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ARTICLE

Testing of Two Selective Flatfish Sorting-Grid Bycatch Reduction Devices in the U.S. West Coast Groundfish Bottom Trawl Fishery

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Abstract
In the U.S. West Coast limited-entry (LE) groundfish bottom trawl fishery, catches of stocks with restrictive harvest limits (e.g., Darkblotched Rockfish *Sebastes crameri*, Sablefish *Anoplopoma fimbria*, and Pacific Halibut *Hippoglossus stenolepis*) continue to hinder many fishermen's ability to fully utilize their quota shares of more abundant flatfish stocks (e.g., Dover Sole *Microstomus pacificus* and Petrale Sole *Eopsetta jordani*). We used a recapture net to examine the size-selection characteristics of two selective flatfish sorting-grid bycatch reduction devices (BRDs), which were designed to reduce catches of Pacific Halibut and non-flatfish species while retaining target flatfishes. The two devices were identical in materials and design except that the sorting-grid dimensions differed (BRD-1: 6.4- × 25.4-cm grid size; BRD-2: 6.4- × 30.5-cm grid size). The size selectivity for rockfishes, other roundfishes, Pacific Halibut, English Sole *Parophrys vetulus*, and Rex Sole *Glyptocephalus zachirus* did not differ significantly between the two designs. However, for 53–58-cm TL Arrowtooth Flounder *Atheresthes stomias*, 39–53-cm TL Dover Sole, and 36–49-cm TL Petrale Sole, BRD-1 retained significantly higher proportions of these length-classes than did BRD-2. Combined, the mean flatfish retention by weight (not including Pacific Halibut) was 89.3% (95% confidence interval [CI] = 87.1–91.5%) for BRD-1 and 81.7% (95% CI = 80.0–83.4%) for BRD-2. Compared to previous flatfish sorting-grid selectivity work conducted in the LE bottom trawl fishery, BRD-1 showed the ability to improve the overall retention of flatfishes while reducing catches of nontarget and constraining species.

Implementing practices that enhance utilization of fishery quotas and provide for an economically sustainable fishery is an objective of the catch shares program for the U.S. West Coast limited-entry (LE) groundfish bottom trawl fishery

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TABLE 1. Specifications of the two bycatch reduction devices (BRDs) tested. Mesh sizes (mm) are stretched measurements between knots (DM = diamond mesh; LL = long link; * = does not account for meshes gored in each selvedge).

Characteristic	BRD-1	BRD-2	Recapture net	Trawl cod end
Grid dimensions (height × length)	6.4 × 25.4 cm	6.4 × 30.5 cm		
Netting	116-mm DM	116-mm DM	116-mm DM	116-mm DM
Twine	4-mm single (top and side panels); 5-mm double (bottom panel)	4-mm single (top and side panels); 5-mm double (bottom panel)	6-mm double	6-mm double
Circumference*	100	100	70	88
Meshes deep	80	80	100	75
Top riblines	32-mm Blue Steel Poly rope, hung at 6%	32-mm Blue Steel Poly rope, hung at 6%	12.7-mm Blue Steel Poly rope, hung at 6%	32-mm Blue Steel Poly rope, hung at 6%
Bottom riblines	12.7-mm LL chain, hung at 6%	12.7-mm LL chain, hung at 6%	12.7-mm Blue Steel Poly rope, hung at 6%	32-mm Blue Steel Poly rope, hung at 6%

(PFMC and NMFS 2011, 2015). In this fishery, participants are held fully accountable for catches of all individual fishing quota (IFQ) species and bycatch of the Pacific Halibut *Hippoglossus stenolepis*, a prohibited species. Catch accountability has encouraged fishermen to fish more selectively to improve the utilization of their catches of IFQ species. However, constraints on stocks with restrictive harvest limits continue to impact fishermen's ability to fully utilize their quota shares of healthier groundfish stocks.

In the LE bottom trawl fishery, fishermen trawling shoreward of 183-m bottom depth and north of 40°10′N latitude are currently mandated to use a two-seam, low-rise selective flatfish trawl (King et al. 2004; Hannah et al. 2005; NOAA 2014). This regulation was implemented in an effort to minimize the catches of overfished and rebuilding stocks of rockfish *Sebastes* spp. when trawling for flatfishes (i.e., English Sole *Parophrys vetulus*, Dover Sole *Microstomus pacificus*, and Petrale Sole *Eopsetta jordani*) over the continental shelf. This trawl has been shown to be successful at reducing catches of some benthopelagic rockfishes (notably Canary Rockfish *Sebastes pinniger*, a previously overfished stock that has recently rebuilt). However, catches of Darkblotched Rockfish *Sebastes crameri*, Sablefish *Anoplopoma fimbria*, and Pacific Halibut often restrict many fishermen from fully utilizing their flatfish IFQs, as relatively limited quota is available. Consequently, developing techniques that minimize catches of constraining species and provide fishermen with more opportunities to fully utilize their catch share quota of healthier fish stocks would be beneficial to fishermen, coastal communities, management, and the resource.

Selectivity studies evaluating sorting-grid bycatch reduction devices (BRDs; Lomeli and Wakefield 2013, 2015, 2016), cod-end mesh sizes and configurations (Wallace et al. 1996; Perez-Comas et al. 1998; Lomeli et al. 2017), and trawl designs (Hannah et al. 2005; King et al. 2004) in the LE bottom trawl fishery have been conducted in an effort to enhance trawl selectivity and catch utilization. For bottom trawl fishermen targeting flatfishes, a sorting-grid BRD was developed to reduce catches of rockfishes, other roundfishes, and Pacific Halibut (Lomeli and Wakefield 2015, 2016). The design consisted of long, rectangular slots (4.4 cm high × 21.6 cm long) to allow flatfishes to pass through and move aft toward the cod end, whereas nontarget species that are unable to pass though the slots are released out of the trawl. During gear trials, the BRD demonstrated the ability to significantly reduce catches of rockfishes, Sablefish, and Pacific Halibut. The mean catch of flatfishes (five species evaluated) ranged from 68.1% to 92.3% by weight, with an overall mean of 85.6%. Although encouraging results were achieved, it was noted that improvements in the BRD's ability to retain flatfishes (particularly larger-sized fish with higher economical value) were desired to enhance the gear's effectiveness in the fishery (Lomeli and Wakefield 2015, 2016).

The objectives of the current study were to (1) examine the size-selection characteristics of two alternative sorting-grid sizes and (2) evaluate their ability to further improve flatfish retention relative to previous studies while reducing the catches of nontarget species.

