was identical to that of commercial one, except the part after the extension, in which two codends were attached in our trawl. The total stretched length of the net was 6.83 m with a circumference of 380 meshes with a mesh size of 36 mm, while the mesh size in the extension part was 28 mm (Fig. 2). The trawl was equipped with two beams in the net mouth, both with a length of 2.2 m, the upper one of made of bamboo, the lower one made of steel (Fig. 2). In short, the experimental trawl and its relative gear rigging were identical to the one used in commercial fishing, except for the codends.

The commercial diamond-mesh codend, with a nominal mesh size of 22 mm, was used as the standard codend (baseline codend) to test and compare with three experimental CSDM codends. Hereafter, we termed the baseline codend as D22. The stretched length of the D22 codend was about 1.15 m with a circumference of 80 meshes. This dimension was used to construct the experimental codends. All the tested CSDM codends had same stretched length as the D22 codend, whereas the mesh shape and mesh sizes were completely different. The CSDM codends constituted a square-mesh section and a diamond-mesh section, and the square-mesh section was mounted to the extension of the trawl (Fig. 2). The square-mesh section of the three CSDM codends was identical, all had 29 bars and 23 bars in the vertical and horizontal direction, made of 35-mm diamond mesh by turning 45° in the direction. The differences between the experimental codends were the mesh sizes in the diamond-mesh section, in which three nominal sizes, 25, 30 and 35 mm were used. To neutralize the potential bias of the circumference to the experiment, the mesh number reduced as the mesh sizes increased in the diamond-mesh section of the CSDM codends. Based on their mesh shape and mesh sizes, we referred to the experimental codends as S35+D25, S35+D30 and S35+D35, respectively (Fig. 2). For them, the mesh sizes of the diamond-mesh section increased from 25 mm to 35 mm.

Normally, in a paired-gear experiment the side of the test and control codends should be switched regularly to avoid possible side-based effects (Pol et al., 2016). In our experiments, however, we kept the place of the test and control codends due to: 1) the safety of gear operation; 2) potential haul-back escape effect. In our fishing vessel, there was only one net drum located in the starboard that is the situation for many shrimp beam trawl vessels in the SCS. So, the codend close to the net drum should be hauled back firstly for the convenience and safety consideration. This can give rise to a question that which one of the codend should be placed in that position and hauled back first, while the other would remain in water for a longer time (about 5-10 min). In order to reduce the potential haul-back escape effect, we kept hauling the experimental codends firstly. Because some studies have demonstrated that fish would escape during the haul-back operation (Madsen et al., 2008; Madsen et al., 2012), if the tested codends were retrieved after the baseline codend, there was great potential that some fish would escape during that period, especially considering our experimental codends were substantially different from the baseline codend, both in mesh size and mesh shape.

Our experimental gears were fishing together with other commercial fishing trawl onboard the same vessel. Given the fact that the fishing vessel hauled 12 trawls simultaneously, we placed our tested trawl in a position closest to the vessel (Fig. 2), to make sure that our gear was hauled up first. During experimental fishing, the tested codends were mounted one at a time for a group of hauls to the same extension. For each haul, catches from the tested codend and the baseline codend were handled separately, and classified into species level. The target and bycatch species were weighed and counted, and the total length of each catch individual was measured. As the length measurement was carried out onboard, to make sure measurement finish before the arrival on deck of the next haul, some species were sub-sampled if the catch individuals were too large.

2.3 Modeling and estimation of the catch efficiency between treatment and baseline codend

We used the statistical analysis software SELNET (Herrmann et al., 2012, 2016) to analyze the catch data and conduct length-dependent catch comparison and catch ratio analyses. Using the catch information (numbers and sizes of shrimp and bycatch species in the two codends fished in parallel), we wanted to determine whether there was a significant difference in the catching efficiency, averaged over deployments, between the baseline (D22) and treatment codend. We also wanted to determine if any potential differences in catch rates were size dependent for shrimp or the bycatch species. The analysis was carried out separately for shrimp and bycatch species and separately for each treatment codend following the procedure described below.

Specifically, to assess the effect of changing from the baseline codend to each of the treatment codends (S35+D25, S35+D30 and S5+D35), we used the method described in Herrmann et al. (2017) and compared the catch data for the two codends fished simultaneously. This method models the length-dependent catch comparison rate (CC_l) summed over hauls:

$$CC_l = \frac{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}+\frac{ns_{lj}}{qs_j}\right\}} \quad (1)$$

where nt_{lj} and ns_{lj} are the numbers of fish length measured in each length class l for the treatment and standard codend in haul j, qt_j and qs_j are subsampling factors quantifying the fraction, based on weight, of the catch in the codends being length-measured in the respective hauls, m is the number of hauls conducted with the specific treatment design. The functional form for the catch comparison rate $CC(l,\mathbf{v})$ (the experimental being expressed by equation 1) was obtained using maximum likelihood estimation by minimizing the following expression:

$$-\sum_l \left\{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\times \ln\left(CC(l,v)\right)+\frac{ns_{lj}}{qs_j}\times \ln\left(1.0-CC(l,v)\right)\right\}\right\} \quad (2)$$

where $\mathbf{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\mathbf{v})$. The outer summation in the equation is the summation over length class l. When the catch efficiency of the baseline and treatment codend is similar, the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge whether or not there is a difference in catch efficiency between the two codends. The experimental CC_l was modelled by the function $CC(l,\mathbf{v})$ using the following equation:

$$CC(l,v)=\frac{\exp(f(l,v_0\ldots,v_k))}{1+\exp(f(l,v_0\ldots,v_k))} \quad (3)$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\mathbf{v}$ describing $CC(l,\mathbf{v})$ were estimated by minimizing equation (2), which was equivalent to maximizing the likelihood of the observed catch data. We considered f of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison $CC(l,\mathbf{v})$. Among these models, estimations of the catch comparison rate were made using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017; Grimaldo et al., 2018).

The ability of the combined model to describe the experimental data was evaluated based on the *p*-value. The *p*-value, which was calculated depending on the model deviance and the degrees of freedom, should not be < 0.05 for the combined model to describe the experimental data sufficiently well, except for cases in which the data are subject to over-dispersion (Wileman et al., 1996; Herrmann et al., 2017). Based on the estimated catch comparison function *CC(l,**v**)* we obtained the relative catch efficiency (also named catch ratio) *CR(l,**v**)* between the two codends fished simultaneously using the following relationship:

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

The catch ratio is a value that represents the relationship between catch efficiency of the treatment and baseline codend. Thus, if the catch efficiency of both codends is equal, *CR(l,**v**)* should always be 1.0. *CR(l,**v**)* = 1.5 would mean that the treatment codend is catching 50% more of the species with length *l* than the baseline codend. In contrast, *CR(l,**v**)* = 0.8 would mean that the treatment codend is only catching 80% of the species with length *l* than the catching of the baseline codend.

The confidence intervals (CIs) for the catch comparison curve and catch ratio curve were estimated using a double bootstrapping method (Herrmann et al., 2017). This bootstrapping method accounts for between-haul variability (the uncertainty in the estimation resulting from between haul variation of catch efficiency in the codends as well as within-haul variability, uncertainty about the size structure of the catch for the individual hauls including the effect of subsampling). However, contrary to the double bootstrapping method (Herrmann et al., 2017), the outer bootstrapping loop in the current study accounting for the between haul variation was performed paired for the treatment and baseline codend, taking full advantage of the experimental design with the codends being fished in parallel in the same hauls. By multi-model inference in each bootstrap iteration, the method also accounted for the uncertainty due to uncertainty in model selection. We performed 1000 bootstrap repetitions and estimated the Efron 95% (Efron, 1982) confidence bands. To identify sizes of species with significant differences in catching efficiency, we checked for length classes in which the 95% confidence bands for the catch ratio curve did not contain 1.0.

