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Modeling of available size selectivity of the SURF-BRD for shrimp beam trawl

Yoritake Kajikawa · Tadashi Tokai · Fuxiang Hu

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Abstract The System of Unwants Ramp-way Filtered-Bycatch Reduction Device (SURF-BRD) was developed to reduce shrimp bycatch in a shrimp beam trawl. It consists of a pair of rectangular net panels, namely, the front panel (FP) and rear panel (RP), and two fish escape vents. In this study, numerical models for expressing available selection by the SURF-BRD were proposed and assessed in several fishing experiments conducted using two types of the BRD: a prototype and an improved type with the BRD attached at a higher point on the side-nets . Contact probability and selectivity parameters of the FP and the RP for four major species were estimated for each BRD type. The improved type with the higher BRD showed a larger contact probability for the FP. Size selectivity of the FP and RP for two species (cinnamon flounder and spotted swimming crab) was almost equivalent to the mesh selectivity of the net panel, but that for lizard fish seemed to depend not on mesh size of the FP but on the swimming behavior of the fish. These results suggest that the smaller mesh size of the RP would be helpful for releasing more fish of smaller size and to exclude more spotted swimming crab, which hinder on-deck sorting by fishermen.

Y. Kajikawa (✉)
Department of Fisheries Science and Technology, National Fisheries University, 2-7-1 Nagata-Honmachi, Shimonoseki, Yamaguchi 759-6595, Japan
e-mail: kajikawa@fish-u.ac.jp

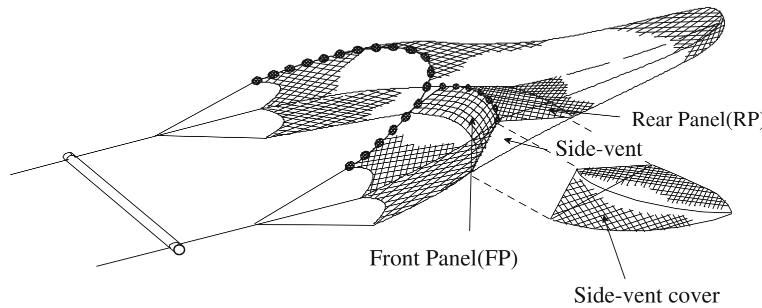
T. Tokai · F. Hu
Graduate School of Marine Science and Technology, Tokyo University of Marine Science and Technology, Minato, Tokyo 108-8477, Japan

Keywords Shrimp beam trawl · Bycatch reduction device · Available selection model · Available size selectivity · Selection process

Introduction

Many studies on bycatch reduction devices (BRDs) in fishing gear used by commercial fisheries have been conducted in Japan, and fishing gear with newly developed BRDs are continuously being implemented by commercial fisheries [1–4]. The authors have developed two types (prototype and improved type) of the SURF (System of Unwants Ramp-way Filtered)-BRD for use by beam trawlers in the coastal waters off Shimonoseki, Yamaguchi Prefecture in western Japan [5–8]. The SURF-BRD comprises a front panel (FP) made of large mesh net and a rear panel (RP) made of fine mesh net, and both are assembled together in a mountain shape and attached as a unit to the lower part of the net mouth (Fig. 1). In both the prototype and improved type, the FP is made out of a square mesh net with a bar length of 40 mm (stretched inner mesh size of 72 mm), and the RP is a diamond mesh with a stretched mesh size of 27.5 mm. An escape vent, which is a triangle-shaped cut-out, is made on each side of the net between the FP and the RP. In the fishing experiments, side-vent cover nets of the same mesh as the cod-end covers escape vents at both sides to catch animals exiting from the escape vents (Fig. 1). In earlier studies, the authors [6] confirmed that the prototype with the FP head-line 0.4 m high during towing had species selection such that target small shrimps were retained while small crabs of no commercial value were excluded from the net and that it also had size selectivity allowing small size fish to escape from the net. Each end of the FP head-line of the prototype was attached

Fig. 1 Schematic diagram of small-scale trawl net to which the System of Unwants Ramp-way Filtered-Bycatch Reduction Device (SURF-BRD) is attached. Side-vent covers were attached in the fishing experiments to examine animals exiting from the escape vents



at one-third of the height of the side net. Model experiments in a flume tank revealed that attachment of the FP head-lines at higher points at each end of the side net maintains the BRD in a more vertical position (taller) [7]. Accordingly, in the improved type, the FP is attached at one-half of the side net height on each side. As previous research [8] indicated, although the height of the SURF-BRD in the prototype was set at about 0.4 m, that in the improved type was set at about 1.8 m. The higher BRD of the improved type allows lizard fish *Saurida* spp. and cinnamon flounder *Pseudorhombus cinnamoneus* to encounter the FP much more frequently than in the prototype, and therefore the size selection of the FP for these species is more effective [8]. Using the improved type, we found that the majority of whiskered velvet shrimp *Matapenaeopsis barbata* entering the net were retained in the cod-end, but that an increased number of spotted swimming crab *Charybdis bimaculata* passed through the FP and were then excluded through the side vent after being blocked by the RP mesh [8].

Quantitative assessment methods have been employed to analyze the separation effectiveness of the BRD, including the contact probability model developed by Tokai et al. [9], Tokai [10], and Zuur et al. [11]. The combination of contact selection and contact probability was termed the available selection model by Millar and Fryer [12]. This available selection model has been used to determine the separation of the grid separator [13, 14], the square mesh bycatch reduction window [15, 16], selectivity for the cod-end when the mesh of the cod-end is clogged by the catch [17], and the effect of the dredge tooth spacing on selectivity for bivalves [18, 19].

In the study reported here, we used catch data obtained in fishing experiments involving both the prototype and improved type of SURF-BRD and attempted to construct a numerical model for the available selection of the SURF-BRD. In this context, we discuss the species- and size-selection process of the SURF-BRD based on the estimated parameters of contact probability and selectivity curve in the available selection numerical model and evaluate the effect of BRD height on contact probability. The appropriate mesh size of the FP and the RP in the SURF-BRD is also discussed in terms of fisheries management.

Materials and methods

Fishing experiments

In this study, catch data were obtained in a small beam trawl that was using two types of SURF-BRD: the prototype and the improved type where the vents at both sides are covered with vent-covers (Fig. 1). The beam trawler Dai San Kaikomaru (2.9 t) belonging to the Izaki Branch of the Yamaguchi Prefecture Fisheries Cooperative Association was chartered and operated in the coastal waters off Shimonoseki, Yamaguchi Prefecture in western Japan. A total of ten tows were conducted with the prototype on 1 July 1996 and on 8 and 10 September 1998, and a total of eight tows were conducted with the improved type on 29 and 30 June 2000. Each tow was conducted for 60 min during the night in areas with depths of 20–30 m. The mesh of the vent-cover was the same as that of the cod-end.

As previously reported [8], the heights of the net mouth and BRD had an influence on species- and size-selectivity by the FP and RP.Depth meters (MDS-TD; Alec Electronics, Japan; resolution 0.125 m; precision FS $\pm$ 0.5 %) were placed at the center of the head rope, the upper edge of the URF-BRD, and at foot rope to measure the heights of the net mouth and the BRD during towing. Data were recorded at 1-min intervals.

The catch from each tow was sampled from the cod-end and both side-vent covers on board the ship and brought back to the laboratory for follow-up measurement of length and weight. Body length was measured in millimeters on a fish body measuring board or in 0.1-mm increments with a digital caliper (SC-15S; Mitsutoyo, Kawasaki, Japan). Total length (TL) for fish, carapace length (CL) for shrimp, and maximum carapace width (CW) for small crabs were measured. An electronic scale (BP6100; Sartorius, Goettingen, Germany; minimum readout 0.01 g) was used for the measurement of body weight.

Data for all individuals from each tow were pooled and analyzed. In our previous reports [6, 8], the data were separated between day and night, although the SURF-BRD used in these tows was the same. In the present study, only data from tows done at night were used for the model analysis because this fishery usually operates at night.

Numerical models used for data analysis

This aim of this study was on selection provided by the SURF-BRD; cod-end selectivity was not evaluated because it could not be examined using the data obtained in the fishing experiments due to the same mesh size being used in both the cod-end and the vent-covers.