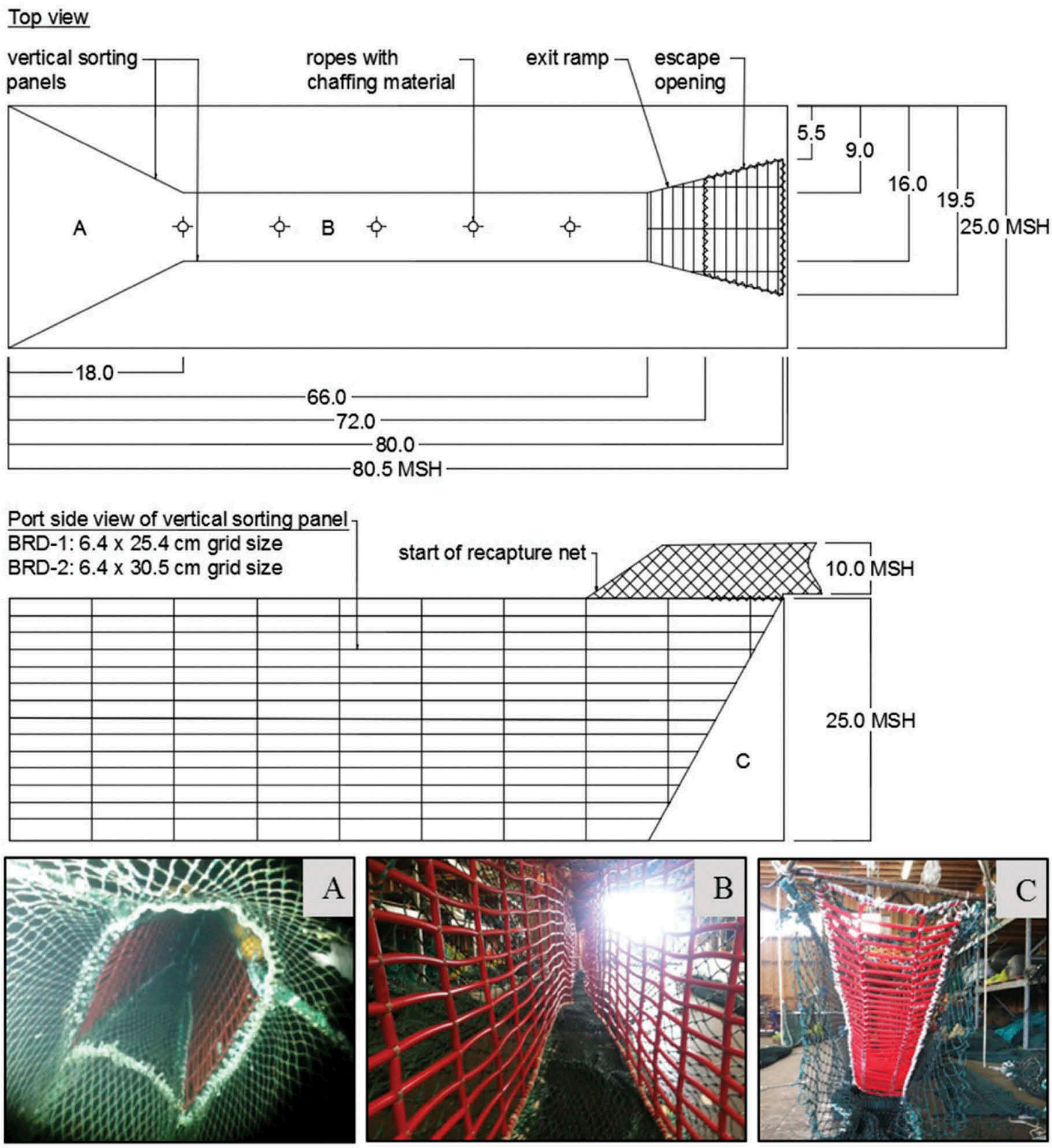

FIGURE 1. Schematic diagram (not to scale) depicting the general design of the flexible sorting grid tested (top; MSH = meshes). The only design difference between the two bycatch reduction devices (BRD-1 and BRD-2) was the grid size. Image A presents the aft view of the forward portion of the gear, where fish enter and encounter the BRD; image B depicts the aft view of the area between the two vertical sorting panels; and image C presents the fore view of the upward-angled exit ramp.

METHODS

*Trawl design.—*The trawl used for this study was a two-seam, Eastern 400 low-rise selective flatfish trawl with a cutback headrope. The headrope was 40.3 m in length, and the chain footrope was 31.2 m in length. The chain footrope was covered with 20.3-cm-diameter rubber discs and outfitted with 35.6-cm-diameter rubber rockhopper discs placed approximately every 58.4 cm over the footrope length. This trawl lacks floats along the central portion of the headrope to reduce fish diving reactions to floats that may occur. Refer to Hannah et al. (2005) and King et al. (2004) for the trawl net plan.

*Gear designs.—*We followed the BRD design of Lomeli and Wakefield (2015, 2016) but tested two different grid dimensions. The BRDs were built within four-seam tubes of 116-mm diamond netting (Table 1) and were inserted between the intermediate section of the trawl and the cod end. A 50-mesh-deep, two- to four-seam transitional tube of netting attached each BRD to the trawl. The two grids tested consisted of elongated slots that were 6.4 cm high × 25.4 cm long (BRD-1) and 6.4 cm high × 30.5 cm long (BRD-2). Each BRD utilized two vertical panels that extended longitudinally down the tube of netting (Figure 1). The concept of the design was that fish smaller than the grid openings would pass through the grid and move aft toward the cod end, whereas fish larger than the grid openings (e.g., roundfishes and most adult Pacific Halibut) would be excluded. Fish that do not pass through the grid openings are guided by an exit ramp and exit out the top of the trawl. Between the two vertical sorting panels, ropes with chafing material wedged through them were positioned to create partial obstructions to fish moving aft; this was done to stimulate fish to move toward the sorting grids. At the aft end of each BRD, the top portion of the vertical panels angled outward to allow for integration of the exit ramp and its associated escape opening. The trawl cod end was a four-seam tube of 116-mm diamond netting. For further design details, refer to Lomeli and Wakefield (2016).

We used a recapture net to quantify fish escapement for the two BRD designs. The recapture net was 100 meshes deep and 70 meshes in circumference (25 meshes on the top and bottom panels; 10 meshes on the side panels) and was constructed of the same webbing material and mesh size as the trawl cod end (Table 1). The recapture net was attached to the BRD just forward of the escape opening to allow excluded fish to be captured. To keep the recapture net from masking the escape opening, two 20.3-cm center-hole floats were placed on each top ribline of the recapture net, above the escape area of the BRD, while two 27.9-cm ear-floats were placed on the top panel webbing in the middle (between the top riblines) of the recapture net.

Gear trials and fish sampling.—We conducted our sea trials aboard the F/V *Miss Sue* (24.7-m-long, 640-hp trawler) off central Oregon (between 44°30′ and 45°32′N and between 124°17′ and 124°48′W) during April 2016. Towing occurred over the continental shelf and shelf break during daylight hours (between 0600 and 1800 hours Pacific daylight time) at bottom fishing depths from 146 to 402 m. The average bottom fishing depth was 249 m. Towing speed over ground ranged from 4.07 to 4.82 km/h (2.2–2.6 knots). Tow durations were set to 1 h. The BRDs were fished in an alternate tow randomized block design. After each tow, all fish were identified to species and weighed by using a motion-compensated platform scale. Flatfishes, Shortspine Thornyheads *Sebastolobus alascanus*, and Lingcod *Ophiodon elongatus* were measured to the nearest centimeter TL, while Sablefish and rockfishes were measured to the nearest centimeter FL.

TABLE 2. Length data used to model (via CLogit) the size selectivity for each bycatch reduction device (BRD) design. Values in parentheses are the fish measurement subsample ratios from the total catch. Flatfishes, Shortspine Thornyheads, and Lingcod were measured to the nearest centimeter TL; Sablefish and rockfishes were measured to the nearest centimeter FL.

Species	Number of tows	Number of fish measured in cod end	Number of fish measured in recapture net	Length range (cm)
BRD-1 (grid size = 6.4 × 25.4 cm)				
Pacific Halibut	10	5 (1.0)	21 (1.0)	55–81
English Sole	13	401 (0.59)	86 (1.0)	23–40
Rex Sole	15	1,170 (0.70)	196 (1.0)	21–52
Arrowtooth Flounder	15	1,028 (0.78)	155 (1.0)	24–66
Dover Sole	15	2,477 (0.43)	451 (1.0)	28–61
Petrale Sole	13	1,492 (0.72)	168 (1.0)	26–56
Darkblotched Rockfish	11	339 (1.0)	176 (1.0)	19–40
Greenstriped Rockfish	12	503 (0.59)	318 (0.55)	19–38
Shortspine Thornyhead	7	298 (0.62)	75 (1.0)	17–44
Sablefish	14	249 (1.0)	556 (1.0)	34–92
Lingcod	13	8 (1.0)	93 (1.0)	45–92
BRD-2 (grid size = 6.4 × 30.5 cm)				
Pacific Halibut	10	5 (1.0)	13 (1.0)	55–91
English Sole	15	261 (0.71)	71 (1.0)	25–42
Rex Sole	15	1,015 (0.68)	191 (1.0)	23–47
Arrowtooth Flounder	15	562 (1.0)	169 (1.0)	26–68
Dover Sole	15	1,919 (0.65)	523 (1.0)	29–61
Petrale Sole	15	1,683 (0.57)	361 (1.0)	26–57
Darkblotched Rockfish	10	171 (1.0)	296 (0.69)	19–45
Greenstriped Rockfish	13	217 (1.0)	183 (1.0)	21–38
Shortspine Thornyhead	6	131 (1.0)	68 (1.0)	19–44
Sablefish	14	102 (1.0)	193 (1.0)	37–77
Lingcod	11	131 (1.0)	207 (0.40)	41–86

Selectivity analysis.—The concept of the tested sorting-grid BRDs is to have flatfishes contact and pass through the grid system and then move aft toward the trawl cod end. Fish that do not contact the grid system are released out of the trawl. Fish that contact the grid system have a length-dependent probability (which decreases for larger-sized

TABLE 3. Catch data by weight (kg) for six flatfish species from the 30 trawl tows conducted in 2016 with two bycatch reduction devices (BRD-1: grid size = 6.4 × 25.4 cm; BRD-2: grid size = 6.4 × 30.5 cm; RN = recapture net; values in parentheses represent 95% confidence intervals).