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

$$
\begin{aligned}
CR_{average} &= \frac{\sum_{l}\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l}\sum_{j=1}^{m}\left\{\frac{ns_{lj}}{qs_j}\right\}} \\
CR_{average-} &= \frac{\sum_{l<MCRS}\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l<MCRS}\sum_{j=1}^{m}\left\{\frac{ns_{lj}}{qs_j}\right\}} \\
CR_{average+} &= \frac{\sum_{l\geq MCRS}\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l\geq MCRS}\sum_{j=1}^{m}\left\{\frac{ns_{lj}}{qs_j}\right\}}
\end{aligned}
\quad (5)
$$

where the outer summations include the size classes in the catch during the experimental fishing period that were under (for $CR_{average-}$) and over (for $CR_{average+}$) the MCRS (80 mm for the shrimp). In contrast to the size-dependent evaluation of the catch ratio $CR(l,v)$, $CR_{average}$, $CR_{average-}$ and $CR_{average+}$ are specific for the population structure encountered during the experimental trials. Therefore, those values are specific for the size structure in the fishery at the time the trials were carried out, and it cannot be extrapolated to other scenarios in which the size structure of the shrimp or bycatch species population may be different unless it should turn out that the catch ratio between the two types of codends fished simultaneously show no dependency of shrimp or bycatch length.

Finally, to investigate how well the size selectivity of the treatment and baseline codends matched the size structure of shrimp species in the area fished, two fishing sustainability indicators (*NRatio*) were estimated directly from the experimental catch data by:

$$NRatio_{Treatment} = \frac{\sum_{l<MCRS}\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l\geq MCRS}\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}$$
$$NRatio_{Baseline} = \frac{\sum_{l<MCRS}\sum_{j=1}^{m}\left\{\frac{ns_{lj}}{qs_j}\right\}}{\sum_{l\geq MCRS}\sum_{j=1}^{m}\left\{\frac{ns_{lj}}{qs_j}\right\}} \quad (6)$$

where the outer summations include the size classes in the catch during the experimental fishing period that were under (in the nominator) and over (in the denominator) the MCRS of shrimp. *NRatio* quantifies the ratio between undersized and target sizes of the species captured. Ideally, *NRatio* should be as low as possible. The value of *NRatio* is affected by both the size selectivity of the codend and the size structure of the species in the fishing grounds. Therefore, it provided an estimate that is specific for the population fished and it could not be extrapolated to other areas and seasons. Uncertainties for the indicators described by equations (5) and (6) were obtained in terms of Efron 95% confidence bands using the double bootstrap method described above.

2.4 Method for estimating relative catch efficiency between the three treatment codends

With the approach described above we can quantify by equations (1)-(4) the length-dependent ratio in catch efficiency between the each of the treatment codends and the baseline codend. Considering that each of the treatment codends (S35+D25, S35+D30 and S35+D35) are compared to the same baseline codend, we can obtain an estimate for relative catch efficiency between the three codends by:

276

$$CR(l)_{(S35+D30)/(S35+D25)} = \frac{CR(l)_{S35+D30}}{CR(l)_{S35+D25}}$$
$$CR(l)_{(S35+D35)/(S35+D25)} = \frac{CR(l)_{S35+D35}}{CR(l)_{S35+D25}} \quad (7)$$
$$CR(l)_{(S35+D35)/(S35+D30)} = \frac{CR(l)_{S35+D35}}{CR(l)_{S35+D30}}$$

277 Where $CR(l)_{S35+D25}$, $CR(l)_{S35+D30}$ and $CR(l)_{S35+D35}$ are the length-dependent catch ratios
278 (obtained by equations (1)-(4)) for each of the treatment codends against the baseline codend,
279 respectively. For simplicity, we have omitted the parameter $\boldsymbol{v}$ in the notation. We obtained
280 95% confidence intervals for $CR(l)_{(S35+D30)/(S35+D25)}$, $CR(l)_{(S35+D35)/(S35+D25)}$ and $CR(l)$
281 $_{(S35+D35)/(S35+D30)}$ based on the three bootstrap population of results (1,000 bootstrap repetitions
282 in each) for respectively $CR(l)_{S35+D25}$, $CR(l)_{S35+D30}$ and $CR(l)_{S35+D35}$ as they are obtained
283 independently. Using these bootstrap results, we created new bootstrap populations of results
284 by:

285

$$CR(l)_{(S35+D30)/(S35+D25)j} = \frac{CR(l)_{(S35+D30)j}}{CR(l)_{(S35+D25)j}}$$
$$CR(l)_{(S35+D35)/(S35+D25)j} = \frac{CR(l)_{(S35+D35)j}}{CR(l)_{(S35+D25)j}} \; j \in [1 \ldots 1000] \; (8)$$
$$CR(l)_{(S35+D35)/(S35+D30)j} = \frac{CR(l)_{(S35+D35)j}}{CR(l)_{(S35+D30)j}}$$

286 where j denotes the bootstrap repetition index. Because sampling was random and
287 independent for the three groups of results, it is valid to generate the bootstrap populations of
288 results for the ratios based on (8) using the three independent generated bootstrap files
289 (Herrmann et al., 2018). Based on the bootstrap populations we can obtain Efron 95%
290 percentile confidence limits for $CR(l)_{(S35+D30)/(S35+D25)}$, $CR(l)_{(S35+D35)/(S35+D25)}$ and $CR(l)$
291 $_{(S35+D35)/(S35+D30)}$.

292 3. Results

293 *3.1. Description of sea trial conditions and catches*

A total of 30 hauls, 11 hauls for the S35+D25 codend, 11 hauls for the S35+D30 codend and 8 hauls for the S35+D35 codend, were finished during the experimental fishing. Only one haul for the S35+D30 codend was invalid due to malfunctioning of the codline. The water depth of the fishing grounds was mainly 6 to 12 m. Haul duration was between 1.00 and 4.75 h, towing speed ranged from 2.4 to 2.6 knots, and covered distance varied from 4.63 to 21.11 km (Table 1). A total weight of 123.98 kg was obtained, and several species were caught and identified. Among them, the target species, greasyback shrimp, and main bycatch species, rabbitfish, were predominantly captured for all hauls. These two dominant species accounted for about 32.84% and 72.63% by weight and number of the total catch from the fishing trials. Hence, they were the species for further analysis. All the catch length data from these two species in valid hauls was put together to analyze their relative catching efficiency.

3.2. Catch comparison between the CSDM codends and the baseline codend

3.2.1.Greasyback shrimp

Compared with the baseline codend, the catch number of greasyback shrimp from the tested codend seemed a little smaller. For instance, the S35+D25 codend caught 1176 individuals, whereas its baseline codend had 1434, and the comparison of the S35+D30 and S35+D35 codend to their relative baseline was 285 vs. 340 and 120 vs. 139, respectively (Table 1). The subsampling ratio varied from 0.17 to 1.0. The length classes of greasyback shrimp ranged from 6 to 14 cm.