Here, we denote the number of fish with length l, passing through the net mouth by N_l. The probabilities of an animal coming in contact with the FP and RP are given by p and q, respectively. We assume that size selection by the FP [expressed as $r_F(l)$] and RP [expressed as $r_R(l)$] can be calculated by the following logistic functions:

$$r_F(l) = 1/[1 + \exp(a_F + b_F l)] \text{ and}$$
$$r_R(l) = 1/[1 + \exp(a_R + b_R l)],$$

where (a_R, b_R) and (a_F, b_F) are parameters of the logistic function for the FP and RP, respectively. As the mesh size of the FP is about threefold larger than that of the RP, the relationship of $r_F(l)$ and $r_R(l)$ are as follows:

$$0 \le r_F(l) \le r_R(l) \le 1$$

In this study, the number of fish of a given l passing through Paths 1–5 in the separation processes of SURF-BRD is represented by the following equations (Fig. 2).

Path 1 Number of fish of given l that do not come in contact with the FP and then are retained by the cod-end: $C_{1l} = (1 - p)N_l$

Path 2 Number of fish of given l that come in contact with the FP but do not pass through the FP and then are retained by the cod-end: $C_{2l} = pr_F(l)N_l$

Path 3 Number of fish of given l that pass through the FP but do not come in contact with the RP and then escape through the escape vent: $C_{3l} = p(1 - q)[1 - r_F(l)]N_l$

Path 4 Number of fish of given l that pass through the FP but do not pass through the RP and then escape through the escape vent: $C_{4l} = pq\ [1 - r_F(l)]\ r_R(l)N_l$

Path 5 Number of fish of given l that pass through both the FP and RP and then are retained in the cod-end: $C_{5l} = pq\ [1 - r_F(l)][1 - r_R(l)]N_l$

Here, N_l is the number of fish with length l that enter the net and is equal to $C_{1l} + C_{2l} + C_{3l} + C_{4l} + C_{5l}$. Individuals that pass through Paths 1, 2, and 5 in the SURF-BRD are retained in the cod-end, while those passing through Paths 3 and 4 escape through the side-vents into the vent-covers (Fig. 3). According to the SELECT method [20], the proportion of fish retained in the cod-end ($C_{1l} + C_{2l} + C_{5l}$) relative to the total number N_l is described by the following equation:

$$\phi_l = (C_{1l} + C_{2l} + C_{5l})/N_l$$

As a function of l, $\phi_0(l)$ is described by the following equation:

$$\phi_0(l) = (1 - p) + pr_F(l) + pq[1 - r_F(l)][1 - r_R(l)] \quad (1)$$

The model of equation $\phi_0(l)$ for which all parameters are actualized ($0 < p < 1$, $0 < q < 1$, $0 < r_F(l) < 1$,

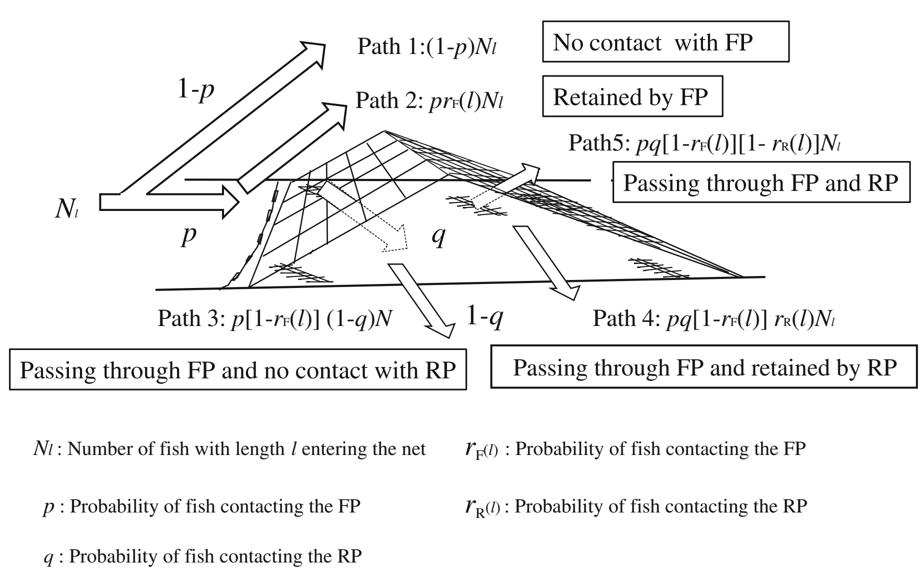


Fig. 2 Selective processes of SURF-BRD in the trawl net mouth

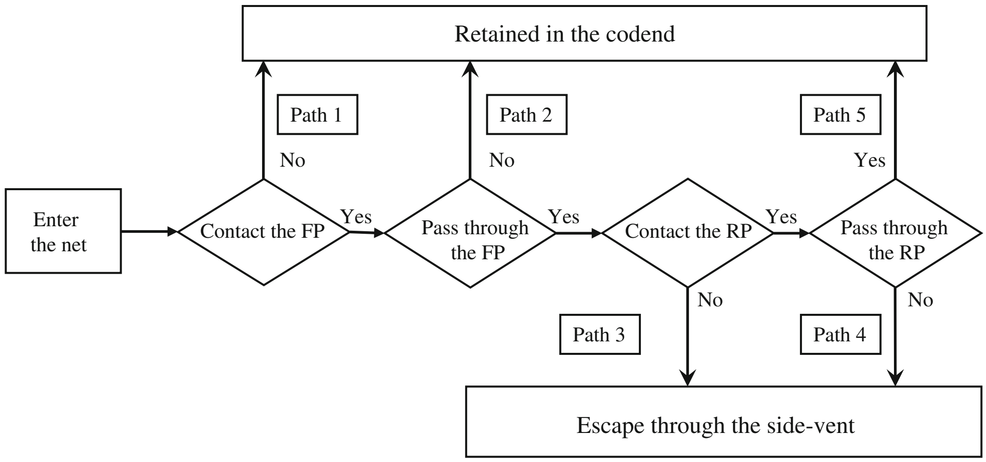


Fig. 3 Flow chart of the selective processes in the trawl net with the SURF-BRD

$0 < r_R(l) < 1$) is hereafter called Model A. In Model A with $0 < p < 1$, $0 < q < 1$, plots of $\phi_0(l)$ against body length l gives a *U*-shaped curve (Fig. 4) and all of the five paths are included. However, all parameters are not always actualized. For example, the contact selectivity of the FP against body length for all individuals becomes 1 when the fish body is too large to pass through the mesh of the FP. In this case, the contact selectivity parameters for the FP drop out of the equation. In this study, in accordance with the combination of $r_F(l) = 0$ and $r_R(l) = 1$ associated with the shape of the model curve, in addition to Model A we prepared three models (Models B, C, and D) having a *U*-shaped curve. Each of these models had some variations, depending on whether each of the two parameters p and q for contact probability were 1 or not. It is also noted that the parameter $p = 1$ and $q = 1$ excludes Path 1 and Path 3, respectively, and that the equations of $r_F(l) = 0$ and $r_R(l) = 0$ exclude Path 2 and Path 4, respectively. Model A_R is represented by Eq. (2) in which q is reduced in Eq. (1). The upper left terminus of the *U*-shaped retention ratio $\phi(l)$ becomes 1 (Fig. 4; Model A, $0 < p < 1$, $q = 1$).

$$\phi_1(l) = (1-p) + pr_F(l) + p[1 - r_F(l)][1 - r_R(l)] \quad (2)$$

Model A_R includes the four other paths and not Path 3 because the contact probability of the RP, $q = 1$ means that all fish passing through the FP come in contact with the RP.

Model A_F is represented by Eq. (3) in which $p = 1$ in Eq. (1) (Fig. 4; Model A, $p = 1$, $0 < q < 1$).

$$\phi_2(l) = r_F(l) + q[1 - r_F(l)][1 - r_R(l)] \quad (3)$$

Model A_F includes all of the other four paths and not Path 1 since the contact probability against the FP, $p = 1$, suggests that all fish come in contact with the FP.