			Pacific Halibut		English Sole		Rex Sole		Arrowtooth Flounder		Dover Sole		Petrale Sole	
Tow	Date in 2016	BRD	RN	Cod end	RN	Cod end	RN	Cod end	RN	Cod end	RN	Cod end	RN	Cod end
1	Apr 20	2	0	0	0.3	0.4	1.5	10.1	15.1	38.1	20.5	72.8	2.4	28.3
2	Apr 21	1	5.0	0	0	1.6	1.4	12.7	3.2	21.5	21.6	101.3	19.0	283.1
3	Apr 21	1	0	0	0.4	4.2	2.0	14.5	6.0	15.6	10.8	77.2	11.6	123.1
4	Apr 21	1	2.8	13.1	7.6	34.6	4.6	10.8	3.4	10.3	10.5	59.3	12.4	94.1
5	Apr 21	1	11.4	0	2.5	24.5	1.5	27.8	6.8	49.5	12.8	65.8	9.4	74.9
6	Apr 21	1	34.9	0	5.5	37.1	1.9	18.1	24.8	107	25.8	159.4	0.6	76.6
7	Apr 22	2	5.6	0	1.9	15.4	3.3	13.0	11.0	50.4	18.1	102.1	0.9	26.1
8	Apr 22	2	5.3	8.8	0.3	4.2	3.6	11.7	12.8	42.2	50.5	164.2	7.2	24.1
9	Apr 22	2	3.8	0	7.7	28.4	0.5	10.8	0	4.4	9.1	50.2	33.1	58.7
10	Apr 22	2	13.3	0	0.3	2.5	0.5	10.3	5.1	24.3	24.9	95.2	6.0	22.0
11	Apr 22	2	4.8	2.9	0.8	2.3	1.5	9.3	13.0	37.1	31.2	82.4	55.4	242.1
12	Apr 23	1	0	3.1	0	0	2.9	8.6	9.5	62.7	75.9	806.4	0	0
13	Apr 23	1	0	0	0	0	0.9	2.4	8.1	23.0	1.4	16.7	0	0
14	Apr 23	1	0	0	0.3	2.4	1.6	19.2	15.6	114.9	23.6	279.1	3.8	59.5
15	Apr 23	1	0	0	5.7	24.1	0	6.3	0.8	5.7	3.4	20.8	0.8	8.7
16	Apr 23	1	7.9	0	0	8.2	2.1	18.1	26.2	140.6	9.7	119.2	6.9	118.8
17	Apr 24	1	0	0	0	3.0	3.7	30.2	30.7	124.2	76.2	720.0	0	9.0
18	Apr 24	1	14.9	3.4	0	3.8	3.1	51.9	1.6	116.9	28.4	377.0	5.2	60.5
19	Apr 24	1	15.0	0	0.6	1.9	2.3	22.1	11.2	84.8	22.8	200.5	0.7	14.1
20	Apr 26	2	3.7	5.1	4.2	12.1	0.6	15.1	0	3.6	38.4	44.5	31.2	173.3
21	Apr 26	2	4.8	4.0	2.0	2.6	3.2	18.1	1.2	4.3	14.8	49.3	0	62.7
22	Apr 26	2	5.6	2.8	0.3	1.8	7.2	30.9	1.3	6.8	28.5	139.1	23.9	139.8
23	Apr 26	2	10.8	0	0	1.4	1.2	6.7	1.9	42.1	10.9	42.1	7.3	23.3
24	Apr 26	2	0	0	1.5	4.8	1.3	10.5	1.7	4.5	26.1	51.8	44.3	353.7
25	Apr 27	2	0	0	0	0.7	2.3	18.5	11.9	42.4	46.1	167.8	13.1	19.7
26	Apr 27	2	0	0	0	1.8	6.1	26.5	26.4	109.9	37.8	198.0	7.1	0
27	Apr 27	2	0	0	0	0.3	1.5	11.5	4.4	9.2	15.2	51.5	0	1.2
28	Apr 27	2	15.9	0	0.7	7.8	6.4	58.6	6.8	34.1	42.4	342.8	16.3	108.8
29	Apr 28	1	11.8	0	0.3	2.0	9.3	28.0	0.5	4.6	27.6	129.6	22.1	96.7
30	Apr 28	1	4.1	9.9	0.3	1.6	3.3	16.9	0	5.2	6.0	42.9	19.4	169.8
Total, BRD-1			107.8	29.5	23.2	149.0	40.6	287.6	148.4	886.5	356.5	3,175.2	111.9	1,188.9
Cod end retention (%)			21.5 (19.0–24.0)		86.5 (81.7–91.3)		87.6 (85.1–90.1)		85.7 (82.9–88.5)		89.9 (86.0–93.8)		91.4 (87.9–94.9)	
Total, BRD-2			73.6	23.6	20.0	86.5	40.7	261.6	112.6	453.4	414.5	1,653.8	248.2	1,283.4
Cod end retention (%)			24.3 (21.9–26.6)		81.2 (77.2–85.2)		86.5 (84.0–88.9)		80.1 (74.6–85.6)		80.0 (77.8–82.2)		83.8 (80.0–87.5)	

TABLE 4. Results of the CLogit model of mean selectivity for flatfishes by the two bycatch reduction device (BRD) designs tested ($L50_{grid}$ and SR_{grid} = passage probability parameters; C_{grid} = fish-size-independent grid contact probability; * = value not defined). Values in parentheses are Efron percentile bootstrap 95% confidence limits.

Species	$L50_{grid}$	SR_{grid}	C_{grid}	*P*-value	Deviance	df
			BRD-1 (grid size = 6.4 × 25.4 cm)			
Pacific Halibut	* (*–60.8)	* (*–45.8)	0.20 (0.07–0.99)	0.1159	12.9	8
English Sole	46.5 (38.0–195.0)	11.1 (0.6–107.1)	0.89 (0.84–0.99)	0.0049	32.9	15
Rex Sole	67.2 (40.0–192.7)	37.6 (0.1–106.0)	0.97 (0.84–0.99)	0.5715	21.2	23
Arrowtooth Flounder	82.5 (62.8–127.8)	43.2 (12.6–100.0)	0.99 (0.90–0.99)	0.1096	46.7	36
Dover Sole	80.6 (56.7–192.2)	24.4 (2.3–108.3)	0.92 (0.89–0.99)	0.4307	29.7	29
Petrale Sole	190.6 (56.1–199.4)	1.6 (0.3–109.7)	0.91 (0.89–0.99)	0.0807	37.8	27
			BRD-2 (grid size = 6.4 × 30.5 cm)			
Pacific Halibut	51.3 (*–63.0)	30.9 (*–70.4)	0.99 (0.17–0.99)	0.0354	16.5	8
English Sole	45.8 (37.4–196.8)	10.0 (0.1–109.4)	0.82 (0.78–0.99)	0.6941	10.9	14
Rex Sole	73.2 (41.5–195.1)	49.1 (0.1–112.4)	0.99 (0.85–0.99)	0.6961	17.3	21
Arrowtooth Flounder	60.4 (55.3–69.4)	24.8 (5.8–38.8)	0.99 (0.86–0.99)	0.0369	51.3	35
Dover Sole	68.2 (56.4–90.9)	39.5 (1.4–77.1)	0.99 (0.81–0.99)	0.0245	45.8	29
Petrale Sole	84.5 (51.1–157.6)	57.2 (0.1–106.6)	0.99 (0.84–0.99)	0.3200	32.0	29