The length-dependent catch comparison and catch ratio rates were estimated and plotted for the three CSDM codends using the commercial D22 codend as baseline (Fig. 3). For the three tested codends, the length-dependent catch comparison rates described the main trend in the experimental data sufficiently well. Therefore, the low *p*-value for the S35+D25 codend was probably due to overdispersion the catch data. The length-integrated average values

($CR_{average}$) indicated that the S35+D25, S35+D30 and S35+D35 codend caught 17.78%, 0.40% and 14.29% fewer shrimp than the baseline codend (Table 2). These differences, however, were not statistically significant, as expressed by their wide confidence intervals, which all covered 100%. Similar trend was found for $CR_{average-}$, $CR_{average+}$ and sustainability indicators (*NRatio*).

The catch comparison and catch ratio curves (Fig. 3), together with the individual $CR(l, v)$ for length class from 6 to 14 cm (Table 2), showed that the relative catch efficiency of the S35+D25 codend increased as the length of shrimp enlarged, while the relative catch efficiency of the S35+D30 reduced a little bit and S35+D35 codend seemed unchanged. Nevertheless, all these changes were not statistically significant, due to their wide confidence intervals.

3.2.2. Rabbitfish

The catch number of rabbitfish from the experimental codends was substantial smaller with respect to that of the baseline codend. The number comparison was 160 vs. 401, 242 vs. 570 and 64 vs. 180 for the S35+D25, S35+D30, and S35+D35 codend, compared with their relative baseline compartment (Table 1). The length classes of rabbitfish ranged from 4 cm to 11 cm.

The length-dependent catch comparison and catch ratio rates were estimated and plotted for the three CSDM codends using the commercial D22 codend as baseline (Fig. 4). For the three tested codends, the length-dependent catch comparison rates described the main trend in the experimental data sufficiently well. Therefore, the low *p*-values for the S35+D25 and S35+D30 codend were probably due to overdispersion of the catch data. The values of average catch ratio demonstrated that the catch efficiency would significantly reduce by 60.10%, 45.98% and 65.41% for the S35+D25, S35+D30 and S35+D35 codend, respectively (Table 3).

For the S35+D25 codend, the relative catch efficiency was significantly lower than the baseline for fish at the length range of 5.2-7.1 cm. Compared with the baseline codend, the S35+D30 codend would always had lower catching efficiency, and the differences were significant for fish with length smaller than 7.2 cm. For rabbitfish with length less than 7.9 cm, the S35+D35 codend would significantly have lower catch efficiency (Fig. 4). The individual *CR(l, v)* for length class from 4.5 to 10 cm (Table 3) also demonstrated the same trend for the three tested codends.

3.3. Estimation of catch efficiency between three CSDM codends

The relative catch efficiency of the three CSDM codends was compared and plotted (Fig. 3 and Fig. 4). Compared with the S35+D25 codend, both the S35+D30 and S35+D35 codend had higher efficiency for greasyback shrimp with length less than 10 cm, whereas the S35+D35 codend had less efficiency for shrimp with length larger than 7 cm than the S35+D30 codend (Fig. 3). All these differences, however, were not statistically significant, due to their confidence intervals covered the zero effect baseline (100%).

For rabbitfish, there was no significant difference between catch efficiency between the S35+D25 and S35+D30 codend, as the confidence intervals of their relative catch ratio covered the boundary of 100% for all available length classes (Fig. 4). The catch efficiency of the S35+D35 codend was significantly lower than that of the S35+D25 codend for fish with length in the range from 6.6 to 6.9 cm. Compared with the S35+D30 codend, the catch efficiency of the S35+D35 codend was significantly smaller for fish with length ranging from 6.1 to 7.4 cm.

4. Discussion

Our results showed that there was no significant change for the target species but a significant reduction on the unwanted bycatch when the CSDM codends were applied.

Compared with the commercial baseline codend, D22, the CSDM codends would reduce the catch efficiency of greasyback shrimp by less than 18%. None of these changes, however, was statistically significant. For the fish bycatch species, rabbitfish, reduction in catch efficiency was greater than ~45% when the CSDM codends were applied, and all these changes were significant. Changes of catch efficiency for rabbitfish were length dependent, and increasing the mesh sizes of the diamond-mesh section would release more undersized fish. These promising results demonstrate that the CSDM codends have a potential for mitigating bycatch issues by reducing rabbitfish in the studied area.

The catch comparison analysis method applied here is often considered as the relative size selectivity (Herrmann et al., 2017). There are many factors affecting the selective properties of a given codend for a specific species (Wileman et al., 1996). Among them, the mesh size and mesh shape are of great importance. The configuration of a CSDM codend is similar to that of codends with a SMP, such as the well-known BACOMA codend used in the Baltic Sea trawl fishery (Graham et al., 2003; Frandsen et al., 2011; Wienbeck et al., 2014; Krag et al., 2017). But compared with the BACOMA codend, the square mesh panel in a CSDM codend covers the whole circumference of the front part of the codend. This characteristic might provide more opportunities for fish to escape. Moreover, previous studies had proven that the release efficiency of a SMP largely affected by its position to the codline, when it was placed in the catch accumulation zone (0-6 m from the codline) it would have a good effect, and the closer it moved to the codline the higher selective properties it would obtained (Graham et al., 2003; Herrmann et al., 2015; Fryer et al., 2016). In our experiments, the square mesh part was only 0.39 m to the codline. It overlapped with the catch accumulation zone, fish would have opportunities to change their swimming direction and attempt to escape during the fishing process.

As recommended by Wileman et al. (1996) that it would not to leave the tested codend in the water while the baseline codend was hauled up first, and some studies have demonstrated that fish did escape during the haul-back process (Madsen et al., 2008; Madsen et al., 2012). So, in our experimental trial, we did not switch the position of the two codends, the test and baseline, and the test codend would be hauled up first. One concern is whether this experimental design would underestimate the catch efficiency of the tested codends if fish escape from the baseline codend during the haul-back operation. Considering that the baseline codend was diamond mesh and with a small mesh size of 22 mm, we assume that relatively few of fish and shrimp could escape from it during the haul-back period. Because Yang et al. (2018b) have demonstrated that the diamond-mesh codend with 25 mm mesh size was nearly non-selective for greasyback shrimp. A conclusion also drawn by Zhang et al. (2010) that it would be applicable to regard the diamond-mesh codend, with mesh size close to 20 mm, as non-selective in China.

Several relevant studies have proved that contact probability between fish and selective devices should be seriously taken into account (Bayse et al., 2016; Santos et al., 2016; Herrmann et al., 2019). Recently, the definition of contact probability has been formally written in Report of the ICES-FAO Working Group on Fishing Technology and Fish Behavior (WGFTFB) in 2018 (ICES, 2018). To roughly estimate the contact probability of the two specific species to the tested CSDM codends, the structural model (Clogit) in Santos et al. 2016 was applied to analyze the fishing data, by assuming the baseline codend to be nonselective. The result indicated that contact ratio of greasyback shrimp was 45.27% (CI: 27.34%-96.88%), 45.59% (CI: 9.63%-99.25%) and 22.67% (CI: 10.41%-100.00%) to the S35+D25, S35+D30 and S35+D35 codend, respectively, whereas for rabbitfish, the relative value was 84.64% (CI: 51.66%-99.06%), 100.00% (CI: 46.08%-100.00%) and 94.81% (CI: 79.03%-100.00%), respectively. These results indicate that less than 50% of greasyback shrimp on average contacted the tested codends, whereas more than 84% of rabbitfish contacted the tested codend. A high contact probability may contribute to a lower catch efficiency of the CSDM codends for rabbitfish. These differences in contact probability might explain why the tested codends had significant lower efficiency for rabbitfish, and not for greasyback shrimp. The variation of contact probability between the two species might be due to their behavioral differences, especially in the codends. There is no literature regarding the swimming and behavior for the studies species, and related investigation is needed.