Model A_{FR} is represented by Eq. (4) in which both of p and q are equal to 1 in Eq. (1) (Fig. 4; Model A, $p = 1$, $q = 1$). This suggests that Model A_{FR} has neither Path 1 nor Path 3.

$$\phi_3(l) = r_F(l) + [1 - r_F(l)][1 - r_R(l)] \quad (4)$$

In Model B, the proportion ϕ_l showed a monotonically decreasing sigmoidal function when $r_F(l) = 0$, suggesting that all of the fish entering the net were of a body size too small to be retained by the mesh of the FP (Fig. 4). Model B is based on p, q, and $r_R(l)$ as represented by Eq. (5) (Fig. 4; Model B, $0 < p < 1$, $0 < q < 1$).

$$\phi_4(l) = (1-p) + pq[1 - r_R(l)] \quad (5)$$

In Model B groups, $r_F(l) = 0$ indicates no Path 2 because all fish coming in contact with the FP can pass through the FP.

Model B_R is represented by Eq. (6) in which $q = 1$ in Eq. (5) (Fig. 4; Model B, $0 < p < 1$, $q = 1$). This indicates no Path 3 of Path 2 in Model B_R.

$$\phi_5(l) = (1-p) + p[1 - r_R(l)] \quad (6)$$

Model B_F is represented by the Eq. (7) in which $p = 1$ in Eq. (5) (Fig. 4; Model B, $p = 1$, $0 < q < 1$), which means that both Path 1 and Path 2 are excluded.

$$\phi_6(l) = q[1 - r_R(l)] \quad (7)$$

Model B_{FR} is represented by Eq. (8) in which both p and q are 1 in Eq. (5) (Fig. 4; Model B, $p = 1$, $q = 1$).

$$\phi_7(l) = 1 - r_R(l) \quad (8)$$

In Model B_{FR}, both Path 1 and Path 3 are excluded because of $q = 1$ and $p = 1$, as well as Path 2.

Model C_F is composed of $r_F(l)$ and p in Eq. (9) when $r_R(l) = 1$, meaning that all of the fish, even those passing

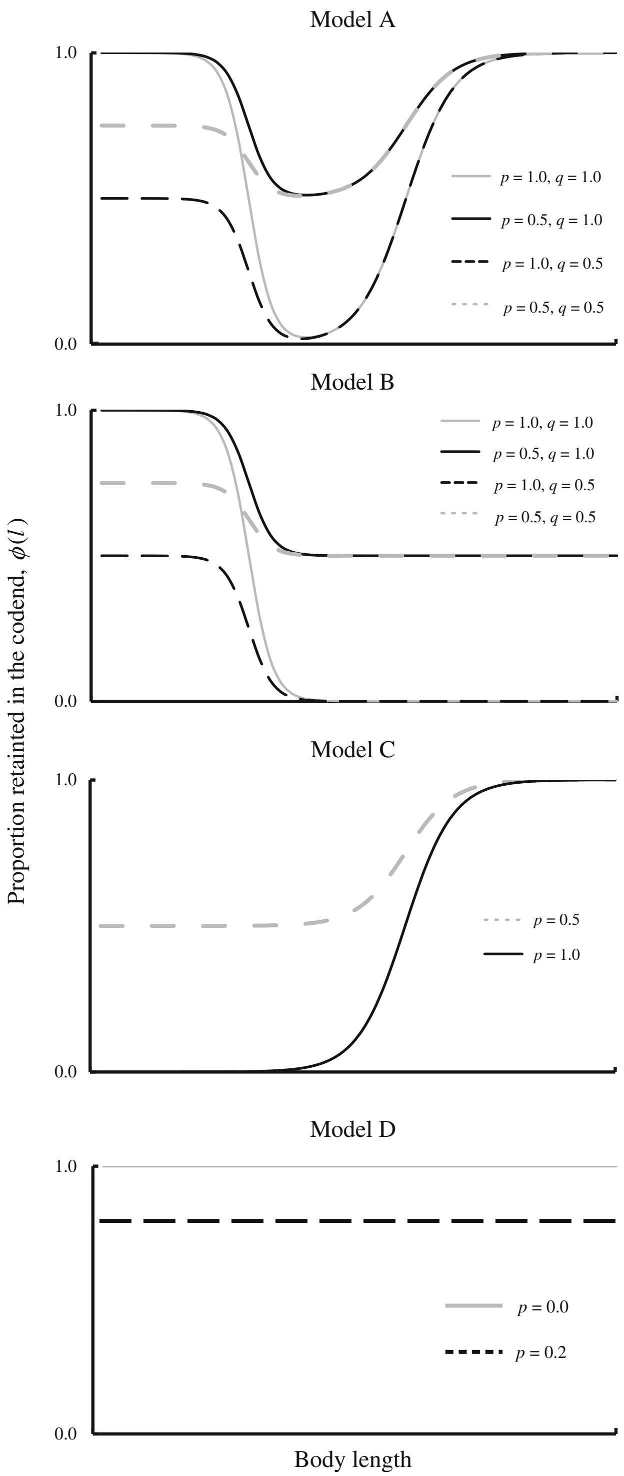


Fig. 4 Curves of the models for expressing the proportion of catch retained in the cod-end

through the FP, were too large to pass through the mesh of the RP, and/or when $q = 0$; that is, none of the fish passing the FP came in contact with the RP (Fig. 4; Model C, $0 < p < 1$). The former [$r_R(l) = 1$] excludes Path 5, and the later means the exclusion of Path 3 with Paths 1 and 2.

The proportion ϕ_l is sigmoidal.

$$\phi_8(l) = (1 - p) + p r_F(l) \tag{9}$$

Model C_R is represented by Eq. (10) in which p is 1 in Eq. (9) (Fig. 4; Model C, $p = 1$). This suggests that Path 1 is also excluded in Model C_F.

$$\phi_9(l) = r_F(l) \tag{10}$$

In Model D, ϕ_l is constant. There appears to be no size selection by body size for fish that enter the trawl (Fig. 4; Model D, $0 < p < 1$).

$$\phi_{10}(l) = 1 - p \tag{11}$$

This would occur after some portion of the fish come in contact with the FP ($p \neq 0$), when $r_F(l) = 0$ and $q = 0$ (meaning Paths 1 and 3), or when $r_F(l) = 0$ and $r_R(l) = 1$ (excluding Paths 2 and 5), implying that all of the fish passing through the FP escape through the side-vent without coming into contact with the RP or after being retained by the RP. Likewise, two formulas, $1 - p + pq$ (when p and q both $\neq 0$) and q (when $p = 1$, excluding Path 1), are derived under the condition of $r_F(l) = 0$ and $r_R(l) = 1$ (excluding Paths 2 and 5), but are indistinguishable from Eq. (11) in terms of parameter estimation.

Model D_F is represented by Eq. (12) when $p = 0$ or when $r_F(l)$, $r_R(l) = 0$ at any p value (Fig. 4; Model D, $p = 0$ or $r_F(l) = 0$), meaning Path 1 expressing that all fish avoid coming in contact with the FP, or excluding Path 4.

$$\phi_{10}(l) = 1 \tag{12}$$

This equation describes the case in which all of the fish passing through the FP also pass through the RP without moving through the side-vent ($q = 1$ and $r_R(l) = 0$, excluding Paths 3 and 4).

In this study, the model that produced a selectivity curve most closely resembling the plots of ϕ_l in the catch data was selected from among the proposed models by the Akaike Information Criterion (AIC) model selection [20, 21]. The two parameters p and q of contact probability and two sets of logistic function parameters (a_F, b_F) and (a_R, b_R), representing the contact selectivities for the FP and RP, respectively, in the model were estimated using the maximum likelihood method [22]. Here, N_{lk} denotes the total number of fish caught by body length class l_k ($k = 1, 2, 3, \ldots, n$), and C_{lk} is the number of fish of body length l_k caught in the cod-end. The function $\phi(l_k)$ expresses the proportion of the cod-end catch number C_{lk} to the total number of fish N_{lk}. The log likelihood function to be maximized for parameter estimation is as follows:

$$\ln L(p, a_F, b_F, q, a_R, b_R) = \sum_k^n \ln \frac{C_K!}{(N_K - C_K)! \cdot C_K!} + \sum_k^n C_k \ln\phi(l_k) + \sum_k^n (N_k - C_k)\ln[1 - \phi(l_k)] \quad (13)$$

The Solver function in Microsoft Excel (Microsoft, Redwood, WA) was used to maximize the log likelihood function [22]. Model fitness was tested by the likelihood ratio test on data in length classes, with sample numbers of at least five, in the same fashion as proposed by Miller and Walsh [23].