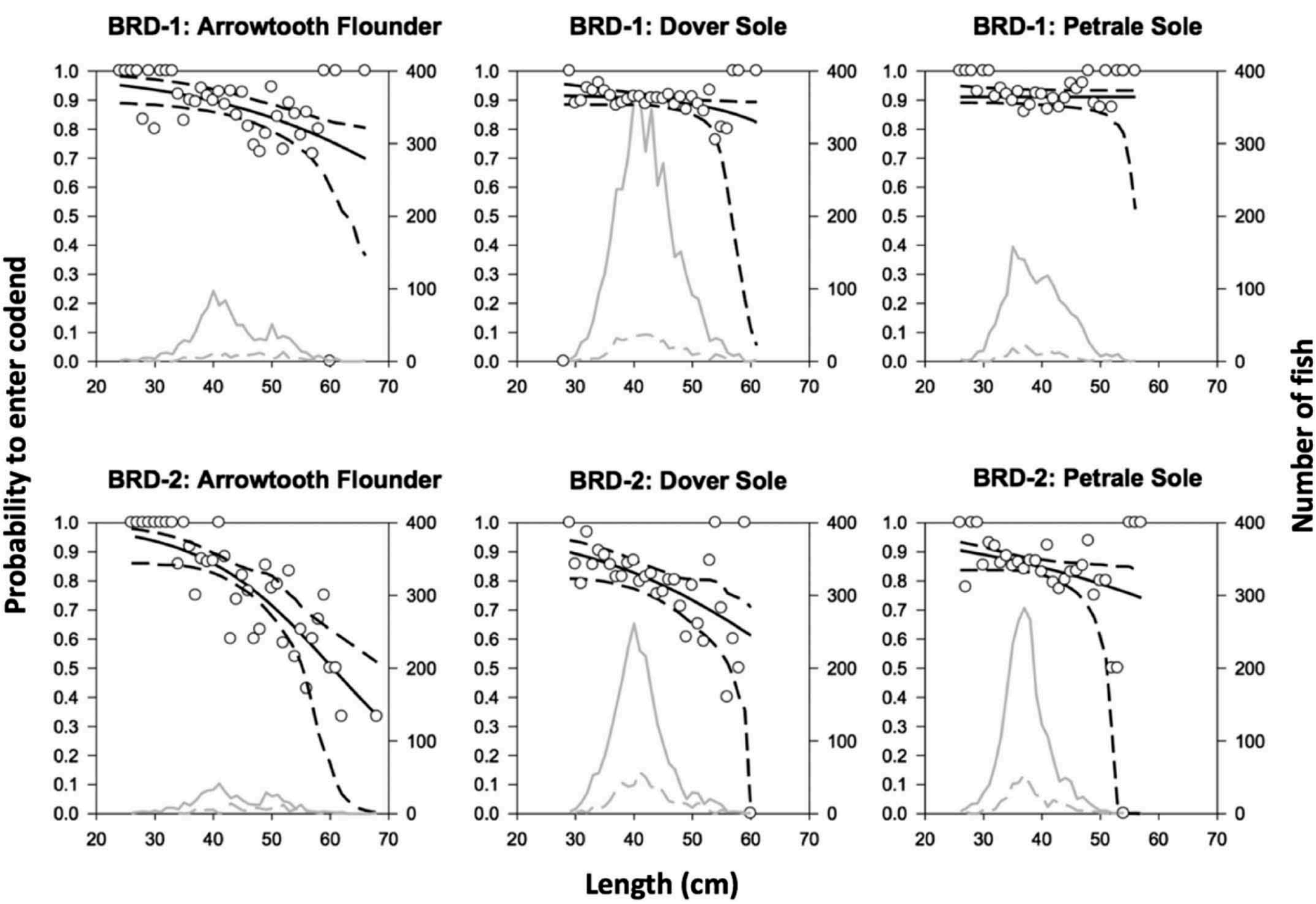

FIGURE 2. Mean selectivity curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as modeled for Arrowtooth Flounder, Dover Sole, and Petrale Sole (length = cm TL). Black solid lines represent the modeled value; black dashed lines represent the 95% confidence interval limits; open circles denote the experimental proportions of the catch observed in the cod end; gray solid lines represent the number of fish caught in the trawl cod end; and gray dashed lines depict the number of fish caught in the recapture net.

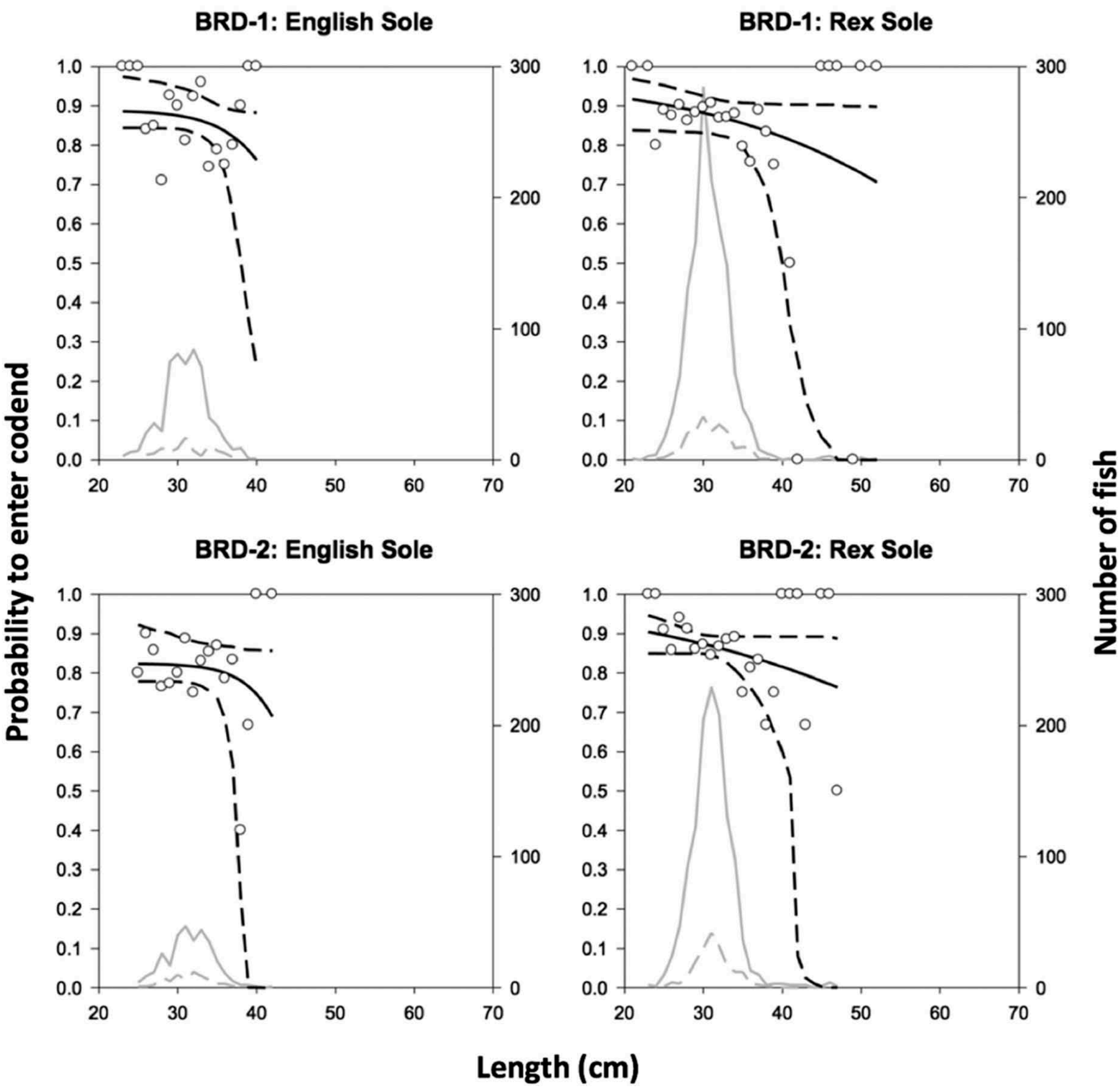

FIGURE 3. Mean selectivity curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as modeled for English Sole and Rex Sole (length = cm TL). Black solid lines represent the modeled value; black dashed lines depict the 95% confidence interval limits; open circles denote the experimental proportions of the catch observed in the cod end; gray solid lines represent the number of fish caught in the trawl cod end; and gray dashed lines depict the number of fish caught in the recapture net.

individuals) of passing through the grid system and entering the cod end; fish that enter the cod end are then subjected to a second size-selection process. The purpose of our analysis was to quantify the length-dependent sorting efficiency of the two tested BRDs. Specifically, we wanted to quantify the length-dependent probability that a fish arriving to the zone of the BRD would subsequently enter the cod end. To obtain this information, we compared the catches in the cod end and recapture net separately, species by species, as described below.

The across-tows averaged experimental probability that a fish in length-class l would be observed in the cod end was

$$\mathrm{PC}_l = \frac{\sum_{i=1}^{m}\left\{\frac{nc_{li}}{qc_i}\right\}}{\sum_{i=1}^{m}\left\{\frac{nc_{li}}{qc_i}+\frac{nr_{li}}{qr_i}\right\}} = \frac{nc_l}{nc_l + nr_l}, \tag{1}$$

where nc_{li} and nr_{li} are the number of fish of length l measured in the cod end and in the recapture net,

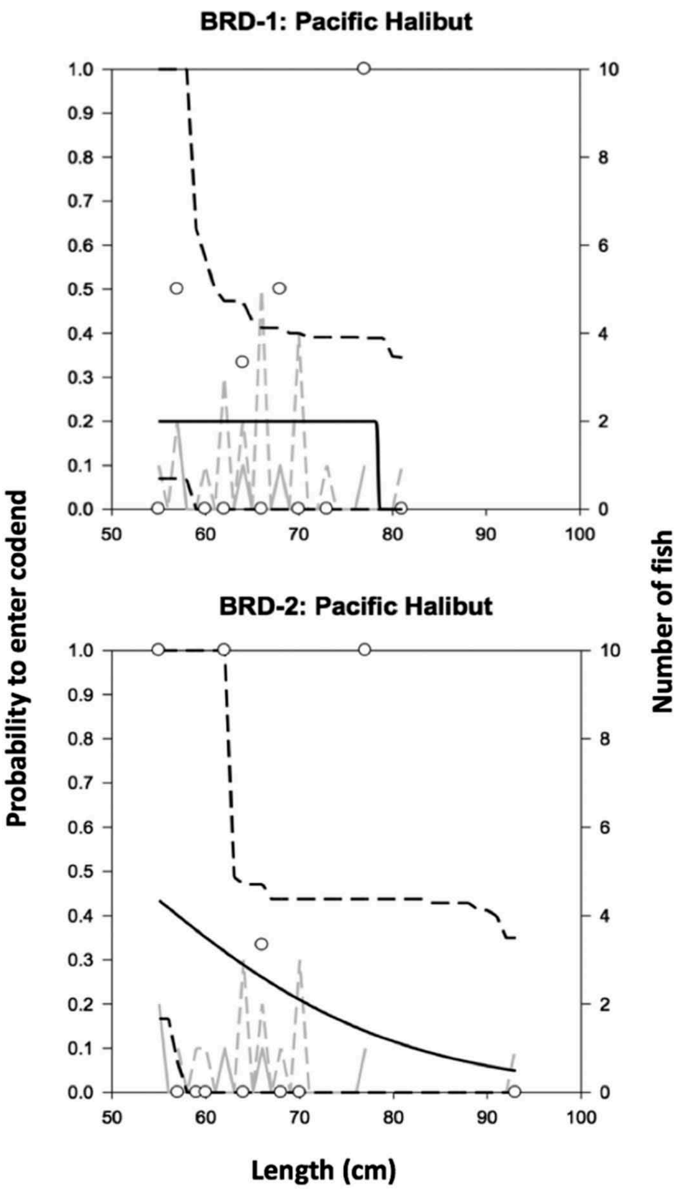

FIGURE 4. Mean selectivity curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as modeled for Pacific Halibut (length = cm TL). Black solid lines depict the modeled value; black dashed lines represent the 95% confidence interval limits; open circles denote the experimental proportions of the catch observed in the cod end; gray solid lines depict the number of fish caught in the trawl cod end; and gray dashed lines represent the number of fish caught in the recapture net.

respectively, for tow i; and qc_i and qr_i are the related subsampling factors (fraction of the catch for which length is measured) for the cod end and recapture net, respectively. The summation is over the m tows conducted with that specific version of the BRD.