As concluded by Sala et al. (2015), it might be difficult to simultaneously improve the size selectivity of both fish and shrimp species due to large differences in their morphological characteristics. In our case, the effect for greasyback shrimp, especially for the undersized individuals, was not significant, and there is still a large proportion, ~54%, of rabbitfish caught by the CSDM codends. To further reduce undersized shrimp and the fish bycatch, their morphological and behavioural differences should be investigated. FISHSELECET (Herrmann et al., 2009) will be an option to distinguish the morphological differences between fish and shrimp species. To identify the behavioural difference of target species and bycatch species, underwater video recording technique should be added to the selective experiments, as Larsen et al. (2017, 2018) did.

As our results show that the CSDM codends have great potential in reducing fish bycatch for the shrimp fishery, the questions become that which one of the tested CSDM codend is the best and how its designs affect the catching efficiency? We tried to explore these questions by comparing the catch ratio between the three tested CSDM codends. The results show that the catch efficiency would, to some extent, reduce as the mesh sizes of the diamond-section increase. Comparing with the S35+D25 and S35+D30 codend, the S35+D35 codend would significantly have lower catch efficiency for fish with a specific length ranges. In short, the

S35+D35 codend had the best performance both in the length-integrated and length-dependent catch efficiency for rabbitfish.

Using the trouser trawl method would eliminate the need of a complicated retrieving procedure and the potential masking-effect, while it failed to collect escapees from the codends. As mentioned above, the selective properties of a CSDM codend are contributed both by the square-mesh and diamond-mesh. To fully understand its selectivity and catching efficiency, it needs to quantify the number of escapees from the square-mesh section and the diamond-mesh section, separately. Though the objective of this study is to evaluate the catch efficiency of the three CSDM codends, it will be benefit to quantify the contribution of the size selectivity from the square-mesh section and diamond-mesh section, respectively. A three-compartment setup by using the covered codend method should be tried and tested in the future (Sistiaga et al., 2010).

In conclusion, our results demonstrate that the CSDM codends have potential to be applied to commercial fishing and fisheries management. Because it satisfies the fishermen by maintaining target shrimp catch, meanwhile reducing unwanted fish bycatch. However, the issue about the catch of undersized shrimp needs to be addressed. Therefore, to further improve the selective properties and optimize the exploitation pattern of the CSDM codends, more future experiments are strictly needed.

ACKNOWLEDGEMENTS

We would like to thank the crew of shrimp beam vessels "*Yueyangdong 12081*" for their cooperation during sea trials. This work was funded by Central Public-interest Scientific Institution Basal Research Fund, South China Sea Fisheries Research Institute, CAFS (NO. 2020YJ01 and 2019CY0303), National Key R&D Program of China (2018YFC1407500 and 2018YFC1407505), and financial support of Ministry of Agriculture and Rural Affair "Standard and management regime of fishing gears".

REFERENCES

Bayse, S. M., Herrmann, B., Lenoir, H., Depestele, J., Polet, H., Vanderperren, E., Verschueren, B., 2016. Could a T90 mesh codend improve selectivity in the Belgian beam trawl fishery? Fish. Res. 174, 201–209.

Broadhurst, M. K., 2000. Modifications to reduce bycatch in prawn trawls: A review and framework for development. Rev. Fish Bio. Fish. 10, 27–60.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference: A Practical Information-theoretic Approach, 2nd edition. Springer, New York.

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)

Chinese Fishery Statistical Yearbook, 2019. Bureau of Fihseries, Ministry of Agriculture and Rural Affairs. China Agriculture Press, Beijing.

Eayrs, S., 2007. A Guide to Bycatch Reduction in Tropical Shrimp-Trawl Fisheries [Revised edition]. FAO, Rome.

Efron, B., 1982. The jackknife, the bootstrap and other resampling plans. In: SIAM Monograph No. 38, CBSM-NSF Regional Conference Series in Applied Mathematics, Philadelphia.

Frandsen, R. P., Herrmann, B., Krag, L.A., 2011. Development of a codend concept to improve size selectivity of Nephrops (*Nephrops norvegicus*) in a multi-species fishery. Fish. Res. 111, 116–126.

Fryer, R. J., O'Neill, F.G., Edridge, A., 2016. A meta-analysis of haddock size-selection data. Fish Fish. 17, 358–374.

Graham, N., Kynoch, R.J., Fryer, R.J., 2003. Square mesh panel in demersal trawls: further data relating haddock and whiting selectivity to panel position. Fish. Res. 62, 361–375.

Grimaldo, E., Herrmann, B., Vollstad, J., Su, B., Moe, F., Larsen, R.B., Tatone, I., 2018. Fishing efficiency of biodegradabale PBSAT gillnets and conventional nylon gillnets used in Norwegian cod (*Gadus morhua*) and saithe (*Pollachius virens*) fishieries. ICES J. Mar. Sci. 75, 2245–2256. https://doi.org/10.1093/icesjms/fsy108.

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.

Herrmann, B., Wienbeck, H., Karlsen, J., Stepputtis, D., Dahm, E., Moderhak, W., 2015. Understanding the release efficiency of Atlantic cod (*Gadu morhua*) from trawls with a square mesh panel: effects of panel area, panel position, and stimulation of escape response. ICES J. Mar. Sci. 72, 686–696.

Herrmann, B., Krag, L.A., Feekings, J., Noack, T., 2016. Understanding and predicting size selection in diamond-mesh codends for Danish seining: a study based on sea trials and computer simulations. Mar. Coast. Fish. 8, 277–291. https://doi.org/10.1080/19425120.2016.1161682.

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

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

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

ICES, 2018. Report of the ICES-FAO Working Group on Fishing Technology and Fish Behaviour (WGFTFB), 4-8 June 2018, Hirtshals, Denmark.

Krag, L. A., Herrmann, B., Feekings, J., Lund, H.S., Karlsen, J.D., 2017. Improving escape panel selectivity in Nephrops-directed fisheries by actively stimulating fish behavior. Can. J. Fish. Aquatic. Sci. 74, 486–493.

Larsen, R. B., Herrmann, B., Sistiaga, M., Brinkhof, J., Tatone, I., Langård, L., 2017. Performance of Nordmøre Grid in Shrimp Trawling and Potential Effects of Guiding Funnel Length and Light Stimulation. Mar. Coast. Fish. 9, 479–492.

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, 1–16.

Madsen, N., Skeide, R., Breen, M., Krag, L.A., Huse, I., Soldal, A., 2008. Selectivity in a trawl codend during haul-back operation—An overlooked phenomenon. Fish. Res. 91, 168–174.

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. Aquati. Living Resour. 25, 231–240.

Melli, V., Herrmann, B., Karlsen, J., Feekings, J., 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

Pol, M.V., Herrmann, B., Rillahan, C., He, P., 2016. Selectivity and retention of pollock Pollachius virens in a Gulf of Maine trawl fishery. Fish. Res. 184, 47–53.

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

Sala, A., Lucchetti, A., Perdichizzi, A., Herrmann, B., Rinelli, P., 2015. Is square-mesh better selective than larger mesh? A perspective on the management for Mediterranean trawl fisheries. Fish. Res. 161, 182–190.