Results

Height of net mouth, BRD and catch composition

Mean height of net mouth ranged from 2.2 to 3.1 m for the prototype, and from 4.1 to 4.5 m for the improved type (Table 1). The mean height of the BRD ranged from 1.6 to 1.8 m for the improved type. Apart from haul No. 5 with a BRD height of about 0.1 m for the prototype, the mean height of the BRD was maintained from 0.4 to 0.8 m. Since the low height of BRD in haul No. 5 implied less effect of FP and RP contact selection, data in haul No. 5 were excluded from further analyses.

Catch composition by catch number and weight for the prototype and improved type used in the fishing experiments is shown in Table 2. The top ten and 11 most abundant fish species caught in the after-sunset trawls using the prototype and improved type are listed in Tables 3 and 4, respectively. Little difference in catch composition was observed between the two types. For example, the portunid swimming crab *Portunus hastatoides* was dominant in the catch with the improved type, but not so in the catch with the prototype. In contrast, although offshore pony *Leiognathus rivulatus* appeared in the top ten species caught by the prototype, but there were no appearances in the list of the top 11 species caught by the improved type. The first four hauls using the prototype were conducted in July and the other six (Haul No. 5–10) were conducted in September, while the hauls using the improved type took place in June (Table 1). Possible explanations for differences in catch composition are differences in towing season and/or in towing ground. Regardless of season or location, the most common and second most common species caught by both the prototype and improved type were whiskered velvet shrimp and spotted swimming crab. Whiskered velvet shrimp accounted for 39 and 28 % and spotted swimming crab for 17 and 26 % of the individuals caught by the prototype and improved type, respectively. For the prototype and the improved type, the most common marketable fish species were cinnamon flounder and lizard fish, and catch numbers for these species were sufficient for conducting analysis on available selection provided by the BRD. In this study, catch data for the four species (whiskered velvet shrimp, spotted swimming crab, lizard fish, and cinnamon flounder) were used for further analysis on available selection.

Body length composition and estimated model curves of available selection

Body length composition of the four species was obtained from the catch data pooled in all hauls for the prototype and improved type, respectively (Fig. 5). The models in

Table 1 Towing conditions in the fishing experiments by beam trawl with the prototype and improved type of SURF-BRD

BRD type	Haul number	Date of tow	Towing time	Height of BRD (m)	Height of net mouth (m)
Prototype	1	1 July 1996	19:51–20:41	0.31	2.50
	2	8 September 1998	19:05–19:55	0.13	2.18
	3		20:10–21:12	0.45	2.47
	4		21:32–22:35	0.67	2.98
	5		22:52–23:52	0.61	2.92
	6	10 September 1998	19:21–20:23	0.69	3.11
	7		20:40–21:42	0.80	3.17
Improved type	1	29 June 2000	19:33–20:30	1.72	4.17
	2		20:50–21:50	1.78	4.34
	3		22:11–23:11	1.78	4.09
	4		23:30–00:31	1.55	4.06
	5	30 June 2000	19:30–20:30	1.91	4.52
	6		20:47–21:47	1.66	4.32

SURF-BRD, System of Unwants Ramp-way Filtered-Bycatch Reduction Device

Table 2 Catch number and weight in the fishing experiment

Type of BRD	Bag	Fish		Crustacea		Cephalopoda		Others		Total	
		Number	Weight (kg)	Number	Weight (kg)	Number	Weight (kg)	Number	Weight (kg)	Number	Weight (kg)
Prototype	Cod-end	1,355	21.82	4,372	19.53	167	5.74	19	0.49	5,913	47.58
	Side-vent cover	201	2.18	1,226	6.38	25	0.34	13	0.22	1,465	9.13
	Total	1,556	24.01	5,598	25.91	192	6.08	32	0.71	7,378	56.71
Improved type	Cod-end	941	20.52	9,799	33.88	36	4.80	4	0.05	10,780	59.24
	Side-vent cover	471	4.99	11,650	50.78	12	0.52	25	0.30	12,158	56.59
	Total	1,412	25.51	21,449	84.65	48	5.32	29	0.35	22,938	115.83
Total		2,968	49.51	27,047	110.56	240	11.40	61	1.06	30,316	172.54

Table 3 Top ten species based on size of catch by the beam trawl with prototype of SURF-BRD

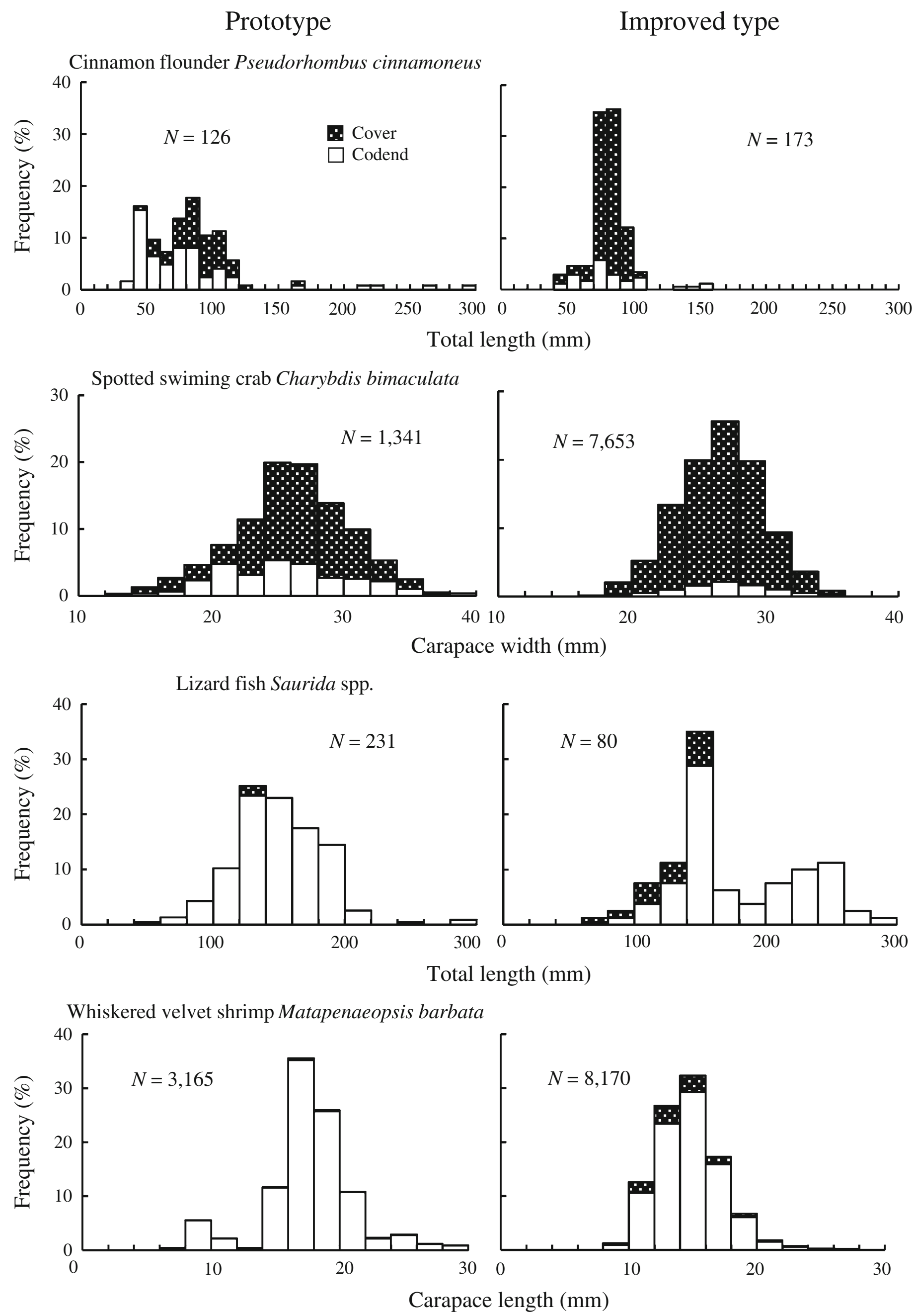
English name	Species name	Catch (*n*)	Percentage
Whiskered velvet shrimp	*Metapenaeopsis barbata*	3,165	39.2
Spotted swimming crab	*Charybdis bimaculata*	1,341	16.6
Tora velvet shrimp	*Metapenaeopsis acclivis*	474	5.9
Southern rough shrimp	*Trachypenaeus curvirostris*	312	3.9
Offshore ponyfish	*Leiognathus rivulatus*	311	3.9
Lizard fish	*Saurida* spp.	231	2.9
Blunt-toothed crab	*Charybdis truncata*	220	2.7
Vertical striped cardinalfish	*Apogon lineatus*	147	1.8
Cinnamon flounder	*Pseudorhombus cinnamoneus*	126	1.6
Halfline cardinalfish	*Apogon semilineatus*	113	1.4
Others	Others	2,918	20.2
Total		9,358	100.0