With the outset in equation (1), we wanted (based on the group of tows carried out for each BRD) to estimate a functional description for the average length-dependent probability (PG[l]) that a fish would pass into the cod end through the BRD because this would quantify the size selectivity of the device. To do so, we first needed to identify a relationship between PG(l) and the observed catch proportions in the cod end and in the recapture net. Let n_l be the number of fish belonging to length-class l arriving to the zone of the BRD; the expected values for the numbers to be observed in the catch of the cod end (nc_l) and recapture net (nr_l), respectively, will then be

$$\begin{aligned} \widehat{nc_l} &= n_l \times \mathrm{PG}(l) \times \mathrm{RC}(l), \\ \widehat{nr_l} &= n_l \times [1.0 - \mathrm{PG}(l)] \times \mathrm{RR}(l), \end{aligned} \tag{2}$$

where RC(l) and RR(l) are the selectivity curves for the cod end and the recapture net, respectively. In equation (2), we used the condition that all fish not entering the cod end will enter the recapture net.

Using equation (2) in equation (1) leads to

$$\widehat{\mathrm{PC}_l} = \frac{\mathrm{PG}(l) \times \mathrm{RC}(l)}{\mathrm{PG}(l) \times \mathrm{RC}(l) + [1.0 - \mathrm{PG}(l)] \times \mathrm{RR}(l)}. \tag{3}$$

Because the cod end and recapture net are made of the same netting type and with the same mesh size, we can assume that they will have similar size selection (i.e., RC[l] ≈ RR[l]). Using this assumption, equation (3) simplifies to

$$\widehat{\mathrm{PC}_l} \approx \mathrm{PG}(l). \tag{4}$$

Using equations (1) and (4) together allows us to estimate the functional description for PG(l) based on comparing the catches in the cod end and recapture net. Specifically, we can estimate it by minimizing,

$$-\sum_l \sum_{i=1}^{m} \left\{ \frac{nc_{li}}{qc_i} \times \log_e[\mathrm{PG}(l,\gamma)] + \frac{nr_{li}}{qr_i} \times \log_e[1.0 - \mathrm{PG}(l,\gamma)] \right\}. \tag{5}$$

In equation (5), we express the length-dependent grid passage probability (probability that a fish will enter the cod end) on the parametric form PG(l, γ). The outer summation is over length-classes in the experimental data. The purpose is to find the values for the parameters γ that minimize equation (5), which is equivalent to optimizing the likelihood for the observed experimental data based on a binomial distribution.

To minimize equation (5), we need to select a model for PG(l, γ), and we will base this on the contact logit (CLogit) model

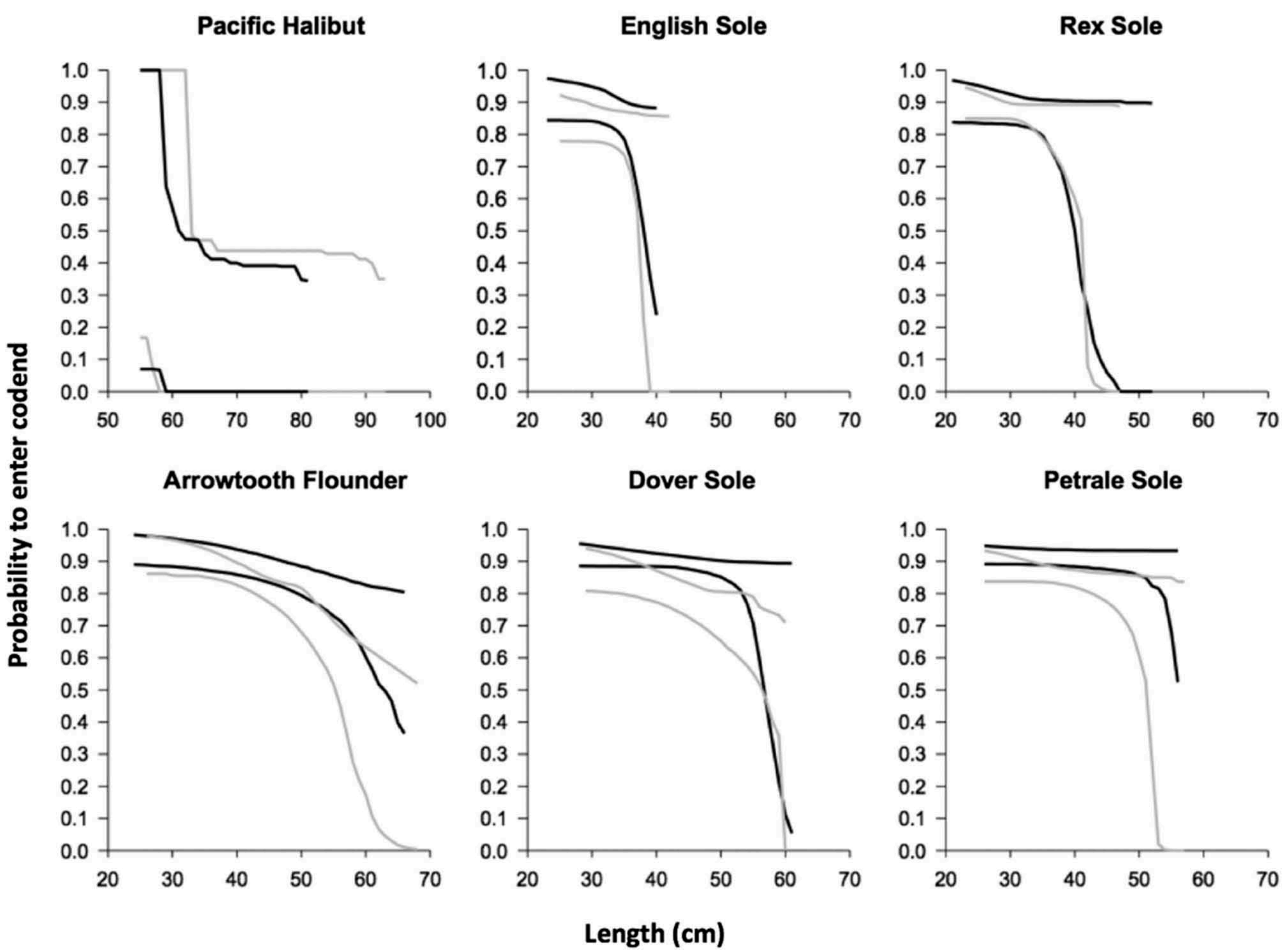

FIGURE 5. Comparison of the 95% confidence interval limits for the size-selection curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as estimated for six flatfishes (length = cm TL). Solid black lines represent BRD-1 (6.4- × 25.4-cm grid size); solid gray lines represent BRD-2 (6.4- × 30.5-cm grid size).

(Herrmann et al. 2013; Larsen et al. 2016, 2017). The CLogit model accounts for the fact that not necessarily all fish arriving to the zone of the BRD will make contact with it and be subjected to a fish-size-dependent probability of passing through the grid. For fish that make contact with the grid, the CLogit model assumes a standard logit model for the grid passage probability with parameters $L50_{grid}$ and SR_{grid} (Wileman et al. 1996). The grid contact probability is modeled by a fish-size-independent number, C_{grid}, that can take on values in the range of 0.0–1.0. Specifically, based on the CLogit model, PG(l, γ) is modeled by

$$\begin{aligned} PG\left(l,\ C_{grid}, L50_{grid}, SR_{grid}\right) &= 1.0 - \text{CLogit}\left(l,\ C_{grid}, L50_{grid}, SR_{grid}\right) \\ &= C_{grid} \times \left[1.0 - \text{Logit}\left(l, L50_{grid}, SR_{grid}\right)\right] \\ &= \frac{C_{grid}}{\exp\left[\frac{\log_e(9.0)}{SR_{grid}} \times \left(l - L50_{grid}\right)\right]}. \end{aligned} \tag{6}$$

Goodness of fit of the selected model for PG(l, γ) to describe the experimental data was determined based on the P-value, model deviance versus degrees of freedom, and inspection of the model curves' ability to reflect the length-based trends in the experimental data expressed by equation (1). Specifically, in a case of poor fit statistics ($P < 0.05$), the deviances between modeled curve and experimental rates were inspected to determine whether the poor result was due to structural problems when modeling the experimental data or due to overdispersion in the data (Wileman et al. 1996). Consult Sistiaga et al. (2010), Herrmann et al. (2013), Grimaldo et al. (2015), Stepputtis et al. (2016), and Larsen et al. (2017) for complete details on the CLogit model and how to apply it.