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

Wienbeck, H., Herrmann, B., Feeking, 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 (*Pleronectes platessa*). Fish. Res. 150, 28–37.

Wileman, D., Ferro, R.S.T., Fonteyne, R., Millar, R.B. (Eds), 1996. Manual of Methods of Measuring the Selectivity of Towed Fishing Gear. ICES Cooperative Research Report No. 215.

Yang, B., Yang, L., Zhang, P., Tan, Y., Yan, L., Chen, S., 2015. Fish by-catch of shrimp beam trawl in the northern South China Sea. J. Appl. Ichth. 31, 714–717.

Yang, B., Yang, L., Tan, Y., Yan, L., Zhang, P., Li, J., 2017a. Analysis of composition of two shrimp beam trawls in South China Sea. South China Fish. Sci. 13, 115–122. (in Chinese, with an English abstract)

Yang, B., Yang, L., Tan, Y., Yan, L., Zhang, P., Li, J., 2017b. Preliminary study of catching performance of a combined diamond- and square-mesh cod-end of a shrimp beam trawl in the northern South China Sea. Mar. Sci. 41, 57–64. (in Chinese, with an English abstract)

Yang, B., Yang, L., Tan, Y., Yan, L., Zhang, P., Li, J., 2018a. Size selectivity of combined square mesh and diamond mesh codends of shrimp beam trawl in South China Sea. South China Fish. Sci. 14, 105–113. (in Chinese, with an English abstract)

Yang, B., Yang, L., Tan, Y., Yan, L., Zhang, P., Li, J., 2018b. Size selectivity of combined square and diamond mesh codends of shrimp beam trawl for banded scad *Caranx (Atule) kalla* in the northern South China Sea. J. Oceanol. Limnol. 36, 1880–1890.

Yang, L. 2002. Marine fishing gears and fishing methods in the South China Sea. Guangdong Science & Technology Press, Guangzhou. (in Chinese)

Yang, L., Tan, Y., Zhang, X., 2002. Selectivity of square and diamond mesh codends of bottom trawl nets in South China Sea. Journal of Zhanjiang Ocean University 22, 19–25. (in Chinese, with an English abstract)

Yang, L. 2007. Small-scaled marine fishing gears and fishing methods in the South China Sea. Guangdong Science & Technology Press, Guangzhou. (in Chinese)

Zhang, J., Shi, J., Zhang, P., Sun, M., 2010. Selection of the mesh size of control codend in analysis of size selectivity of multi-codends beam trawls. J. Fish. China 34:160–167. (in Chinese, with an English abstract)

578 Zhang, W., Liu, M., Sadovy de Mitcheson, Y., Cao, L., Leadbitter, D., Newton, R., Little, D., 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

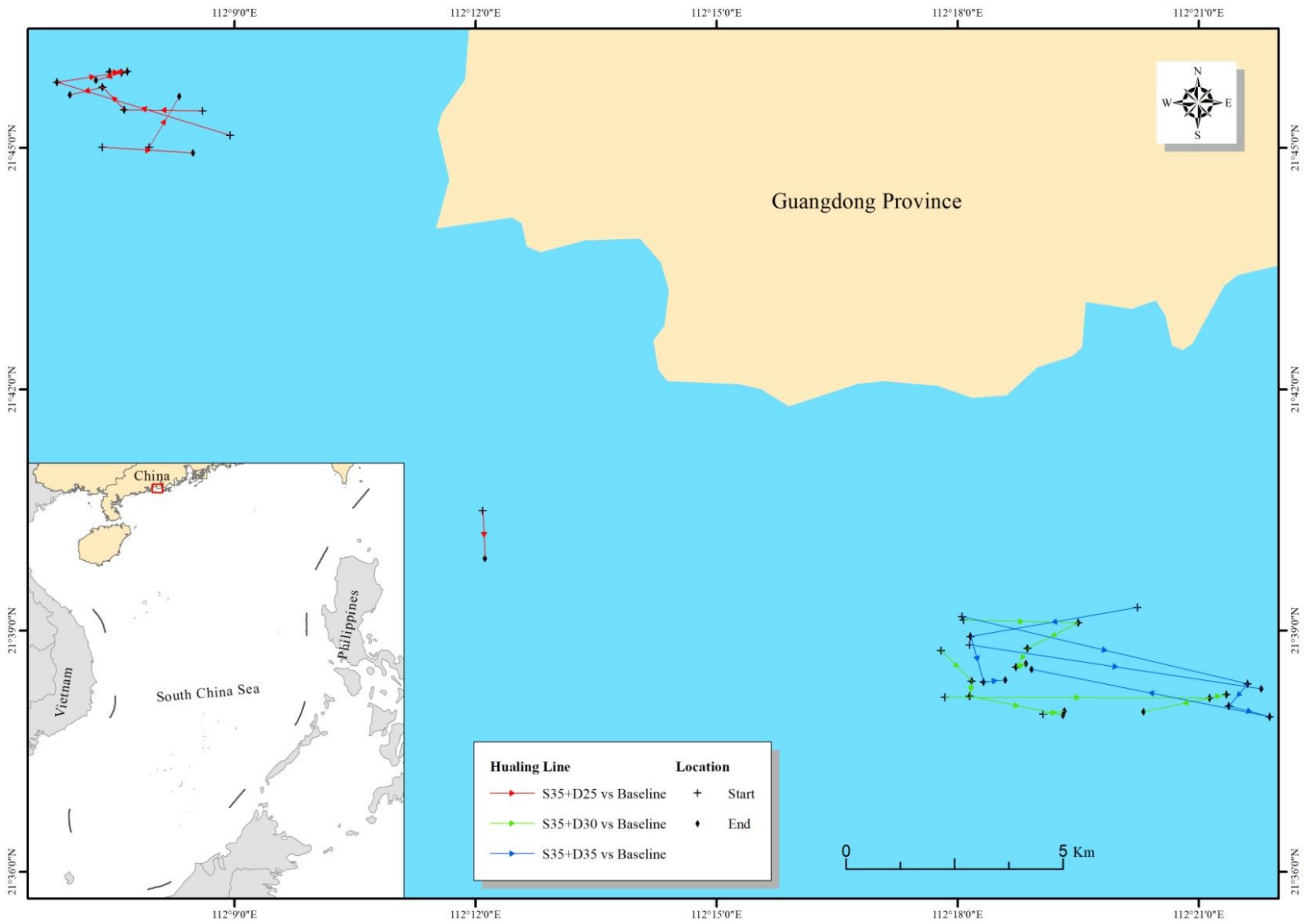

Fig. 1. Location of sea trials: the colorful lines represent hauling lines (red lines represent the S35+D25 vs Baseline comparison, purple lines represent the S35+D30 vs Baseline comparison, and green lines represent the S35+D35 vs Baseline comparison, respectively).

