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T90 Codends Improve the Size Selectivity and Catch Efficiency of Shrimp Trawl Fisheries for Southern Velvet Shrimp (*Metapenaeopsis palmensis*) in the South China Sea

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Abstract: In order to obtain gear-based management instruments of shrimp trawl fishery for southern velvet shrimp in the South China Sea (SCS), the size selectivity and catch efficiency of four codends were tested and compared. These codends included two mesh sizes, 30 and 35 mm, and two mesh shapes, T0 (diamond-mesh) and T90 (diamond-mesh turned by 90°), respectively. Our results demonstrated that increasing the mesh-sizes of the T0 codends or/and applying the T90 codends would statistically and significantly improve the size selectivity and catch efficiency. Comparing the size selectivity and catch efficiency of four codends tested, and accounting for the results of the previous study, we conclude that the T0 codend with a mesh size of 35 mm (T0_35) or T90 codend with a mesh size of 30 mm (T90_30) would be potential choices for mitigating the bycatch issue of undersized individuals for southern velvet shrimp (*Metapenaeopsis palmensis*) in the SCS. We recommend that they are applied as the compulsory gears in the fishery management regulation. Our study will be beneficial for the decision-making regarding gear-based management for sustainable fishing in the specific shrimp trawl fishery of the SCS.

Keywords: shrimp trawl; codend selectivity; size selectivity; catch efficiency; T90

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1. Introduction

Globally, with declining resources for most traditional fish species, shrimp fisheries have becoming ever-increasingly relevant [1–3]. The situation is the same in China, which is the greatest contributor of marine capture production. During the past decade, the annual catch volume of all shrimp species was above 1,200,000 t from Chinese domestic marine fisheries [4,5].

Shrimp fisheries are also social-economically important in the South China Sea (SCS), in which environmental and climatic conditions are excellent for fisheries resources, such as finfish and shrimp species, to reside [6,7]. The relevance of shrimp fisheries is further manifested, due to overexploitation of most finfish stocks [8]. In 2020, the total landing of shrimp species was 235,642 t in the SCS, and it has been estimated that more than 3000 vessels are involved in shrimp fishing [9]. The number of shrimp species were once reported as 350, in which, about 35 species were economically relevant in fisheries [6,7]. In these species, southern velvet shrimp (*Metapenaeopsis palmensis*) is a typical species, due to their (1) wide distribution [10,11] and (2) small body size, with most individuals less than 10 cm in total length [9].

To target shrimp species, fishermen in the SCS apply demersal trawls, and there are mainly two kinds of fishing methods: one is shrimp beam trawling, and the other is out-rig trawling (Figure 1) [6,9]. In order to ensure catch efficiency for shrimp species, especially for the ones with small body sizes, such as southern velvet shrimp, there are two points in common for the fishing approaches: (1) diamond-mesh netting applied, and (2) small mesh sizes used in the codends [9]. Due to the characteristics of diamond-mesh codends and the demersal fishing technique, shrimp trawl fisheries in the SCS often induced serious bycatch problems [12,13]. The main challenge for the fisheries management is the bycatch of undersized shrimp individuals. Although the minimum mesh size (MMS) regulation, 25 mm mesh size in the trawl codend, has been implemented, the bycatch issue did not mitigate. For instance, a recent selectivity study by Yang et al. [9] demonstrated that the size selectivity of legal D25 codend (diamond-mesh with a mesh size of 25 mm) was poor for southern velvet shrimp, and more than 43% of undersized individuals were retained. Their results also demonstrated that increasing the mesh size was a simple and effective modification to mitigate the bycatch problem, and they recommended that the MMS regulation should be revised to 35 mm for the specific fishery targeting southern velvet shrimp in the SCS. However, a 10 mm increment, from 25 to 35 mm, might be easy for the decision-maker, but hard for the fishermen. The largest concern will be the loss of marketable shrimp, and this has also been outlined by Yang et al. [9]. Thus, it is necessary to develop alternative gear modifications to better trade-off releasing undersized individuals and retaining the legal ones.

Figure 1. A shrimp beam trawl in operation (**left**) and out-rig trawler with the nets hanging behind (**right**).

Numerous selectivity studies have proven that turning the traditional diamond-mesh codend (T0) 90° into a T90 codend would improve the size selectivity for many species all around the world [14–21]. For more detailed information regarding T90 codend selectivity, please refer to ICES [22] and Kennelly and Broadhurst [23]. Compared with the T0 codends, the benefits of applying the T90 codends can be listed as: (1) more mesh opening and good selective properties, (2) simple modification and easily accepted by the fishermen. Based on the positive outcomes of these previous studies, we hypothesize that applying a T90 codend with a mesh size near 35 mm might obtain satisfactory selective properties for the specific trawl fishery targeting southern velvet shrimp in the SCS. Therefore, applying T90 codends could potentially be a fishery management tool to address the bycatch issue of undersized southern velvet shrimp, without compromising the capture efficiency of the target sizes.

For the purpose of addressing the problems and issues mentioned above, we investigated the size selectivity and exploitation patterns of four codends, two T0 and two T90, with mesh sizes of 30 and 35 mm, respectively, for shrimp trawl fishery targeting southern velvet shrimp. Our study focused on these research questions:

(1) How would the size selectivity and exploitation pattern change when substituting the T0 codends to T90 codends with the same mesh sizes?

(2) How would the size selectivity and exploitation pattern change when substituting the T0 codends to T90 codends with larger mesh sizes?
(3) Would these potential differences be length-dependent or not?

2. Materials and Methods

2.1. Sea Trials

The sea trials were conducted in November 2020, onboard on commercial shrimp trawler, named 'Guibeiyu 96899' (total length: 38 m, engine power: 280 kW). The fishing area was around the Weizhou Island (Figure 2), which is a traditional fishing ground for targeting southern velvet shrimp in the SCS. The fishing ground was selected due to the fact that four sea trials had been successfully conducted in or near this area before 2020 and obtained sufficient catch data of the target species for selectivity analysis. For more information, please refer to Yang et al. [9].