Table 4 Top 11 species based on size of catch by the beam trawl with improved type of SURF-BRD

English name	Species name	Catch size (*n*)	Percentage
Whiskered velvet shrimp	*Metapenaeopsis barbata*	8,170	28.2
Spotted swimming crab	*Charybdis bimaculata*	7,653	26.4
Blunt-toothed crab	*Charybdis truncata*	2,341	8.1
Portunid swimming crab	*Portunus hastatoides*	1,595	5.5
Tora velvet shrimp	*Metapenaeopsis acclivis*	477	1.6
Vertical striped cardinalfish	*Apogon lineatus*	414	1.4
Cinnamon flounder	*Pseudorhombus cinnamoneus*	173	0.6
Golden cusk	*Sirembo imberbis*	164	0.6
Chinese mud shrimp	*Solenocera koelbeli*	156	0.5
Southern rough shrimp	*Trachypenaeus curvirostris*	115	0.4
Lizard fish	*Saurida* spp.	80	0.3
Others	Others	2,388	26.3
Total		23,726	100.0

which the parameters converged were limited (Table 5). For cinnamon flounder, the parameters were successfully estimated in seven and six models (except Model C) from data collected with the prototype and the improved type, respectively (Table 5). The model parameters of spotted swimming crab were estimated in all models except Model C_F for the prototype and in all models for the improved type except Model B of monotonic decrease and Models A_F and A_{FR}, assuming that all spotted swimming crabs contacted the FP ($p = 1$). There was no convergence in

Fig. 5 Length distributions of the four species



Model B in the monotonic decrease for lizard fish. Parameter estimation was successful only for Model D for whiskered velvet shrimp. Of the models in which the parameters converged in the maximum likelihood analysis for the four species, the AIC values are also shown in Table 5. The observed proportion of fish retained in the cod-end, ϕ_l was plotted against body length with the estimated $\phi(l)$ curve of the model selected as the model with the best fit by the AIC (Fig. 6). The estimated parameters of contact probability and the contact selection curve for the FP and RP estimated for these four species are shown in Table 6.

Cinnamon flounder

The mode in TL distribution of the cinnamon flounder caught in the cod-end and cover was from 80 to 90 mm for both the prototype and improved type (Fig. 5). While the TL range was from 30 to 300 mm for the prototype and from 40 to 160 mm for the improved type, the TL range

Table 5 Akaike information criterion values of each model for the four species

Model[a]	Cinnamon flounder *Pseudorhombus cinnamoneus*		Spotted swimming crab *Charybdis bimaculata*		Lizard fish *Saurida* spp.		Whiskered velvet shrimp *Matapenaeopsis barbata*	
	Prototype	Improved type	Prototype	Improved type	Prototype	Improved type	Prototype	Improved type
A	39.7	32.9	108.0[b]	76.9	26.0	–	–	–
A_R	37.7[a]	32.0	114.9	74.9	37.7	–	–	–
A_F	40.3	–	114.9	–	–	–	–	–
A_{FR}	40.0	30.0[b]	112.9	–	–	–	–	–
B	45.8	57.9	119.4	–	–	–	–	–
B_R	43.7	56.7	147.1	–	–	–	–	–
B_F	–	–	247.9	–	–	–	–	–
B_{FR}	–	70.3	245.9	–	–	–	–	–
C	–	–	137.8	71.1[b]	20.5[b]	21.5	–	–
C_F	–	–	–	94.8	–	15.5[b]	–	–
D	63.1	–	166.5	97.6	24.3	33.8	53.9[b]	114.6[b]

–, Not converged

[a] For a detailed description of the models, see section "Numerical models used for data analysis"

[b] Best fitted model with the smallest Akaike information criterion (AIC)

within which five or more individuals were caught by the prototype and improved type was from 40 to 120 mm and from 40 to 110 mm, respectively (Fig. 5). For the prototype, the ϕ_l values decreased from 1 to about 0.3 within the TL range from 40 to 120 mm. In contrast, for the improved type, the ϕ_l values decreased from approximately 0.6 to 0.1 within the TL range from 50 to 90 mm, and then increased to 0.67 at the 100- to 110-mm TL class (Fig. 6a). In the >200-mm TL class for the prototype and the 130- to 150-mm TL class for the improved type, the $\phi_l = 1$, although the catch numbers were less than five. Thus, the plots of ϕ_l values versus TL were a *U*-shaped curve in the two SURF-BRD types for this species (Fig. 6a). In fact, of the Model A groups that have *U*-shaped curves, those in Model A_R and Model A_{FR} were selected by the AIC model selection as the best fit for the prototype and improved types, respectively (Table 5). The results of the model selection suggested that the contact probability was 1 for fish against the RP in the prototype and 1 for fish against FP and RP in the improved type. The estimated probability of this species coming in contact with the FP was 0.70 for the prototype. The likelihood ratio tests [12, 23] showed that there was no lack of goodness-of-fit (p >0.05), nor was there systematic bias in the deviance residuals versus TL (Fig. 6a). There was a difference in the 50 % selection length of the FP between the two types (172 mm for the prototype vs. 107.6 mm for the improved type), which was probably due to having too small sample numbers within the TL range relative to the FP size selection for the two types of BRD (Fig. 6a). On the other hand, no large difference was found in the 50 % selection length of RP (69.4 vs. 53.3 mm in TL) between the two types (Table 6).

Spotted swimming crab

Five or more individuals for the spotted swimming crab were caught within the CW range from 12 to 40 mm for the prototype and from 16 to 36 mm for the improved type (Fig. 6b). Apart from the two CW classes of 18–20 and 20–22 mm, the ϕ_l value for the spotted swimming crab caught by the prototype were around 0.25, fluctuating for CW between 14 to 32 mm and increasing for CW over 32 mm to 1 in the 38 to 40 mm CW class. In contrast, the ϕ_l for this species for the improved type appeared to be constant within the CW range from 18 to 30 mm. Model A was the most complicated one selected for the prototype by the AIC comparison (Table 5). However, the likelihood ratio test showed a lack of fit (Table 6), and values over 2 in deviance residual were found for four of the CW classes: 12–14, 16–18, 20–22, 38–40 mm. In contrast, Model C was the best fitted for the improved type without any lack of fitness in the likelihood ratio test (P >0.05) and any systematic bias in deviance residual versus CW (Fig. 6b). This suggests that there is no effective size selection of the RP within the CW range of this species. The estimated contact probability of the FP was 0.92 (Table 6), which means that 8 % of the spotted swimming crab encountering the net mouth entered the cod-end through Path 1 without coming in contact with the FP. The values of l_{50} for the FP were

Table 6 Parameter values[a] estimated in the best fitted model with the smallest Akaike information criterion value for the four species