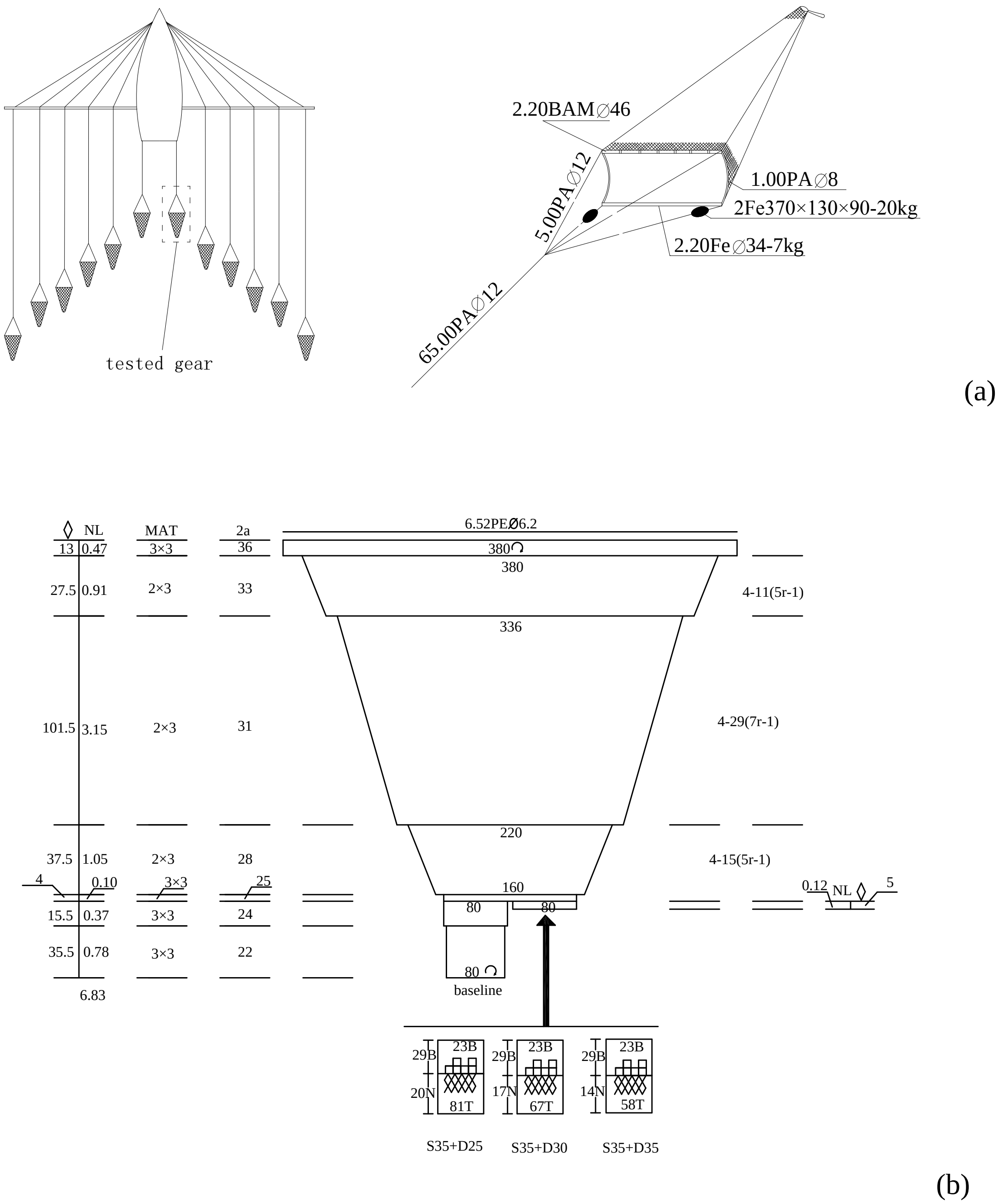

Fig.2. Schematic drawing of the shrimp beam trawl (a). The detailed net plan of the trouser trawl, the baseline codend and three tested CSDM cod ends (b).

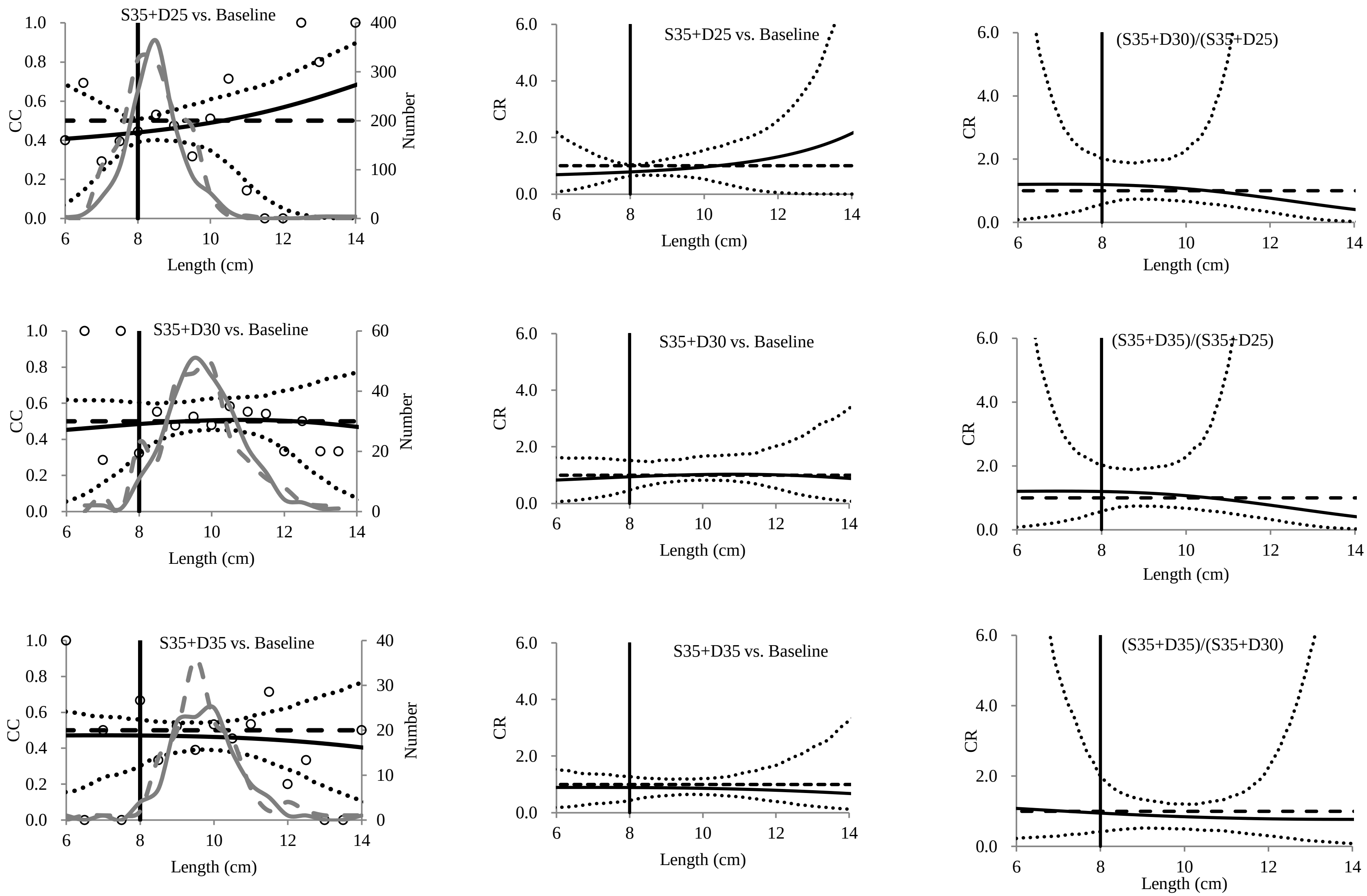

Fig. 3. Catch comparison rate (CC, first column), catch ratio (CR, second column) and catch ratio comparison (CR, third column) curves of the three CSDM cod ends for greasyback shrimp. The circle marks represent the experimental rates. The thin dotted curves

represent the 95% confidence limits for the CC and CR curves. The grey full-line curves represent summed population for the tested CSDM codends. The grey stippled curves represent summed population for the baseline cod end. The horizontal black stippled lines show CC (0.5) and CR (1.0) in case of no effect of the specific codend comparing with its baseline. The vertical black lines show the minimum conservation reference size (MCRS) of greasyback shrimp.