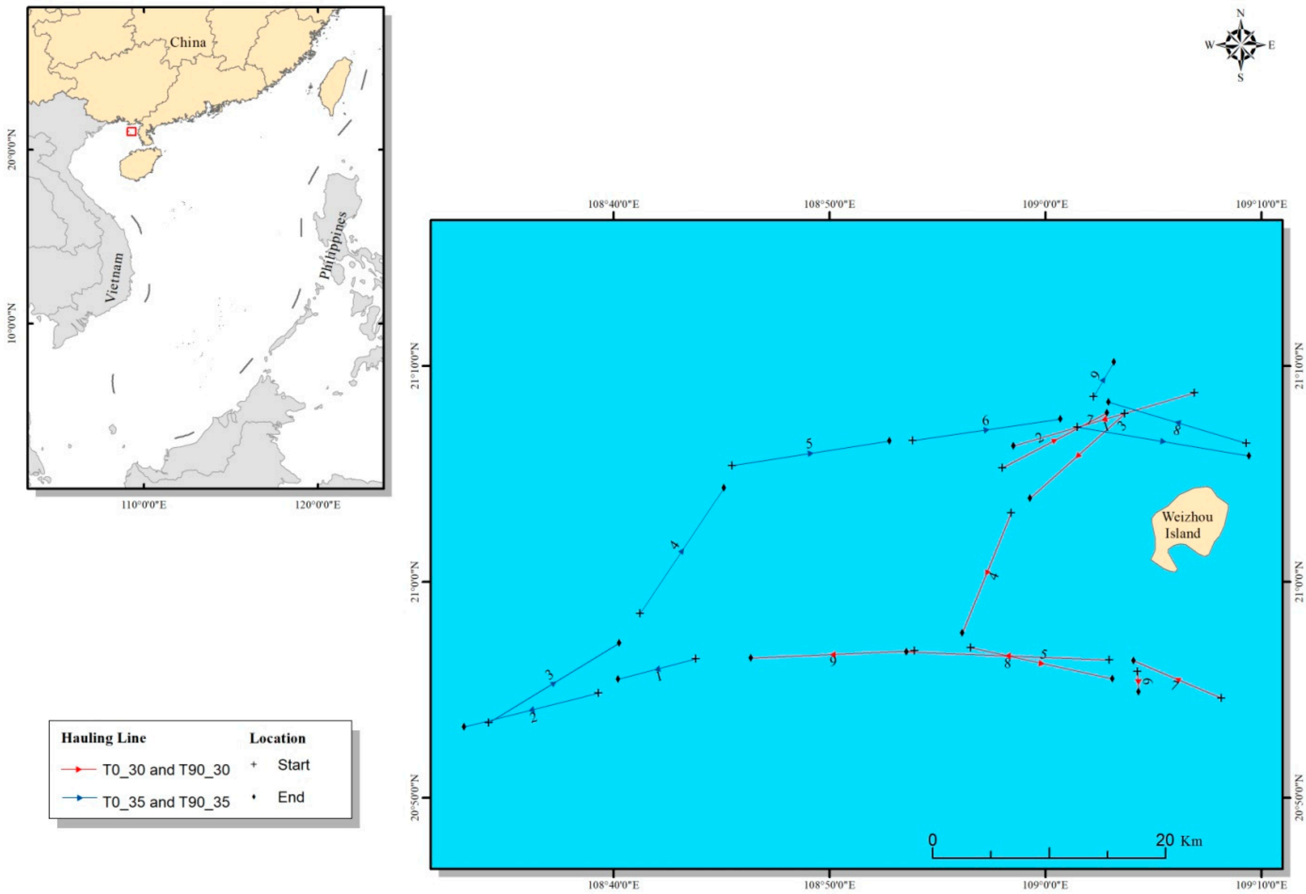

Figure 2. Map of the fishing grounds where the sea trials were carried out. The red lines indicate the T0_30 vs. T90_30 codend tests, while the blue lines represent the T0_35 vs. T90_35 codend tests.

2.2. Experimental Setup

As our research priority is to test and compare the size selectivity and exploitation pattern of T90 and T0 codends, we applied the trawl-net system of the commercial fishing vessel, except the codends. The fishing method is so-called out-rig trawling, where two identical trawls are towed simultaneously from the ends of out-rigger derricks using two sets of otter board to spread them (Figure 3). The fishing circle of the trawls was constructed with 860 meshes, with a 45 mm mesh size, while the headline and footrope lengths were 28 and 36 m, respectively. A chain with 80 m in length, weighted 210 kg, was attached to the footrope to act as the ground gear. The dimension of the otter board, made of wood and steel, was 1.90 × 0.83 m (length × width) and weighted approximately 250 kg. The codends used in commercial fishing are diamond-mesh with a size of 25 mm, with 220 meshes around the circumference, and the total stretched length is 4.8 m. This codend, however, was replaced by our tested codends.

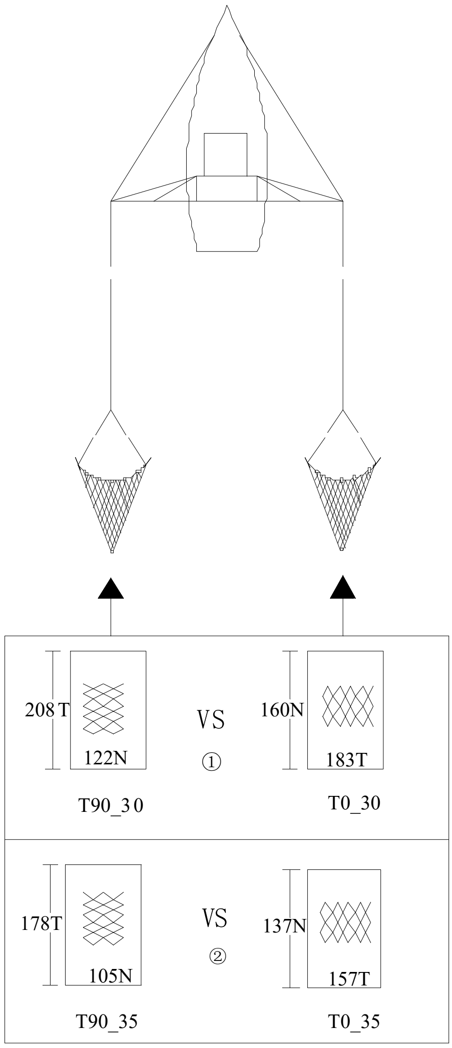

Figure 3. Schematic view of the fishing vessel and the tested codends: ① indicates the first comparison (T90_30 vs. T0_30) test, and ② represents the second comparison (T90_35 vs. T0_35) test.