Species name	Type of BRD	The best fitted model[b]	Front panel					Rear panel					Likelihood ratio test for model fit		
			p	a_F	b_F	l_{50}	S.R.	q	a_R	b_R	l_{50}	S.R.	Deviance	*df*	*p* value
Cinnamon flounder *Pseudorhombus cinnamoneus*	Prototype	Model A_R	0.70	−0.13	21.74	172.04	17.39	(1.00)	−0.08	5.77	69.36	26.44	6.67	3	0.08
	Improved	Model A_{FR}	(1.00)	−0.29	29.94	102.63	7.54	(1.00)	−0.07	3.93	53.25	29.79	2.39	3	0.50
Spotted swimming crab *Charybdis bimaculata*	Prototype	Model A	0.79	−0.48	17.63	36.55	4.55	0.37	−0.99	22.46	22.73	2.22	35.87	7	<0.01
	Improved	Model C	0.92	−0.65	24.04	36.85	3.37	–	–	–	–	–	16.67	7	0.46
Lizard fish *Saurida* spp.	Prototype	Model C	0.04	−0.18	25.37	138.98	12.03	–	–	–	–	–	4.67	4	0.32
	Improved	Model C_F	(1.00)	−0.05	5.12	112.13	48.10	–	–	–	–	–	1.14	5	0.95
Whiskered velvet shrimp *Metapenaeopsis barbata*	Prototype	Model D	0.01	–	–	–	–	–	–	–	–	–	21.98	11	0.02
	Improved	Model D	0.11	–	–	–	–	–	–	–	–	–	61.35	9	<0.01

Each value in parenthesis was fixed at 1 in the model

[a] p, q parameters of contact probability for the front panel (FP) and rear panel (RP), respectively; (a_F, b_F) and (a_R, b_R), logistic function parameters representing the contact selectivities for the FP and RP, respectively; l_{50}, length of 50 % retention; S.R., selection range

[b] For a detailed description of the models, see section "Numerical models used for data analysis"

Fig. 6 **a** Proportion of cinnamon flounder *Pseudorhombus cinnamoneus* retained in the cod-end with curves of the fitted model and deviance residuals, **b** proportion of spotted swimming crab *Charybdis bimaculata* retained in the cod-end with curves of the fitted models and deviance residuals, **c** proportion of lizard fish *Saurida* spp. retained in the cod-end with curve of the fitted model and deviance residuals, **d** proportion of whiskered velvet shrimp *Matapenaeopsis barbata* retained in the cod-end with curves of the fitted models and deviance residuals. **a–d** *Long* and *short broken lines* Selection curve of FP and RP, respectively, *AIC* Akaike information criterion, with the smallest AIC indicating the best fitted model, *p* probability in likelihood ratio test for model fit ▶

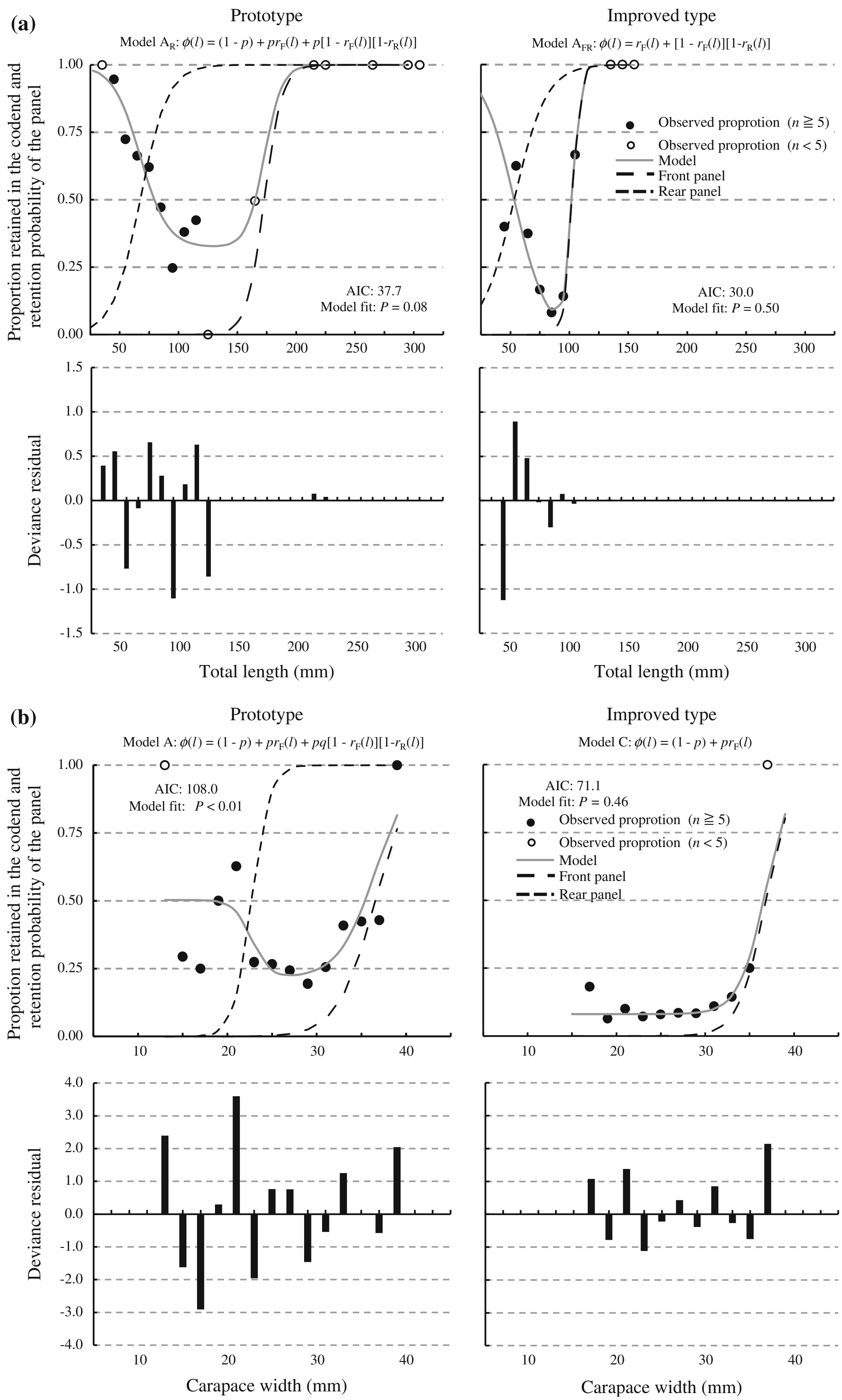
very close between the two types; 37.6 mm for the prototype and 36.9 mm for the improved type.

Lizard fish

The range of the TL for lizard fish was from 40 to 300 mm for the prototype and from 60 to 300 mm for the improved type (Fig. 6c). For the prototype, $\phi_l = 1$, except for 0.93 for the 120- to 140-mm TL class. On the other hand, the ϕ_l values for the improved type showed a sigmoidal increase from 0.5 to 1.0, with increasing TL from 60 to 180 mm, and these were constant at 1.00 for TL >180 mm (Fig. 6c). The AIC model selected Model C for the prototype and Model C_F for the improved type (Table 5). There was no lack of fitness by the likelihood ratio test (p >0.10; Table 6). The FP contact probability for this species was estimated to be 0.04 for the prototype (Table 6), while all of the lizard fish encountering the net mouth came in contact with the FP in the improved type, as suggested by Model C_F selected by the AIC. The 50 % selection length of the FP for this species was 139 mm for the prototype and 112 mm for the improved type.

Whiskered velvet shrimp

The CL of the whiskered velvet shrimp ranged from 6 to 30 mm for the prototype and from 8 to 28 mm for the improved type, and sample sizes seemed to be sufficient for analysis at these CL length classes (Fig. 5). The ϕ_l values for this species for the prototype were almost 1 (0.92–1.00), while those for the improved type were slightly smaller, ranging from 0.76 to 0.92 (Fig. 6d). Even though Model D was selected by the AIC model selection for both the prototype and the improved type (Table 5), likelihood ratio testing indicated a lack of model fitness (Table 6). Much worse, deviance residuals of >2 were found for several CL classes for both types (Fig. 6d). The plots of ϕ_l values against CL showed a convex upward curve for the improved type, which was definitely distinct from the other curves proposed in this study (Fig. 4). Still, the value of parameter p estimated by Model D was 0.01 for the prototype and 0.11 for the improved type. This implies that