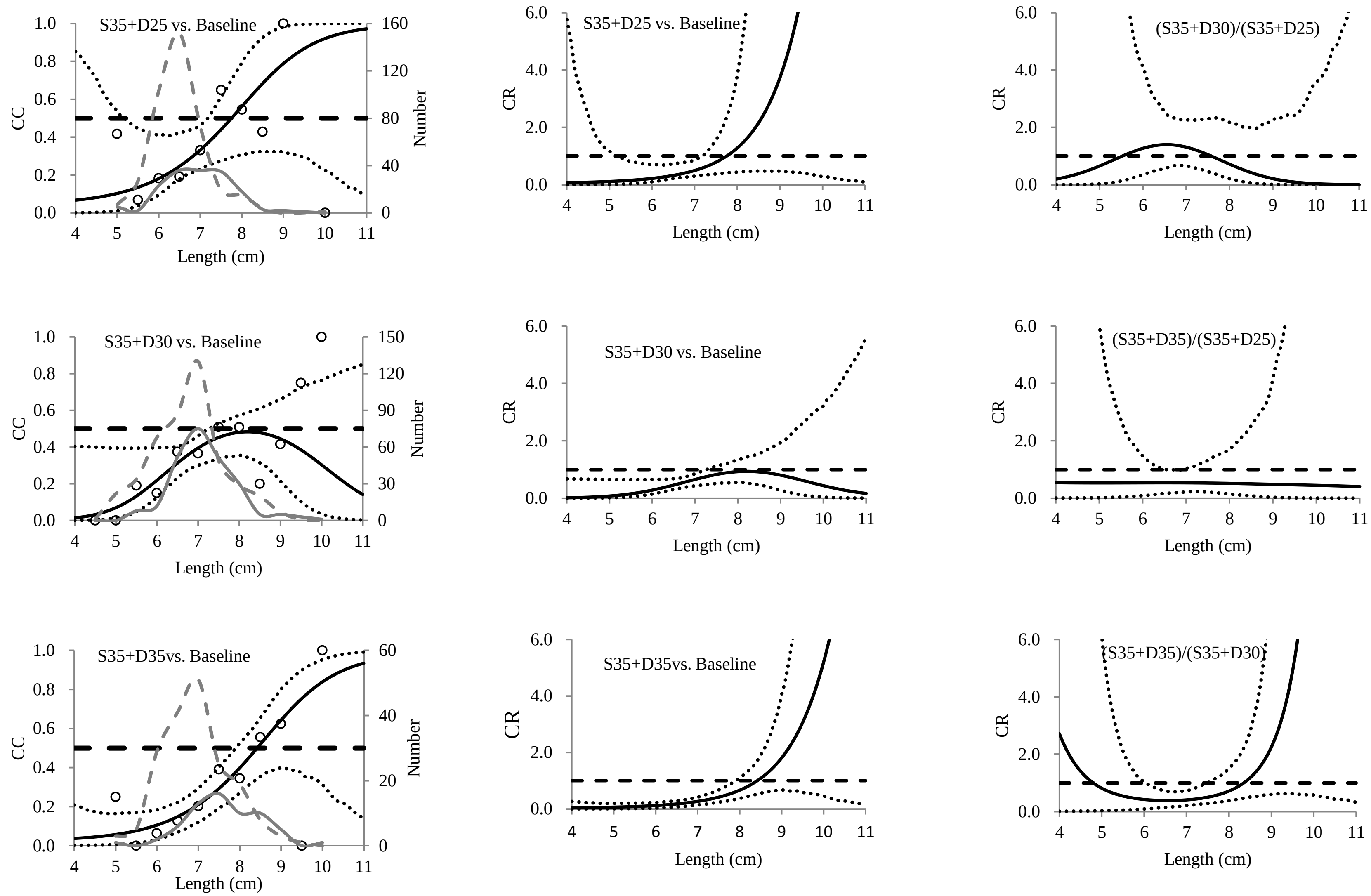

Fig. 4. Catch comparison rate (CC, first column), catch ratio (CR, second column) and catch ratio comparison (CR, third column) curves of the three CSDM cod ends for Rabbitfish. The circle marks represent the experimental rates. The thin dotted curves represent

the 95% confidence limits for the CC and CR curves. The grey full-line curves represent summed population for the tested CSDM cod ends. The grey stippled curves represent summed population for the baseline codend. The horizontal black stippled lines show CC (0.5) and CR (1.0) in case of no effect of the specific cod end comparing with its baseline.

Lists of Tables

Table 1. Overview of 30 hauls with date, towing time (TT), speed (S), distance (D), catch number (nt for the test and ns for the baseline cod end) of greasyback shrimp and Rabbitfish, and subsampling ratio (qt for the test and qs for the baseline cod end), '-' indicates that there is no available data.

						Greasyback shrimp				Rabbitfish			
						Catch number		Subsampling ratio		Catch number		Subsampling ratio	
Haul	Cod end	Date in 2017	TT (h)	S(kn)	D (km)	test (*nt*)	baseline (*ns*)	test (*qt*)	baseline (*qs*)	test (*nt*)	baseline (*ns*)	test (*qt*)	baseline (*qs*)
1	S35+D25	Sept 6	1.00	2.5	4.63	8	14	1.00	1.00	11	16	1.00	1.00
2	S35+D25	Sept 6	2.17	2.4	9.63	24	43	1.00	1.00	9	57	1.00	1.00
3	S35+D25	Sept 6	1.83	2.4	8.15	56	101	1.00	0.48	43	198	1.00	0.25
4	S35+D25	Sept 6	2.33	2.4	10.37	159	256	0.31	0.21	7	18	1.00	1.00
5	S35+D25	Sept 7	2.50	2.4	11.11	190	267	0.26	0.19	17	20	1.00	1.00
6	S35+D25	Sept 7	1.00	2.5	4.63	28	12	1.00	1.00	2	0	1.00	-
7	S35+D25	Sept 7	1.00	2.5	4.63	54	57	1.00	1.00	3	6	1.00	1.00
8	S35+D25	Sept 7	2.00	2.5	9.26	258	292	0.20	0.17	26	22	1.00	1.00
9	S35+D25	Sept 7	1.92	2.5	8.87	184	207	0.27	0.26	10	12	1.00	1.00
10	S35+D25	Sept 7	2.17	2.6	10.43	87	68	0.57	0.74	2	3	1.00	1.00
11	S35+D25	Sept 8	2.00	2.5	9.26	128	117	0.45	0.43	30	49	1.00	1.00
12	S35+D30	Sept 8	2.00	2.4	8.89	-	39	-	1.00	-	123	-	0.41
13	S35+D30	Sept 8	2.33	2.4	10.37	30	20	1.00	1.00	61	146	0.82	0.34
14	S35+D30	Sept 8	2.50	2.4	11.11	3	0	1.00	-	45	61	1.00	0.82
15	S35+D30	Sept 8	4.75	2.4	21.11	10	9	1.00	1.00	44	54	1.00	1.00
16	S35+D30	Sept 9	2.00	2.4	8.89	21	17	1.00	1.00	0	13	-	1.00
17	S35+D30	Sept 9	2.67	2.4	11.85	39	48	1.00	1.00	37	57	1.00	1.00
18	S35+D30	Sept 9	2.75	2.4	12.22	15	14	1.00	1.00	0	25	-	1.00
19	S35+D30	Sept 10	2.42	2.4	10.74	68	99	0.72	0.56	12	23	1.00	1.00
20	S35+D30	Sept 10	2.33	2.4	10.37	64	65	1.00	1.00	26	35	1.00	1.00
21	S35+D30	Sept 10	2.25	2.6	10.83	23	19	1.00	1.00	10	22	1.00	1.00