The experimental codends were designed with the dimension of the commercial codend and consideration of previous selectivity study by Yang et al. [9] Two modest mesh sizes were selected, 30 and 35 mm, and we developed four codends with different mesh shapes, two T0 and two T90 codends, respectively. The diamond-mesh codends, termed as T0_30 and T0_35, had the same stretched length (both in circumference and vertical direction) as the commercial codend, but with different mesh sizes. The T90 codends, hereafter termed T90_30 and T90_35, were constructed using the dimension of the T0 codends. Based on some previous studies [24,25], the mesh number of a T90 codend should be about 33% less in the circumference and 30% more in the length direction, compared with those in the T0 codend with the same mesh size. All these codends were constructed by the same manufacturer, using the same netting materials. The specifications of these codends are listed in Table 1 and Figure 3.

Table 1. Specifications of the experimental codends and cover. SE indicates standard errors.

Codend	Mesh Opening ± SE (mm)	Twine Diameter ± SE (mm)	Number of Meshes in Circumference	Number of Meshes in Length
T0_30	29.79 ± 0.65	1.24 ± 0.12	183	160
T90_30	29.79 ± 0.65	1.24 ± 0.12	122	208
T0_35	35.66 ± 1.06	1.29 ± 0.08	157	137
T90_35	35.66 ± 1.06	1.29 ± 0.08	105	178
Cover	12.51 ± 0.78	1.18 ± 0.10	550	480

Based on the protocol of Wileman et al. [26], we used the covered codend approach to collect escapees of the target species. A cover-net with small mesh size, about 12 mm, and about 1.5 times larger and longer, compared with the tested codends, was used. To keep the cover-net away from the tested codends, we attached a total of 12 kites around the covers [9,27,28]. Moreover, to check how these kites work and observe the escaping behavior of the target species, underwater videos recordings, constructed by GoPro HERO 4, were applied during the experiments. Moreover, for the convenience of accessing the catch from the tested codends, we attached a zipper, with a length of 1.1 m, to the lateral meshes of the cover-net.

The out-rig trawling method provided us with an excellent comparison of the tested codends, in which the two codends with identical mesh sizes, but different mesh shapes, were fished simultaneously (Figure 3). We first tested the T0_30 vs. T90_90 codend for several hauls, then moved on to the T0_35 vs. T90_35 test. In every fishing haul, catch from the tested codends were firstly obtained through the zippers. All catch of southern velvet shrimp were collected and sub-sampled if the catch number was large. Sampled catch were kept in special containers and frozen, once the sea trials finished, they were taken back to the laboratory on land for length measurement.

2.3. Estimation of Size Selectivity

Despite the fact that two codends were tested simultaneously in our experiments, the experimental method allowed us to analyze the data of the target species as binominal data, as, in the specific codend tested, an individual shrimp was either caught by the specific codend or cover. Even for the same codend, the size selectivity can be expected to vary between different hauls [29]. In this study, however, our primary interest was the size selectivity of codend tested averaged over all hauls, as this information would provide us the average consequences of the size selectivity process when using a specific codend in the commercial fishery. The average size selection can be described as $r_{codend}\ (l, \boldsymbol{v_{codend}})$, in which $\boldsymbol{v_{codend}}$ is a vector that consists of the selective parameters. These parameters can be obtained by minimizing the following expression, which is equal to maximizing the likelihood of obtaining the observed experimental data:

$$-\sum_{j=1}^{m}\sum_{l}\left\{\frac{nR_{lj}}{qR_j}\times\ln[r_{codend}(l,\boldsymbol{v_{codend}})]+\frac{nE_{lj}}{qE_j}\times\ln[1-r_{codend}(l,\boldsymbol{v_{codend}})]\right\} \quad (1)$$

where nR_{lj} and nE_{lj} are the number of shrimp in the codend and cover for length class l in haul j, while qR_j and nE_j are the sub-sampled ratios from the codend and cover, respectively. In Equation (1), the outer summation comprises the hauls (m) conducted for the specific codend tested, while the inner summation over length class l is the catch data. Four parametric models, including Logit, Probit, Gompertz, and Richards, were used as candidates to present $r_{codend}\ (l, \boldsymbol{v_{codend}})$ for each codend. Three models, Logit, Probit, and Gompertz, can be fully described by two selectivity parameters, L50 (50% retention length) and SR (selection range = L75–L25), while the last model (Richards) needs an additional parameter (1/δ) to describe the asymmetry. For more information about the models, please refer to Wileman et al. [26] or Santos [30].

First, all candidate models were initially fitted to Equation (1) by calculating and comparing their Akaike's information criterion (AIC) values [31] to select the best model (the one with lowest AIC value). Second, using the best model selected for each codend, a double bootstrapping approach was applied to estimate the Efron percentile 95% [32] confidence intervals (CIs) for the selectivity parameters and curves, accounting for both within-haul and between- haul variations [9,33,34]. The ability of the selected model to present the experimental data sufficiently well could be evaluated by its *p*-value. For most cases, the *p*-value should be >0.05; in some cases, where *p*-value <0.05, it will need to inspect the residuals to determine if this low value was due to structural problems of the selected model or just a result of overdispersion in the catch data [9,26].

2.4. Estimation of Delta Selectivity between Different Codends Tested

The differences of size selectivity between codends tested can be compared with delta selectivity, $\Delta r\ (l)$, by this equation:

$$\Delta r(l) = r_a\ (l) - r_b\ (l) \tag{2}$$

where a and b indicate the different codends. The 95% CIs for delta selectivity can be obtained by the two bootstrap populations resulting from $r_a\ (l)$ and $r_b\ (l)$, respectively. Applying Equation (2), we can not only calculate the delta selectivity between codends tested in the present experiments, but also compare our results with the previous selectivity study conducted with the same or similar codends configuration [9]. For more information about this method, please refer to Herrmann et al. [35,36].