(a)
Prototype
Model A$_R$: $\phi(l) = (1 - p) + pr_F(l) + p[1 - r_F(l)][1 - r_R(l)]$
Improved type
Model A$_{FR}$: $\phi(l) = r_F(l) + [1 - r_F(l)][1 - r_R(l)]$
Proportion retained in the codend and retention probability of the panel
Observed proprotion (n ≧ 5)
Observed proprotion (n < 5)
Model
Front panel
Rear panel
AIC: 37.7
Model fit: P = 0.08
AIC: 30.0
Model fit: P = 0.50
Deviance residual
Total length (mm)
(b)
Prototype
Model A: $\phi(l) = (1 - p) + pr_F(l) + pq[1 - r_F(l)][1 - r_R(l)]$
Improved type
Model C: $\phi(l) = (1 - p) + pr_F(l)$
Propotion retained in the codend and retention probability of the panel
AIC: 108.0
Model fit: P < 0.01
AIC: 71.1
Model fit: P = 0.46
Observed proprotion (n ≧ 5)
Observed proprotion (n < 5)
Model
Front panel
Rear panel
Deviance residual
Carapace width (mm)

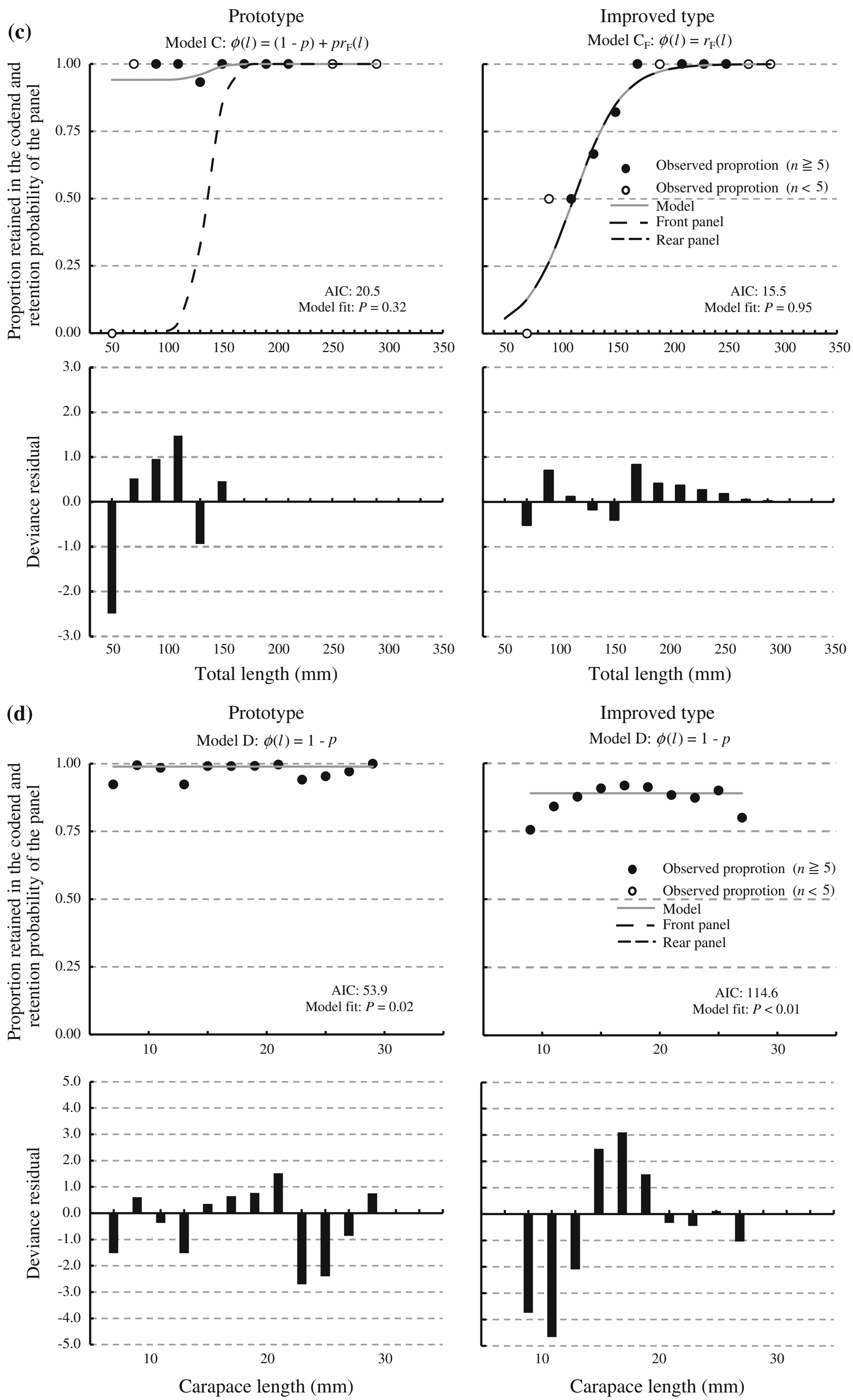


Fig. 6 continued

almost all of the whiskered velvet shrimp entering the net mouth were retained in the cod-end of the prototype and that only small numbers of this species pass through the FP and escaped through the side vent.

Discussion

Validity of models describing the selection process for the SURF-BRD

In this study, the parameters describing size selection of the FP were estimated for three species: cinnamon flounder, spotted swimming crab, and lizard fish (Table 6). Size selection parameters of the RP were obtained for cinnamon flounder and spotted swimming crab. It is well accepted that mesh size is one of the most important factors in size selection of the trawl cod-end. Here, to examine the validity of the model proposed in this study, we compared the estimated size selection parameters of the FP and RP with previously reported size selection parameters of the cod-end. The shape of the mesh of the FP used in the SURF-BRD was square. It is also well accepted that for round-bodied fish a cod-end with a square mesh has a higher 50 % retention length (L_{50}) than a cod-end with a diamond mesh [24], whereas for plaice the opposite is true [25]. He [26] recently reported that mesh shape (diamond or square) has no significant effect on the L_{50} for round-bodied fish while square mesh cod-ends have significantly smaller L_{50} for flounders. For the two fishes and the two crustaceans evaluated in this study, the mesh selectivity of a square mesh cod-end is still unknown; therefore, we compared our results with the mesh selectivity of diamond mesh cod-ends reported in a number of previous reports.

The L_{50} of the FP for cinnamon flounder was estimated to be 102 mm in TL in the improved type, apart from that estimated from data of small sample size in the prototype (Table 6). From data on body size measurement of cinnamon flounder sampled in the fishing experiment, the relationship between TL l and body height l_D was estimated by the following equation;

$$l_D = 0.42\,l - 2.32\ \left(\text{coefficient of determination},\ R^2 = 0.98;\ n = 28\right) \quad (14)$$

With this equation, the body height corresponding to the TL of 50 % selection was calculated to be 41 mm, and the selection factor in terms of body height (50 % body height/stretched mesh size: l_D/m) was 0.566. Tokai [27] reported that the retention probability of the cod-end mesh ranged from 0 to 1 as the ratio of body height l_D to mesh size m increased from approximately 0.5 to 1.0 with a diamond mesh and a target catch of ridged-eye flounder *Pleuronichthys cornutus* and marbled flounder *Pseudopleuronectes yokohamae*, suggesting that flatfish with a body height larger than the mesh opening are unable to pass through the mesh. Yamasaki et al. [28] reported a similar result for willowy flounder *Tanakius kitaharai* in a cod-end made of diamond mesh. The estimated l_D/m of 50 % retention in the FP of the prototype was 0.566, which is slightly lower than previously reported results [27, 28]. One possible explanation is that it is slightly more difficult for flatfishes to pass through square mesh than through diamond mesh, as has been pointed out in several papers [e.g., 24, 26, 29]. In any case, these results suggest that size selection of the FP for cinnamon flounder was mainly due to the mesh selection.

The L_{50} of the cod-end with 27.5-mm diamond mesh for five spot flounder *Pseudorhombus pentophthalmas*, which has a body shape similar to that of cinnamon flounder, has been reported to be a TL of 61 mm [30], and in our study this length was close to the L_{50} of the RP (TL = 69 mm for the prototype and TL = 53 mm for the improved type; Table 6). In addition, using Eq. (14), we showed that the l_D/m values of 50 % selection were 0.96 and 0.73 in the prototype and improved types, respectively, which are also close to previously reported results [24, 25]. These results suggest that the size selection of the RP is equivalent to that of the cod-end mesh.