22	S35+D30	Sept 11	2.17	2.6	10.43	12	10	1.00	1.00	7	11	1.00	1.00
23	S35+D35	Sept 11	1.25	2.5	5.79	0	3	-	1.00	2	2	1.00	1.00
24	S35+D35	Sept 11	2.58	2.5	11.96	23	24	1.00	1.00	18	61	1.00	0.82
25	S35+D35	Sept 11	2.42	2.5	11.19	24	22	1.00	1.00	2	11	1.00	1.00
26	S35+D35	Sept 12	3.00	2.5	13.89	17	19	1.00	1.00	3	12	1.00	1.00
27	S35+D35	Sept 12	2.25	2.5	10.42	3	3	1.00	1.00	2	5	1.00	1.00
28	S35+D35	Sept 12	2.25	2.5	10.42	36	47	1.00	1.00	22	45	1.00	1.00
29	S35+D35	Sept 12	1.00	2.5	4.63	9	14	1.00	1.00	9	24	1.00	1.00
30	S35+D35	Sept 12	1.17	2.5	5.40	8	7	1.00	1.00	6	20	1.00	1.00

Table 2. Catch ratio (CR) results and fit statistics of three CSDM cod ends for greasyback shrimp using the commercial D22 as baseline (DOF denotes degrees of freedom).

Statistics	S35+D25 vs. Baseline	S35+D30 vs. Baseline	S35+D35 vs. Baseline
$CR(6.0, v)$ (%)	68.72 (8.04-219.36)	82.66 (5.90-162.38)	89.19 (18.43-152.38)
$CR(6.5, v)$ (%)	70.81 (16.69-175.85)	85.46 (10.53-160.35)	89.30 (22.62-142.76)
$CR(7.0, v)$ (%)	73.10 (31.51-142.55)	88.36 (18.99-159.86)	89.32 (30.61-136.41)
$CR(7.5, v)$ (%)	75.66 (49.08-117.72)	91.26 (29.44-156.69)	89.23 (35.67-133.51)
$CR(8.0, v)$ (%)	78.56 (63.80-103.37)	94.06 (47.92-151.96)	89.00 (42.39-127.34)
$CR(8.5, v)$ (%)	81.89 (67.22-110.51)	96.64 (63.88-148.85)	88.60 (54.35-121.38)
$CR(9.0, v)$ (%)	85.77 (65.83-123.99)	98.91 (74.48-153.53)	88.01 (60.32-118.70)
$CR(9.5, v)$ (%)	90.35 (61.50-139.00)	100.78 (80.86-158.14)	87.21 (64.25-118.84)
$CR(10.0, v)$ (%)	95.80 (53.23-156.13)	102.14 (82.42-167.14)	86.16 (63.88-120.27)
$CR(10.5, v)$ (%)	102.33 (38.50-170.91)	102.93 (81.65-169.33)	84.86 (60.63-124.99)
$CR(11.0, v)$ (%)	110.24 (23.04-192.97)	103.06 (76.68-173.83)	83.28 (55.92-136.37)
$CR(11.5, v)$ (%)	119.86 (11.86-217.65)	102.47 (68.52-179.60)	81.42 (47.83-150.29)
$CR(12.0, v)$ (%)	131.66 (5.54-260.42)	101.11 (53.64-202.40)	79.27 (39.27-167.06)
$CR(12.5, v)$ (%)	146.20 (2.29-325.43)	98.95 (35.77-225.46)	76.82 (31.04-197.11)
$CR(13.0, v)$ (%)	164.22 (0.73-421.20)	96.03 (23.24-261.98)	74.09 (22.88-230.16)
$CR(13.5, v)$ (%)	186.65 (0.22-584.95)	92.45 (13.73-294.62)	71.10 (16.69-266.07)
$CR(14.0, v)$ (%)	214.64 (0.07-862.94)	88.42 (7.87-335.99)	67.90 (11.96-325.22)
$CR_{average}$ (%)	82.22 (67.23-102.64)	99.60 (79.93-143.67)	85.71 (64.13-117.54)
$CR_{average-}$ (%)	58.12 (29.63-109.29)	100.00 (0.00-500.00)	66.67 (0.00-500.00)
$CR_{average+}$ (%)	88.19 (69.06-114.27)	99.59 (81.01-138.29)	86.15 (64.08-117.91)
$NRatio_{treatment}$	0.16 (0.10-0.22)	0.02 (0.01-0.04)	0.02 (0.00-0.04)
$NRatio_{baseline}$	0.25 (0.14-0.40)	0.02 (0.00-0.04)	0.02 (0.00-0.04)
p-value	<0.05	0.20	0.21
Deviance	35.56	13.48	15.60
DOF	11	10	12

Table 3. Catch ratio (CR) results and fit statistics of three CSDM cod ends for Rabbitfish using the commercial D22 as baseline (DOF denotes degrees of freedom).

Statistics	S35+D25 vs. Baseline	S35+D30 vs. Baseline	S35+D35 vs. Baseline
$CR(4.5, v)$ (%)	8.86 (0.38-245.10)	3.37 (0.27-66.47)	4.74 (0.26-21.29)
$CR(5.0, v)$ (%)	11.47 (1.19-117.22)	7.51 (1.32-65.13)	6.11 (0.56-19.72)
$CR(5.5, v)$ (%)	15.59 (3.77-80.76)	15.35 (5.06-64.98)	8.32 (1.22-20.43)
$CR(6.0, v)$ (%)	22.13 (10.53-68.36)	28.11 (14.48-65.79)	11.86 (3.28-22.52)
$CR(6.5, v)$ (%)	32.62 (21.72-71.76)	45.60 (30.25-68.25)	17.52 (7.30-28.57)
$CR(7.0, v)$ (%)	49.77 (30.10-86.22)	65.34 (42.85-85.62)	26.64 (13.60-41.86)
$CR(7.5, v)$ (%)	78.56 (37.71-156.04)	82.69 (51.11-112.12)	41.50 (23.60-67.23)
$CR(8.0, v)$ (%)	128.21 (43.99-382.43)	92.51 (54.84-134.45)	66.18 (36.99-110.08)
$CR(8.5, v)$ (%)	215.87 (47.78-1228.23)	91.55 (45.84-156.03)	108.02 (55.05-190.51)
$CR(9.0, v)$ (%)	372.99 (47.71-5091.97)	80.23 (27.26-194.09)	180.24 (66.17-403.67)
$CR(9.5, v)$ (%)	655.48 (41.09-26916.27)	62.46 (11.39-259.45)	305.44 (58.82-883.60)
$CR(10.0, v)$ (%)	1158.60 (28.88-160160.98)	43.54 (3.68-322.20)	519.18 (45.67-1984.06)
$CR_{average}$ (%)	39.90 (25.56-81.05)	54.02 (37.62-74.54)	34.59 (22.68-51.05)
p-value	<0.05	<0.05	0.21
Deviance	27.38	22.54	8.33
DOF	5	7	6