2.5. Estimation of Exploitation Pattern Indicators

In order to investigate how the codends tested would impact the exploitation pattern of the target species under different fishing population scenarios, we estimated three exploitation pattern indicators: $nP-$, $nP+$, and $dnRatio$. First, five population scenarios, with different size structures $nPop_l$ of the target shrimp species, were generated using the approach of Melli et al. [37]. Then, the size selectivity curves of the codends tested were applied to estimate the exploitation pattern indicators with the following equation:

$$\begin{aligned} nP- &= 100 \times \frac{\sum_{l<MCRS}\{r_{codend}(l,\boldsymbol{v_{codend}})\times nPop_l\}}{\sum_{l<MCRS}\{nPop_l\}} \\ nP+ &= 100 \times \frac{\sum_{l\geq MCRS}\{r_{codend}(l,\boldsymbol{v_{codend}})\times nPop_l\}}{\sum_{l\geq MCRS}\{nPop_l\}} \\ dnRatio &= 100 \times \frac{\sum_{l<MCRS}\{r_{codend}(l,\boldsymbol{v_{codend}})\times nPop_l\}}{\sum_{l}\{r_{codend}(l)\times nPop_l\}} \end{aligned} \tag{3}$$

where $r_{codend}\ (l, \boldsymbol{v_{codend}})$ is the size selectivity of the specific codend, and $nPop_l$ represents different size structure of fishing shrimp population, while MCRS represents minimum conservation reference size (7.0 cm) of southern velvet shrimp in the SCS [9]. The Efron percentile 95% CIs for the exploitation pattern indicators can be estimated with the double bootstrapping method.

All the data analyses were finished using the software SELNET [34]. We applied statistical software tool R (version 4.1.2) [38] to produce plots in selectivity analyses using the ggplot2 package [39].

3. Results

3.1. Experimental Data

In total, 36 valid hauls were conducted in the sea trial; nine hauls for each codend tested (Figure 2, Table 2). The towing speed was about 3.5 knots, towing duration mainly kept at 2 h, and water depth ranged from 18 to 39 m (Table 2). In all hauls, southern velvet shrimp was the most dominant species caught, so we obtained sufficient data for selective analysis, and our study focused on this species. In total, 4602 individuals of southern velvet shrimp were sampled and length measured, in which, 1518 were from the specific codends, and 3084 were from the relative covers, respectively. In addition to the data from the experiments, we obtained five fishing population scenarios of southern velvet shrimp from previous sea trials (Figure 4).

Table 2. Overview of the experimental fishing conducted in the sea trials. Towing duration, water depth, and number of shrimp length measured from the codend (*nR*) and cover (*nE*), while *qR* and *qE* indicate the sub-sampled ratios from the codend and cover, respectively.

Codend	Haul ID	Duration (min)	Depth (m)	*nR*	*qR*	*nE*	*qE*
T0_30	H1	158	20	28	0.33	129	1.00
T0_30	H2	115	21	24	0.33	156	1.00
T0_30	H3	137	20	63	0.33	114	1.00
T0_30	H4	123	22	24	0.50	65	1.00
T0_30	H5	127	26	25	0.50	25	1.00
T0_30	H6	132	22	26	0.50	15	1.00
T0_30	H7	129	20	31	0.33	12	1.00
T0_30	H8	124	21	23	0.50	17	1.00
T0_30	H9	144	26	80	0.50	15	1.00
T0_35	H1	124	32	119	0.50	58	0.50
T0_35	H2	124	34	44	0.50	34	0.50
T0_35	H3	125	39	32	0.50	54	0.33
T0_35	H4	130	30	15	0.50	27	0.33
T0_35	H5	139	26	43	0.33	138	0.25
T0_35	H6	134	22	26	0.50	92	0.25
T0_35	H7	141	21	83	0.50	97	0.33
T0_35	H8	134	18	17	0.50	144	0.25
T0_35	H9	127	20	71	0.50	198	0.33
T90_30	H1	158	20	51	0.33	213	1.00
T90_30	H2	115	21	44	0.33	188	1.00
T90_30	H3	137	20	22	0.33	90	1.00
T90_30	H4	123	22	11	0.50	51	0.50
T90_30	H5	127	26	20	0.50	24	0.50
T90_30	H6	132	22	44	0.50	63	1.00
T90_30	H7	129	20	46	0.33	67	1.00
T90_30	H8	124	21	13	0.50	61	1.00
T90_30	H9	144	26	45	0.50	62	0.50
T90_35	H1	124	32	52	0.50	62	0.50
T90_35	H2	124	34	33	0.50	42	0.50
T90_35	H3	125	39	79	0.50	49	0.25
T90_35	H4	130	30	66	0.50	60	0.25
T90_35	H5	139	26	121	0.33	205	0.25
T90_35	H6	134	22	13	0.50	144	0.25
T90_35	H7	141	21	13	0.50	108	0.33
T90_35	H8	134	18	16	0.50	89	0.25
T90_35	H9	127	20	55	0.50	116	0.33

3.2. Size Selectivity

By comparing the AIC values, we chose Gompertz, Probit, Probit, and Gompertz as the best models for the relative codend (Table 3). These selected models reflected the main trends of the experimental fishing data (Figure 5). As a result, we considered that a p-value < 0.05 for the T90_30 and T90_35 codend was probably due to overdispersion in the fishing data. The selectivity parameters, both L50 and SR, significantly increased when increasing the mesh size from 30 to 35 mm for diamond-mesh codends (T0_30 to T0_35) or substituting T0_30 with T90_30, and the increment was further manifested by applying the T90_35 codend. For instance, L50 was 5.33 (CI: 4.99–5.63) cm for the T0_30 codend; it significantly increased to 6.35 (CI: 6.11–6.66) for the T0_35 codend and 7.07 (CI: 6.73–7.69) for the T90_35 codend (Table 4). The size selectivity patterns could be demonstrated by the selectivity curves (Figure 5). With the modification in mesh sizes and/or shape, escapement of the target species increased, and the capture of undersized individuals was mitigated.