All tows and length-classes caught were used in the analysis. Efron percentile bootstrap 95% confidence intervals (CIs; Efron 1982) for $L50_{grid}$, SR_{grid}, C_{grid}, and the PG (l, γ) curve for all relevant fish sizes were estimated from 1,000 bootstrap repetitions using a double bootstrapping

TABLE 5. Catch data by weight (kg) for five roundfish species from the 30 trawl tows conducted in 2016 with two bycatch reduction devices (BRD-1: grid size = 6.4 × 25.4 cm; BRD-2: grid size = 6.4 × 30.5 cm; RN = recapture net; values in parentheses represent 95% confidence intervals).

			Darkblotched Rockfish		Greenstriped Rockfish		Shortspine Thornyhead		Sablefish		Lingcod	
Tow	Date in 2016	BRD	RN	Cod end	RN	Cod end	RN	Cod end	RN	Cod end	RN	Cod end
1	Apr 20	2	5.7	4.1	4.6	3.2	0.4	1.3	37.4	20.1	2.6	0
2	Apr 21	1	0.8	3.9	17.5	13.4	0	0	1.2	0	4.1	1.3
3	Apr 21	1	1.0	8.7	117.6	91.7	0	0	1.2	0	11.7	0
4	Apr 21	1	0	0.2	20.1	12.3	0	0	2.4	0.8	20.2	5.4
5	Apr 21	1	5.4	36.5	7.0	3.4	0	0	13.8	4.9	11.0	1.4
6	Apr 21	1	0	23.4	6.9	8.3	0	0	148.2	31.7	103.0	0
7	Apr 22	2	11.5	8.2	1.6	3.2	0	0.5	22.4	9.5	67.8	10.2
8	Apr 22	2	4.9	3.4	3.6	2.1	0	0	28.9	21.7	22.1	0
9	Apr 22	2	0	0	56.8	26.6	0	0	2.7	1.1	496.9	196.8
10	Apr 22	2	5.3	12.4	2.4	2.1	0	0.2	4.9	7.4	14.4	0
11	Apr 22	2	0.4	0.4	1.7	2.9	0	0	12.1	5.7	0	0.7
12	Apr 23	1	0	0	0	0	7.1	9.7	87.9	26.3	0	0
13	Apr 23	1	0	0	0	0	7.2	5.1	24.0	0	0	0
14	Apr 23	1	1.8	1.0	0.9	1.2	3.1	8.8	84.9	51.7	41.9	0
15	Apr 23	1	0	0	0	0.3	0	0	1.2	0	6.2	1.0
16	Apr 23	1	0	1.0	2.0	1.4	1.8	3.1	9.4	10.8	13.2	0
17	Apr 24	1	73.2	25.5	0	0	14.1	44.7	119.0	26.2	9.3	0
18	Apr 24	1	2.0	0	2.5	12.2	1.3	0.6	100.3	48.7	19.1	1.0
19	Apr 24	1	1.5	3.4	0.7	0.5	1.4	10.4	147.8	58.2	28.4	3.2
20	Apr 26	2	0	0	4.8	8.6	0	0	0	0	0	0
21	Apr 26	2	0.2	0.6	2.7	1.6	0	0	0	0.5	0	0
22	Apr 26	2	0	1.0	6.8	3.2	0	0	2.1	0.9	0	0
23	Apr 26	2	0.3	0.7	0.4	2.7	0	0	11.3	5.6	1.2	0
24	Apr 26	2	0	0	2.2	6.8	0	0	13.6	11.6	10.1	2.1
25	Apr 27	2	1.2	0.2	0.6	0.2	2	4.3	22.0	4.5	2.7	0
26	Apr 27	2	281.6	36.5	0	0	4.9	13.2	62.7	3.6	0	0
27	Apr 27	2	0	0	0	0	20.2	11.7	21.1	2.4	0	0
28	Apr 27	2	0	0	0	7.4	0	0	12.6	6.2	32.9	3.7
29	Apr 28	1	0.5	2.3	13.0	22.7	0	0	1.4	0	11.7	0
30	Apr 28	1	0	0	2.0	2.8	0	0	0	0	2.1	0
Total, BRD-1			86.2	105.9	190.2	170.2	36.0	82.4	742.7	259.3	281.9	13.3
Cod end retention (%)			55.1 (50.6–59.6)		47.2 (42.6–51.8)		69.6 (57.8–81.4)		25.9 (24.6–27.2)		4.5 (1.2–7.8)	
Total, BRD-2			311.1	67.5	88.2	70.6	27.5	31.2	253.8	100.8	650.7	213.5
Cod end retention (%)			17.8 (15.7–20.0)		44.4 (41.7–47.1)		53.2 (42.7–63.7)		28.4 (27.2–29.6)		24.7 (19.5–29.9)	

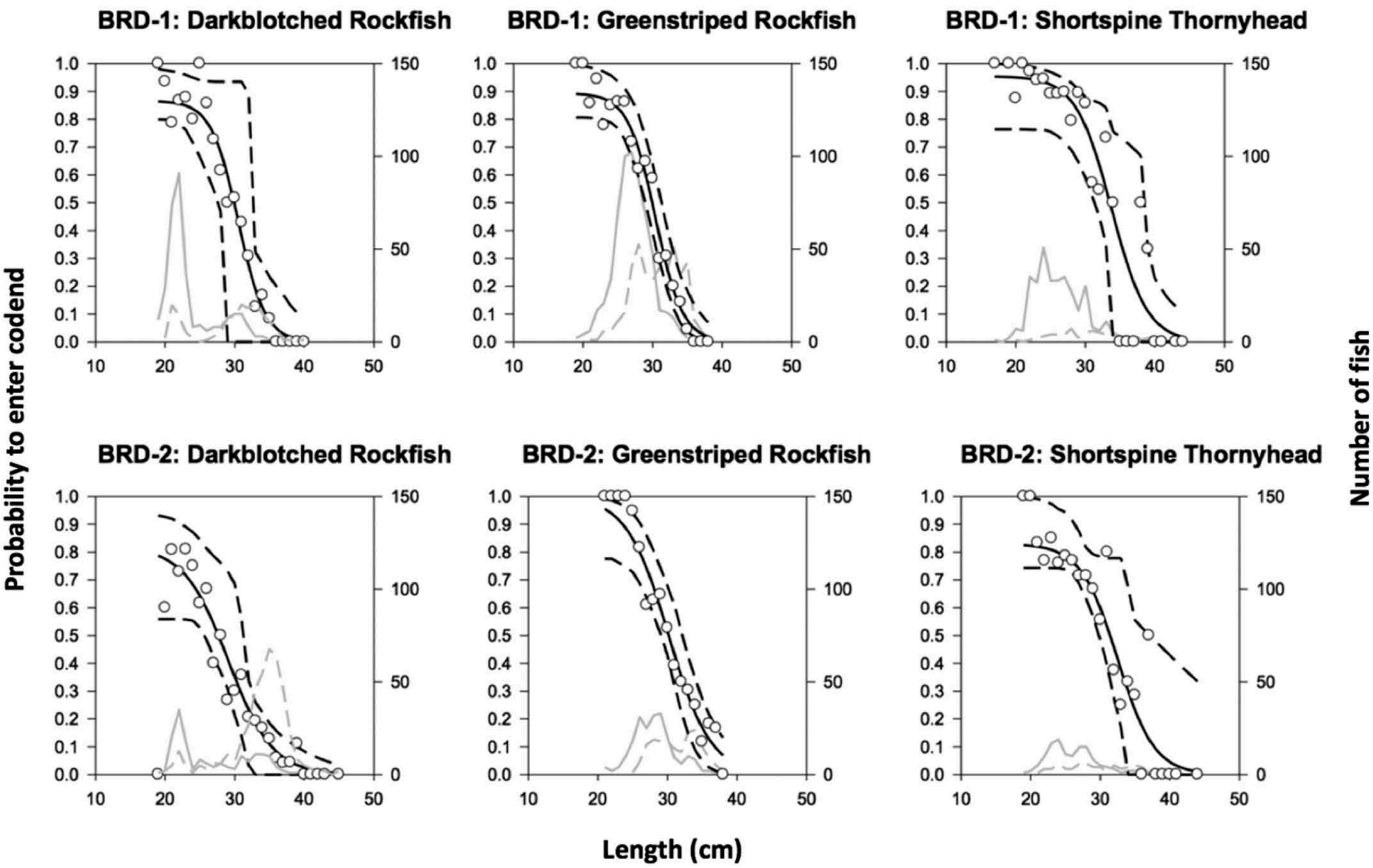

FIGURE 6. Mean selectivity curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as modeled for Darkblotched Rockfish (length = cm FL), Greenstriped Rockfish (cm FL), and Shortspine Thornyheads (cm TL). Black solid lines represent the modeled value; black dashed lines depict the 95% confidence interval limits; open circles denote the experimental proportions of the catch observed in the cod end; gray solid lines depict the number of fish caught in the trawl cod end; and gray dashed lines represent the number of fish caught in the recapture net.

method to account for both within-tow and between-tow variation. This method is used to avoid underestimating confidence limits for selectivity curves when pooling tow data (Sistiaga et al. 2010; Herrmann et al. 2012).