In this study, Model A was selected to describe the available selection of the prototype for the spotted swimming crab, but the statistical test indicated no fitness of the model (p <0.01), while the fitness of the Model C for the improved type was quite good. The estimated value of 37 mm as the 50 % selection CW of the FP for spotted swimming crab in both types (Table 6) was very close to the 39 mm reported previously as the 50 % retention CW for diamond mesh cod-end of the same nominal 80-mm mesh size as the FP [31]. On the other hand, the estimated 50 % selection CW of the RP in the prototype for this species was 22 mm (Table 6), which is relatively larger than the 13 mm reported as the 50 % retention CW in diamond mesh cod-end of the same nominal 27.5-mm mesh size [31]. The CW range for spotted swimming crab caught in the fishing experiments exceeded 12 mm for the prototype and 16 mm for the improved type (Fig. 5), making the sizes too large to estimate the contact selection parameters for the RP of the BRD. This implies that Model C should have been selected as the better model for the prototype as well as for the improved type.

Liang et al. [32] reported that the 50 % retention TL of Wanieso lizardfish *Saurida wanieso* in the diamond mesh cod-end with nominal 80-mm mesh size (stretched mesh size 72 mm) was 307 mm TL and also pointed out that round-bodied fish like the lizard fish are likely to pass through a square mesh more easily than through a diamond mesh. In this study, however, the 50 % selection TL of the

FP for lizards was estimated to be 138 mm for the prototype and 112 mm for the improved type (Table 6), which is less than half of the 50 % retention TL of diamond mesh cod-end. The TL of lizard fish caught in the fishing experiments did not exceed 300 mm (Fig. 5) and, therefore, these could have passed through the FP square mesh based on body size relative to the mesh opening. This results suggests that lizard fish with a larger body size swam up over the BRD without coming in contact with the FP. Generally, larger fish are more likely to have better swimming ability [33]. Thus, we ascribe size selection of the FP for lizard fish to avoidance behavior dependent on fish body size rather than on the contact selection of the FP.

For the whiskered velvet shrimp, as mentioned above in the methods, Model D in which ϕ_l values were constant against body sizes was selected by the AIC, but no information was provided to distinguish between Path 1 of $1 - p$, the Path 5 of q, and the Paths 1 and 5 of $(1 - p) + pq$. Tora velvet shrimp *Metapenaeopsis acclivis*, which is a relative species to the whiskered velvet shrimp, has a quite similar body shape. Tokai and Sakaji [34] reported that the retention probability of the 25.1-mm diamond mesh cod-end for the tora velvet shrimp increased from 0 to 1 with an increase in CL from 10 to 18 mm and that the 50 % retention CL was about 13.5 mm. The range of CL values of the whiskered velvet shrimp caught in our fishing experiments was from 6 to 30 mm (Fig. 5). Shrimp of this size would be able to physically pass through the FP square mesh of 80-mm mesh size as its body size is sufficiently smaller than the mesh opening. Moreover, if whiskered velvet shrimp do come into contact with the RP, shrimp with a CL of >18 mm would be without question retained by the RP, which has 27.5-mm diamond mesh, and excluded through the side-vent, meaning a low ϕ_l value for CL >18 mm. Shrimp with CL <11 mm would always pass through the RP mesh, which leads to a high ϕ_l value. These findings suggest that Model A or B should have been selected as the best model when effective mesh selection of the RP is taken into account. However, Model D was selected and there are no indications of good of fitness (Tables 5, 6). A possible explanation is that the whiskered velvet shrimp passing through the FP did not come in contact with the RP and were washed out through the side-vent with the water mass that may be stalled in front of the RP with a fine mesh net. Accordingly, we concluded that all of the whiskered velvet shrimp caught in the cod-end entered the cod-end through Path 1 (Fig. 3).

The height of the improved type was about threefold higher than that of the prototype (Table 1), and the four main species studied here had a higher probability of coming in contact with the FP in the improved type than in the prototype (Table 6). For the lizard fish, the difference in contact probability between the two types was marked. Of the lizard fish entering the net, most could avoid coming in contact with the FP in the prototype because of their good swimming ability, but all came in contact with the FP in the improved type (Table 6; Fig. 6). In contrast, some portion of the spotted swimming crabs did not come in contact with the FP because the BRD height of the prototype was not as high as that in the improved type for which contact probability was estimated to be 0.92 (Table 6; Fig. 6b). Small shrimps, including the whiskered velvet shrimp, usually burrow into the sea bed during the day and swim some distance away from the sea bed at night [35–38]. In our study, we utilized data obtained for night towing when the whiskered velvet shrimp may have been off the sea bed. Consequently, it is possible not as many shrimp as expected came into contact with the FP. This results indicates that both the height of the BRD and the swimming behavior of the animal are the principal factors affecting the probability of animals coming in contact with the FP.

Of the mixed model proposed in this study, although model A was selected as the best one by the AIC model selection process to describe available selection of the prototype for spotted swimming crab, models with a small number of parameters were also run for the other species (Table 5). For the lizard fish, no fish passed through the FP or came in contact with the RP; consequently, the contact selection of this species for the RP could not be estimated. Contact selection parameters were not estimated for species such as the whiskered velvet shrimp not only because the body size ranges were out of the range of the FP and RP contact selection but also because the sample sizes of the body size ranges relevant for estimating model parameters were too small. To express available selection of BRD with sorting panels, such as large mesh panels and grids, the mixed model with contact probability and size selection should be considered, and the appropriate model best fitted to the data should be chosen from the mixed models by some criterion, such as the AIC. When none of the mixed models provide a good fit to the data, the species- and size-selective process other than the available selection proposed in this study should be considered.

Further improvements in the device based on model evaluations

Cinnamon flounder is a marketable species, and fishermen who trawl off Shimonoseki target members of this species with a TL of >100 mm [39]. The TL range of cinnamon flounder caught in the fishing experiments was 30–300 mm (Fig. 5). In the improved type, all cinnamon flounder entering the net encountered the FP, and thereafter cinnamon flounder of larger sizes were retained by the FP and came into the cod-end through Path 2, while smaller ones with a TL of approximately 50 mm entered the cod-end after passing through both the FP and the RP—that is, Path 5 (Fig. 6). The FP which has a 50 % selection TL of 107 mm was partially effective in catching cinnamon flounder with a TL >100 mm. However, it should be possible to improve the system by switching the RP to a smaller mesh size, which may result in an increased effectiveness in terms of preventing smaller cinnamon flounder from entering the cod-end through Path 5. And, there may still be a possibility for cinnamon flounder to exit through the side-vent without coming into contact with the RP.

The spotted swimming crab is of no commercial value and actually hinders on-deck sorting by fishermen; thus, it should be excluded from the net. Most of the spotted swimming crabs caught in the fishing experiment were <34 mm CW (Fig. 5) and easily passed through the FP. While some spotted swimming crabs were retained in the cod-end of the prototype, the majority of the spotted swimming crabs were successfully excluded in the improved type through the use of an appropriate mesh size for the FP and RP and due to the higher contact probability.

The lizard fish is marketable, as is cinnamon flounder, and the target size has been reported to be >50 mm TL [39]. The prototype appeared to have almost no size selection for this species for TL >50 mm (Fig. 5). In contrast, the 50 % selection TL of the FP was 112 mm in the improved type (Table 6), and thus in order to retain all lizard fish of the target size, a smaller mesh size for the FP would be better. However, the minimum maturity sizes of male and female lizard fish have been reported to be 235 and 249 mm, respectively, for the slender lizard fish *Saurida elongate* [40] and 180 and 228 mm, respectively, for *Saurida umeyoshii* [41]. From the point-of-view of fisheries resources management for lizard fishes, the FP mesh size should be greatly enlarged.

Based on the results of this study, we propose mixed models with specific probabilities of animals coming in contact with the sorting panel and size selectivity of the sorting panel to express the available selection of the SURF-BRD, which has the two sorting panels, FP and RP. We estimated the parameters of contact probability and selectivity in the mixed models and then chose the model that best fit the data for each species through the AIC model selection. Appropriate mesh sizes of the sorting panels could be determined based on the estimated available selectivity model. The selectivity parameters of FP and RP in the model were attributed mainly to mesh size selectivity, but for some species also partially to fish swimming ability. Differences in contact probabilities among the species were associated not only with animal behavior but also with the dimension and configuration of the BRD. The mixed models and the model selection process are useful for evaluating the selective processes of the BRD with a sorting panel, such as mesh windows, grids, among others. These models, therefore, are also useful for understanding species- and size-selectivity of the BRD with the sorting panel.

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