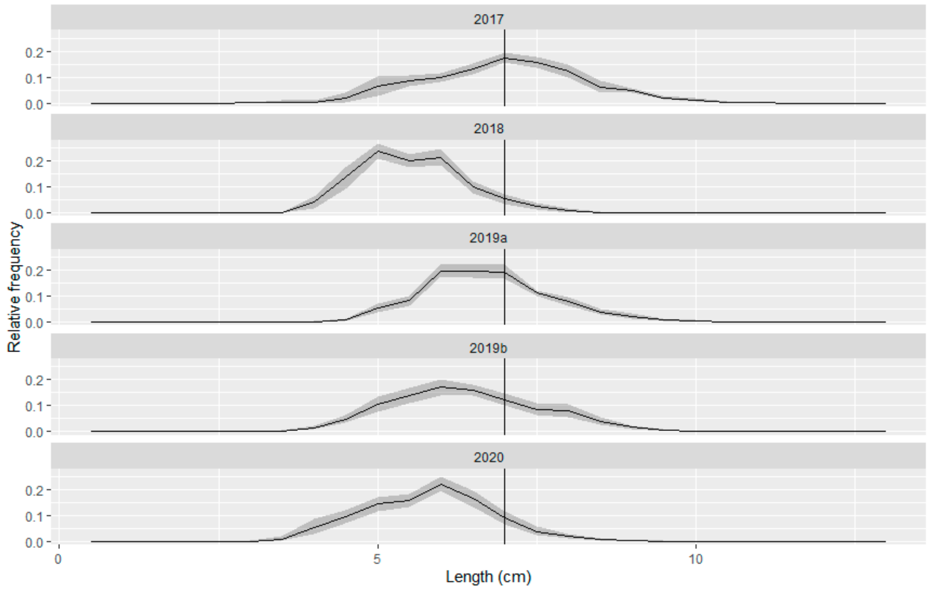

Figure 4. Fishing population scenarios of southern velvet shrimp, based on catch data in the sea trials conducted between 2017 and 2020. Gray bands show the 95% Efron confidence intervals, while the vertical lines indicate the minimum conservation reference size (MCRS, 7.0 cm) of southern velvet shrimp in the SCS.

Table 3. The estimated Akaike's information criterion (AIC) values of candidate models for the codends tested. Selected model in bold.

	Model			
Codend	**Logit**	**Probit**	**Gompertz**	**Richards**
T0_30	1099.31	1096.08	**1094.62**	1096.01
T0_35	2667.4	**2657.4**	2671.97	2661.47
T90_30	1906.4	**1900.9**	1908.27	1908.33
T90_35	3748.02	3740.33	**3706.04**	3709.79

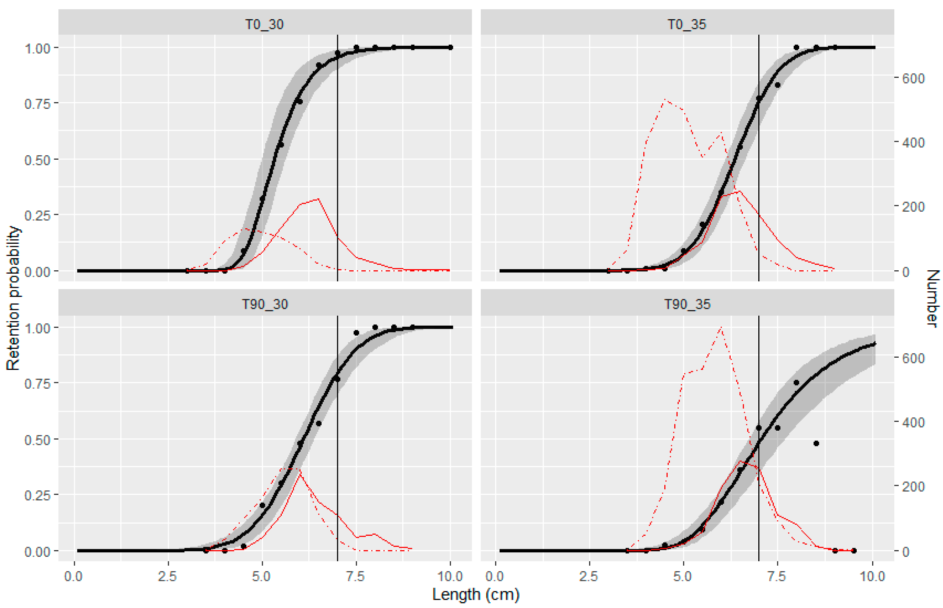

Figure 5. Experimental fishing proportion and selectivity curves obtained for the T0 and T90 codends tested. Black dots represent experimental catch proportion. Solid black curves show selectivity curves,

and grey bands describe the 95% confidence intervals. Red solid curves represent the size distribution of shrimp caught by the codend, and the dotted ones represent the catch from the cover. Vertical lines represent the minimum conservation reference size (MCRS, 7.0 cm) of southern velvet shrimp in the SCS.

Table 4. Selectivity parameters and fit statistics obtained from the selected models for the codends, with comparison of the previous study. The selective parameters of the D25-D54 codends were from the study by Yang et al. [9]. DOF represents degree of freedom.

	Parameters					
Codends	**Model**	**L50 (cm)**	**SR (cm)**	***p*-Value**	**Deviance**	**DOF**
T0_30	Gompertz	5.33 (4.99–5.63)	0.98 (0.74–1.23)	0.8970	6.36	12
T0_35	Probit	6.35 (6.11–6.66)	1.26 (1.06–1.47)	0.4846	10.52	11
T90_30	Probit	6.11 (5.91–6.40)	1.48 (1.17–1.85)	0.0473	18.49	10
T90_35	Gompertz	7.07 (6.73–7.69)	2.15 (1.73–2.93)	0.0115	24.32	11
D25		5.47 (5.20–5.67)	0.89 (0.62–1.14)			
D30		5.85 (5.47–6.18)	0.81 (0.61–1.04)			
D35		6.22 (4.99–7.01)	1.90 (1.37–3.47)			
D40		6.92 (5.77–7.62)	2.05 (1.38–4.21)			
D45		7.49 (7.09–8.71)	2.37 (1.45–9.36)			
D54		7.72 (6.63–12.93)	4.01 (1.96–19.68)			

3.3. Delta Selectivity

By comparing the length-dependent size selectivity of the codends tested, it was found that modifications in mesh sizes and/or mesh shapes would significantly impact the retention probability for the target species. For instance, increasing the mesh size from 30 to 35 mm of the diamond-mesh codend (T0_30 to T0_35) or substituting T0_30 with T90_30 would significantly reduce the retention probability of shrimp in the length range of ~5.0 to 7.9 cm. The T90_35 codend had significantly lower retention probability for shrimp above 4.6 and 6.0 cm, when compared with the diamond-mesh codends (T0_30 and T0_35), and the effect was significant for nearly all shrimp, when compared with the T90_30 codend (Figure 6). There was only one exception in which the comparison between the T90_30 and T0_35 codend was not statistically significant (Figure 6).