The statistical analysis software SELNET (SELection in trawl NETting) was used to conduct the analysis (Sistiaga et al. 2010; Herrmann et al. 2012). Table 2 presents the length data that were used to obtain the selectivity results for each BRD design.

RESULTS

We completed 30 tows (15 tows for each BRD design). Combined, flatfishes comprised 62.9% of the total catch by weight, with Pacific Halibut, English Sole, Rex Sole *Glyptocephalus zachirus*, Arrowtooth Flounder *Atheresthes stomias*, Dover Sole, and Petrale Sole comprising 98.3% of flatfish catches. The remaining 37.1% of the total catch consisted of 36 species, including rockfishes (predominantly Darkblotched Rockfish and Greenstriped Rockfish *Sebastes elongatus*), other roundfishes (mainly Shortspine Thornyheads, Sablefish, and Lingcod), and elasmobranchs (primarily Longnose Skates *Raja rhina*). Size-selectivity characteristics for elasmobranchs were not evaluated due to limited sample sizes.

Flatfishes

Mean cod-end retention rates (by weight) for English Sole, Arrowtooth Flounder, Dover Sole, and Petrale Sole were substantially higher in BRD-1 than in BRD-2. The largest differences in mean retention between the two BRDs were observed for Dover Sole and Petrale Sole, with BRD-1 retaining significantly more (by weight) than BRD-2 (Table 3). For BRD-1, Petrale Sole (91.4%) and Dover Sole (89.9%) displayed the highest mean retention. Rex Sole (86.5%) and Petrale Sole (83.8%) showed the highest mean retention for BRD-2. Mean retention of Pacific Halibut and Rex Sole was similar between the two BRDs; however, the sample sizes of these species in the catch were low. Combined, the mean retention (by weight)

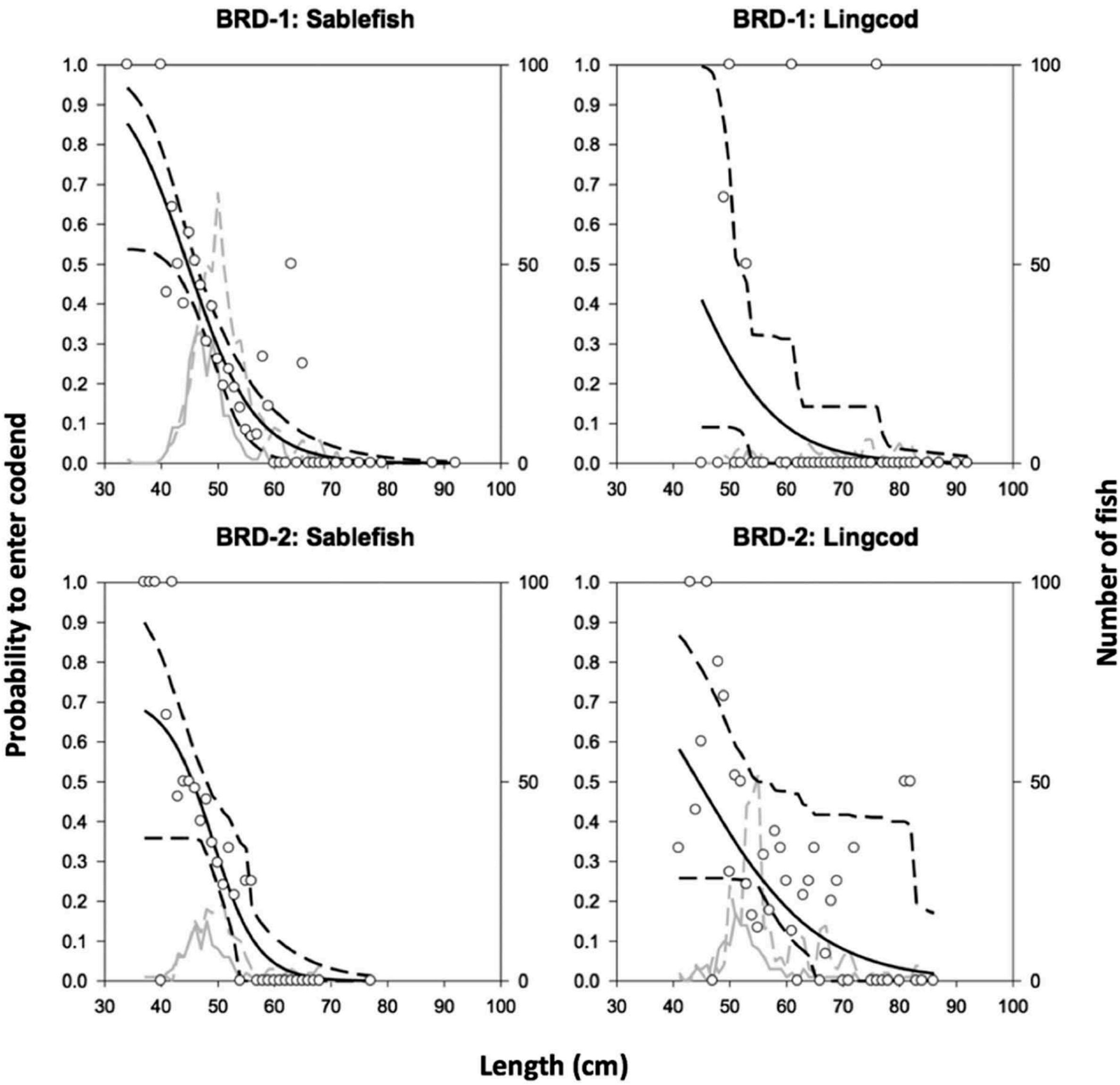

FIGURE 7. Mean selectivity curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as modeled for Sablefish (length = cm FL) and Lingcod (cm TL). Black solid lines depict the modeled value; black dashed lines represent the 95% confidence interval limits; open circles denote the experimental proportions of the catch observed in the cod end; gray solid lines depict the number of fish caught in the trawl cod end; and gray dashed lines represent the number of fish caught in the recapture net.

of target flatfishes was 89.3% (95% CI = 87.1–91.5%) for BRD-1 and 81.7% (95% CI = 80.0–83.4%) for BRD-2.

Model fit statistics for English Sole in BRD-1 and for Pacific Halibut, Arrowtooth Flounder, and Dover Sole in BRD-2 had *P*-values less than 0.05 and required further assessment to determine whether the models were adequately describing the experimental data for these species (Table 4). Inspection of the fit between the experimental catch data and the modeled mean curve for these species indicated that the *P*-values less than 0.05 were due to overdispersion of the data rather than to the model's inability to adequately describe the data.

The size-selectivity characteristics for BRD-1 and BRD-2 for the six flatfish species evaluated are depicted in Figures 2–4. Mean C_{grid} values, ranging from 0.89 to 0.99 for BRD-1 and from 0.82 to 0.99 for BRD-2, revealed that target flatfishes displayed a high probability of contacting the grid system. The general selectivity trend demonstrated that BRD-1 retained more fish than BRD-2, but the size-selectivity parameters for

TABLE 6. Results of the CLogit model of mean selectivity for roundfishes by the two bycatch reduction device (BRD) designs tested ($L50_{grid}$ and SR_{grid} = passage probability parameters; C_{grid} = fish-size-independent grid contact probability; * = value not defined). Values in parentheses are Efron percentile bootstrap 95% confidence limits.