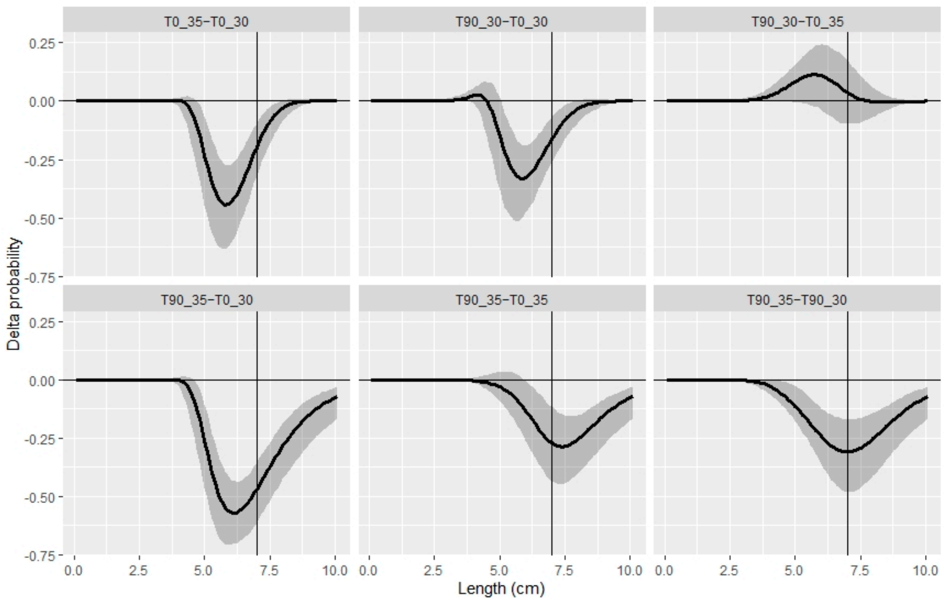

Figure 6. Delta selectivity of comparisons between the tested codends in the experiments. The black curves show the delta selectivity, and the grey bands are the 95% confidence intervals. Vertical lines are the minimum conservation reference size (MCRS, 7.0 cm) of southern velvet shrimp in the SCS.

3.4. Exploitation Pattern Indicators

The results of exploitation pattern indicators seemed vary, depending on the fishing population scenarios. However, for the same fishing population, the main trend was nearly identical: when the mesh size of diamond-mesh codend increased from 30 to 35 mm, or substituting the T0_30 with T90_30 codend, the retention of undersized shrimp could be significantly reduced, and the reduction was further significantly manifested by applying a T90_35 codend. For instance, when encountering the fishing population in 2017, the estimated $nP-$ was 79.56% for the T0_30 codend, and the ratios dropped to 54.24 and 60.33% for the T0_35 and T90_30 codend, respectively, while the estimated value was 35.12% for the T90_35 codend (Table 5). The trend was similar for the retention of marketable size shrimp ($nP+$). That is, increasing the mesh size or applying the T90 codend would lose some of desired shrimp individuals. One difference was that the reduction was not statistically significant, when comparing the T0_35 and T90_30 with the T0_30 codend. The values of legal size retention ($nP+$) for the T90_35 codend, however, were significantly lower than other codends in all fishing population scenarios (Table 5). Relative high discard ratios were observed for all tested codends, and the differences were statistically significant for one or two cases.

Table 5. Exploitation pattern indicators estimated for the codends under five fishing population scenarios.

Population	Codend	*nP−* (%)	*nP+* (%)	*dnRatio* (%)
2017	T0_30	79.56 (69.55–89.19)	99.42 (98.13–99.90)	69.36 (63.59–74.07)
	T0_35	54.24 (44.17–64.68)	97.87 (94.58–99.27)	61.06 (54.84–65.88)
	T90_30	60.33 (51.15–68.64)	97.64 (93.72–99.34)	63.61 (58.05–68.33)
	T90_35	35.12 (24.00–44.26)	77.24 (63.51–85.41)	56.26 (49.26–61.52)
2018	T0_30	52.84 (41.04–67.34)	99.08 (97.22–99.83)	98.39 (97.06–99.76)
	T0_35	24.77 (17.92–32.39)	96.22 (90.94–98.66)	96.73 (93.96–99.48)
	T90_30	32.95 (24.77–39.37)	95.97 (90.01–98.80)	97.53 (95.55–99.58)
	T90_35	15.50 (9.15–20.86)	70.91 (56.24–80.35)	96.17 (93.32–99.40)
2019a	T0_30	81.66 (72.47–89.98)	99.36 (97.97–99.89)	81.94 (78.93–84.92)
	T0_35	52.41 (42.58–60.96)	97.64 (93.91–99.21)	74.76 (70.14–78.70)
	T90_30	59.43 (50.73–66.13)	97.40 (93.00–99.24)	77.10 (73.08–80.49)
	T90_35	33.59 (22.96–40.84)	76.12 (62.30–84.55)	70.89 (65.57–75.45)
2019b	T0_30	69.95 (59.64–80.28)	99.32 (97.83–99.88)	80.78 (75.51–86.16)
	T0_35	41.38 (32.59–49.75)	97.47 (93.62–99.13)	71.70 (65.60–78.04)
	T90_30	48.80 (40.05–56.13)	97.21 (92.63–99.20)	74.97 (69.31–80.46)
	T90_35	26.41 (17.98–33.23)	75.22 (61.30–83.83)	67.70 (60.65–74.77)
2020	T0_30	60.55 (49.37–72.61)	99.22 (97.52–99.85)	95.25 (92.98–96.97)
	T0_35	32.28 (24.06–40.54)	96.93 (92.44–98.92)	91.62 (88.34–94.39)
	T90_30	40.06 (31.62–46.88)	96.67 (91.56–99.05)	93.15 (90.36–95.49)
	T90_35	20.35 (12.85–26.48)	73.29 (59.07–81.99)	90.11 (86.31–93.61)

3.5. Comparison with Previous Diamond-Mesh Codends Selectivity Study

Recently, Yang et al. (2021) documented the size selectivity of six diamond-mesh codends; mesh sizes ranged from 25 to 54 mm for southern velvet shrimp in a shrimp trawl fishery of the SCS. To better understand the outcomes of the experiments, we compared the results with the previous study by Yang et al., 2021. Compared with the currently legal codend, with a 25 mm diamond-mesh (D25), two of our codends tested had statistically significant lower retention for shrimps, with some given length ranges, 5.2 to 8.0 cm for the T0_35 codend and 5.4 to 8.1 cm for the T90_30 codend, respectively (Figure 7). Increasing the mesh size of the diamond-mesh codend from 30 to 35 mm, T0_35 vs. D30 comparison, or substituting the D30 with a T90_30, would result in significantly fewer shrimp in the length range of approximately 6 to 8 cm (Figure 7). The size selectivity of these two codends, T0_35 and T90_30, was not significantly different from the D35 codend previous tested by Yang et al., 2021 (Figure 7).

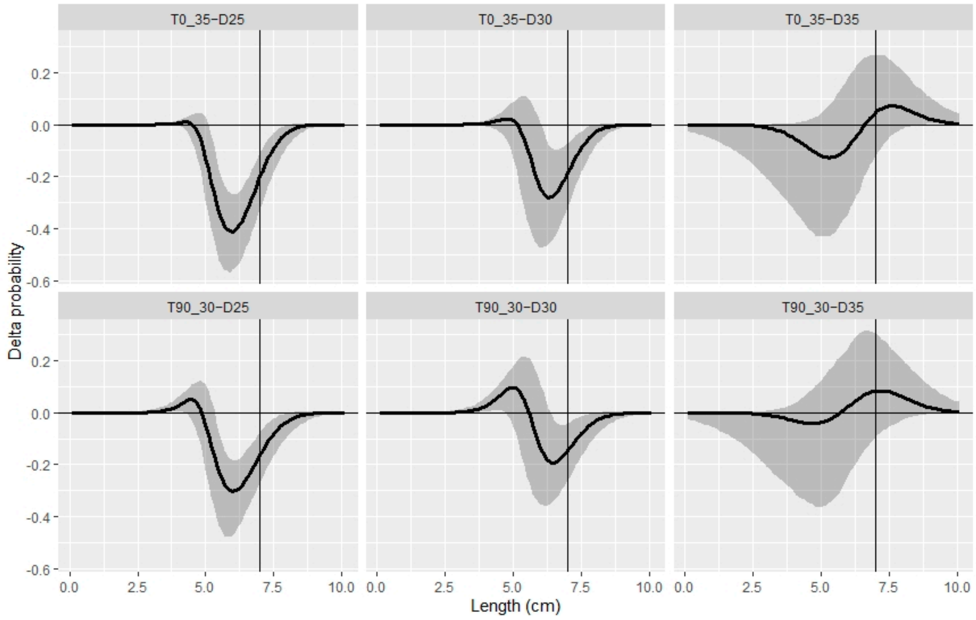

Figure 7. Delta selectivity of comparisons between the present experiments and previous study [9]. The black curves show the delta selectivity, and the grey bands are the 95% confidence intervals. Vertical lines are the minimum conservation reference size (MCRS, 7.0 cm) of southern velvet shrimp in the SCS.

4. Discussion

In the present study, we investigated the size selectivity and exploitation pattern of four codends with different mesh sizes and mesh shapes for southern velvet shrimp in the SCS. Our results demonstrated that increasing the mesh sizes or/and applying T90 codends would significantly improve the size selectivity. We fully took advantage of the commercial fishing method by testing two codends simultaneously. This practice not only improved our working efficiency in the data collection, but also eliminated some potential uncertainty in the between-haul variations, when comparing the size selectivity of T90 codends with those of T0 codends with the same mesh sizes.

To better benefit fishery management, gear modification to improve size selectivity should be both simple, effective, and easily accepted by the fishermen [23,40,41], especially for the one adopted in the complicated context of marine capture fishery in China [42–44]. Our results demonstrated that the bycatch of undersized individuals of the target species could be significantly mitigated by increasing the mesh size of the diamond-mesh codend to 35 mm or applying a T90 codend with a 30 mm mesh size. Using the T90 codend with bigger mesh size, 35 mm, the size selectivity could be further improved; however, the loss of individuals with marketable size was of concern. Specifically, the loss of individuals with legal sizes ($nP+$) was about 20–25% for the T90_35 codend, compared with the T0_35 or T90_30 codend (Table 5).

The improvement of size selectivity with increasing the mesh sizes of diamond-mesh codends or applying the T90 codends can be reflected by the differences in L50 values, exploitation pattern indicators, and delta selectivity between codends. For instance, compared to the T0_30 codend, the T0_35 and T90_30 codends had: (1) significantly higher L50 values, (2) significantly lower $nP-$ values, but comparable $nP+$ values, and (3) significantly lower retention probability for undersized shrimp individuals (Tables 4 and 5, Figure 6). Furthermore, the positive outcomes of our study can also be reflected by comparing the selectivity results from the previous experiment. By comparing the size selectivity of currently compulsory codend, D25, which has been demonstrated to be poor by Yang et al. (2021), both the T0_35 and T90_30 codends tested in our experiment had better selective properties, due to: (1) significantly higher L50 values and (2) significantly lower retention probability for undersized shrimp individuals (Table 4, Figure 7). When comparing with the D30 codend tested by Yang et al. (2021), the T0_35 and T90_30 codends had higher L50 values, but the differences were not significant because of overlapping CIs (Table 4). Significantly lower retention probability could still be observed for shrimp, with some length ranges (Figure 7). The T0_35 and T90_30 codends had similar size selectivity than that of the D35 codend by Yang et al. [9], in terms of close L50 values, and no significant difference in delta selectivity for shrimp with all length range (Table 4, Figure 7). Based on the results of our experiment, as well as the comparison with the previous study, we concluded that the T0_35 and T90_30 codends would be better choices to address the bycatch issue of undersized individuals for shrimp fishery targeting southern velvet shrimp in the SCS.

Our results demonstrated that the T0_35 and T90_30 codends had better and similar selective properties. This will be beneficial to the fishery management by providing two options for the fishermen to improve the size selectivity: (1) increase the mesh size of diamond-mesh codend to 35 mm or (2) if they are reluctant to use a larger mesh size, the T90 codend with a 30 mm mesh size will be an alternative. Moreover, our modifications are inexpensive and can be easily accepted by the local fishermen. It is noteworthy that the T0_35 codend has been previously recommended by Yang et al. [9]. Our study further confirmed and validated their conclusion. Additionally, we offered an alternative modification to the T0_35 codend with the consideration that some fishermen might more easily accept the T90 codend with a smaller mesh size. Based on the positive outcomes of our study, we recommend that the mandatory codend in shrimp trawling should be revised to diamond-mesh codend with 35 mm mesh size (T0_35) or T90 codend with 30 mm (T90_30) in the trawl fishery management of the SCS. As compared with the current legal codend, our options would significantly improve the size selectivity and exploitation pattern for the target species. The improvement of size selectivity not only reduce the handling time of fishermen onboard, but also leads to a higher sustainable yield and good ecosystem [45]. Although our study was conducted in the SCS and focused on southern velvet shrimp, our results will have relevant implications for fishery management in nationwide fishing regions of the whole of China. All shrimp fishing vessels were subjected to the same MMS regulation in the codend, with 25 mm mesh size in the coastal fishing areas of China. However, few scientific works have been carried out to test and evaluate the effectiveness and efficiency of this MMS regulation [46,47]. The experimental design, data analysis, and method of interpreting the results will provide examples for future selectivity study in other fishing areas, such as the East China Sea and Yellow Sea. Moreover, our results and implications will be helpful to the fishery management of some other Asian countries, which are adjacent to the SCS, including Indonesia, Malaysia, Myanmar, Philippines, Thailand, and Vietnam. As these countries suffer the same barriers and challenges in the management of trawl fishing [41], our study will provide simple and effective mitigation options to improve trawl selectivity and exploitation patterns and be helpful for the fisheries management.

T90 codends have been demonstrated to be more size selective than traditional diamond-mesh codends for many species all around the world, both experimentally [15,16,20,24] and theoretically [18,48,49]. Our study documented the first comparison of size selectivity between T90 and T0 codends for southern velvet shrimp in the SCS. The positive outcomes can be due to: (1) more mesh opening in the T90 codends, as shown in Figure 8, and (2) the swimming behaviour of the target species recorded by our underwater video recordings. With the opening mesh, the target shrimp could easily pass through the T90 codends and escape; as a result, the size selectivity could be improved.

Figure 8. The mesh opening of the T90_35 (left) and T0_35 codend (right) in natural conditions after experimental fishing.

Our study demonstrated that the size selectivity of demersal trawl for southern velvet shrimp could be improved through modifications in the codend. However, there is no official minimum landing size (MLS) regulation implemented to match with these modifications. Formal MLS is strictly needed for southern velvet shrimp in the SCS. Additionally, the results of exploitation pattern indicators demonstrated that applying the present MCRS value (7.0 cm) would induce high discarded ratios (*dnRatio*) for some fishing population scenarios. This implies that, if the MLS is set to be close to 7.0 cm, more gear modifications should be considered and tested to further improve the size selectivity. A lot of potential modifications, such as using square mesh panel (SMP), shortening lastridge ropes, and applying light-emitting diodes (LED), have been proven to be effective in improving the size selectivity for many species [50–58]. Another relevant direction for future work is to estimate the mortality of southern velvet shrimp escaping from the selective codends because the final benefits of improving the size selectivity depends on the survival of escapees [59].

Some precaution should be required, due to the fact that our sea trials were based on only 36 hauls, and the number of target species was limited to 4602 individuals. This might lead to some degrees of uncertainty in the estimation of the size selectivity. The power for the modeled size selectivity, however, can be judged from the 95% CIs [21]. The results of our study demonstrate a high predictive power, since all CIs from the selectivity parameters, selectivity curves, and exploitation pattern indicators were relatively narrow in all codends tested. It has been previously demonstrated by Herrmann et al. [60] that using the covered codend method, the one we applied in our experiments, would allow for obtaining high degree of accuracy in selectivity estimation, with a relatively small number of individuals to be measured. Moreover, we generated five fishing population scenarios, in which, a total of 14,154 individuals of southern velvet shrimp were measured, in order to estimate the exploitation pattern indicators. With such sufficient catch data, we are confident that we can fully mimic the commercial fishing situation and our results can be beneficial to the fishery management.

5. Conclusions

By comparing the size selectivity and catch efficiency of the four codends tested and accounting for the results of the previous study, we draw the main conclusions, as follows:

(1) The T0_30 codend had poor size selectivity and exploitation patterns for southern velvet shrimp and, thus, did not mitigate the bycatch issue of juvenile southern velvet shrimp. The implication for fishery management is that the present 25 mm MMS regulation should be revised.
(2) Compared with the T0_30 codend, the T0_35 and T90_30 codends had significantly better size selectivity and exploitation patterns for the target species. These two options provide excellent revision for the existing 25 mm MMS codend regulation in the fishery management, in order to obtain sustainable fishing for southern velvet shrimp in the SCS.
(3) The T90_35 codend performed the best in size selectivity and exploitation for the studied species. However, the loss of individuals with marketable size was of concern.

Our results will be beneficial to the fishery management by informing others of the drawbacks of the present MMS regulation and offering potential solutions to revise it. Considering that this MMS regulation is common and national for all shrimp trawl fisheries, our study will also have implications for management revision and investigation preparation for shrimp trawl fishing in other coastal areas of China. Moreover, our results and implications will be helpful to the fishery management of some other Asian countries.

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