Species	$L50_{grid}$	SR_{grid}	C_{grid}	*P*-value	Deviance	df
BRD-1 (grid size = 6.4 × 25.4 cm)						
Darkblotched Rockfish	29.9 (27.6–32.8)	5.4 (0.1–8.9)	0.87 (0.80–0.99)	0.6009	16.8	19
Greenstriped Rockfish	29.9 (28.9–31.3)	5.1 (3.9–7.2)	0.89 (0.81–0.99)	0.5104	16.2	17
Shortspine Thornyhead	33.5 (31.4–38.5)	6.0 (0.1–10.8)	0.95 (0.76–0.99)	0.6511	19.9	23
Sablefish	44.6 (41.3–46.1)	13.3 (*–21.6)	0.99 (0.54–0.99)	0.6990	30.2	35
Lingcod	42.2 (*–51.5)	17.2 (*–35.4)	0.99 (0.91–0.99)	0.6117	33.0	36
BRD-2 (grid size = 6.4 × 30.5 cm)						
Darkblotched Rockfish	27.6 (25.7–31.3)	10.2 (*–14.6)	0.82 (0.56–0.99)	0.9782	11.4	23
Greenstriped Rockfish	30.2 (29.1–32.1)	6.6 (3.3–9.0)	0.99 (0.79–0.99)	0.6957	11.8	15
Shortspine Thornyhead	31.4 (29.8–37.1)	8.1 (*–19.6)	0.83 (0.74–0.99)	0.9953	8.0	21
Sablefish	45.5 (*–48.0)	* (*–17.8)	0.71 (0.36–0.99)	0.9771	16.6	30
Lingcod	44.4 (*–54.7)	23.0 (*–51.8)	0.99 (0.26–0.99)	0.0032	66.0	38

Pacific Halibut, English Sole, and Rex Sole did not differ significantly between the BRDs, as indicated by their selectivity curves' overlapping 95% CIs (Table 4; Figure 5). However, for 53–58-cm Arrowtooth Flounder, 39–53-cm Dover Sole, and 36–49-cm Petrale Sole, BRD-1 retained significantly more fish of these length-classes (cm TL) than did BRD-2 (Figure 5).

Rockfishes and Other Roundfishes

Both of the tested BRDs were effective at minimizing catches of rockfishes and other roundfishes (Table 5). Both BRDs exhibited relatively steep selectivity curves (Figures 6, 7). For the five roundfish species evaluated, mean $L50_{grid}$ values did not differ significantly between the two BRDs, as indicated by their selectivity curves' overlapping 95% CIs (Table 6; Figure 8). For Darkblotched Rockfish, Greenstriped Rockfish, and Shortspine Thornyheads, mean $L50_{grid}$ values were 29.9, 29.9, and 33.5 cm, respectively, in BRD-1 and 27.6, 30.2, and 31.4 cm, respectively, in BRD-2 (Table 6; Figure 6). Sablefish and Lingcod—species that are more elongated and round in shape than rockfishes and Shortspine Thornyheads—displayed slightly higher mean $L50_{grid}$ values. For BRD-1, mean $L50_{grid}$ values for Sablefish and Lingcod were 44.6 and 42.2 cm, respectively; their mean $L50_{grid}$ values for BRD-2 were 45.5 and 44.4 cm, respectively.

Except for Lingcod, the CLogit model adequately described the data for BRD-1 and BRD-2, as depicted by the model fit statistics (Table 6). Examination of the model output for Lingcod suggested that the *P*-value less than 0.05 was attributable to overdispersion of the data rather than the model's inability to adequately describe the experimental data.

The C_{grid} mean values were relatively high in both BRDs, indicating that the species evaluated have a high likelihood of contacting the grid system. Although the mean values were not significantly different, higher C_{grid} values were observed for Darkblotched Rockfish, Shortspine Thornyheads, and Sablefish in BRD-1 than in BRD-2 (Table 6). The opposite was noted for Greenstriped Rockfish. For Lingcod, mean C_{grid} values were the same between the two BRDs.

DISCUSSION

The two BRDs we tested substantially reduced the catches of rockfishes, other roundfishes, and Pacific Halibut that otherwise would have been retained if the BRDs had not been used. Size-selection characteristics did not differ significantly between the BRDs for two of the target flatfishes, English Sole and Rex Sole. However, there were differences for Arrowtooth Flounder, Dover Sole, and Petrale Sole, with significantly more fish of larger size-classes caught in BRD-1 than in BRD-2. This result was not anticipated, as flatfish retention was expected to be higher in BRD-2 because of its larger grid size. These unexpected results could be due to a relatively low sample size or to a true gear effect of the larger grid size—for example, after fish pass through a grid opening and begin moving back toward the cod end, the larger grid dimensions might increase their probability of passing back through the grid and then being released out of the trawl. Further work using video camera or imaging sonar could reveal whether the latter is happening.

In the LE bottom trawl fishery, the shoreside trawl annual catch limit for Dover Sole has been approximately 45,980 metric tons (NOAA 2015). However, recent catches

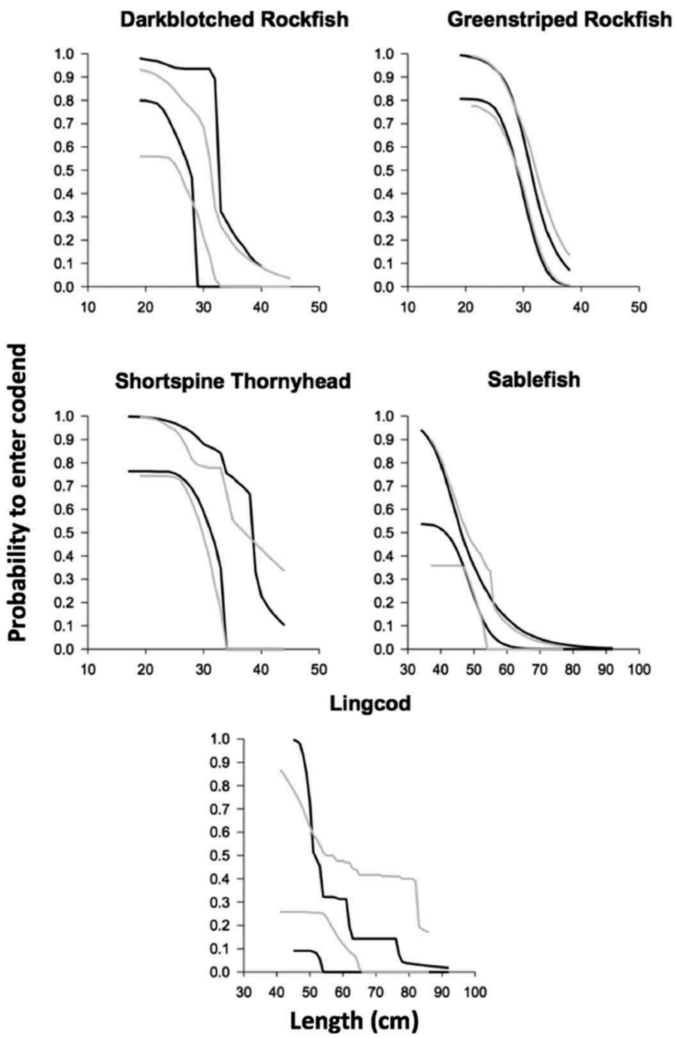

FIGURE 8. Comparison of the 95% confidence interval limits for the size-selection curves quantifying a fish's probability of entering the cod end of a trawl equipped with one of two bycatch reduction devices (BRD-1 and BRD-2), as estimated for five roundfishes (length = cm TL for Shortspine Thornyheads and Lingcod; cm FL for all others). Solid black lines represent BRD-1 (6.4- × 25.4-cm grid size); solid gray lines represent BRD-2 (6.4- × 30.5-cm grid size).

of Dover Sole have been about 6,250 metric tons (PacFIN 2015), which represents only 13.6% attainment of the shoreside trawl allocation, with full attainment being limited by constraining species, such as Darkblotched Rockfish, Sablefish, and Pacific Halibut. In this study, BRD-1 was effective at retaining Dover Sole across all size-classes (89.9% retained by weight overall) while substantially minimizing the catches of nontarget and constraining species. For fishermen seeking more opportunities to capitalize on the Dover Sole allocation and increase their net economic benefits, the BRD-1 design evaluated in this study could provide further opportunities to access this resource.

Results from our prior work (Lomeli and Wakefield 2015, 2016) examining a 4.4- × 21.6-cm grid size showed similar mean flatfish retention rates between the two studies: 84.6% by weight (95% CI = 82.3–87.0%) for the 2015 study versus 85.6% by weight (95% CI = 84.9–86.3%) for the 2016 study. Due to limited vessel time, sampling logistics, and previous results, the 4.4- × 21.6-cm grid size was not incorporated into the current study. Compared to the prior research, the larger grid dimension of BRD-1 (6.4 × 25.4 cm) increased the overall retention of flatfishes by weight while still substantially lowering the catches of rockfishes, other roundfishes, and Pacific Halibut. Overall, BRD-1 retained 89.3% of the flatfishes encountered. The most notable improvement in the gear's performance (compared to the earlier work) was the overall retention of Arrowtooth Flounder. For BRD-1, the mean retention of Arrowtooth Flounder was 85.7% (95% CI = 82.9–88.5%) by weight, whereas the mean retention of this species in the previous research was 68.1% (95% CI = 67.1–69.2%). Catch improvements for larger-sized Dover Sole and Petrale Sole (e.g., >39 cm TL) were also noted for BRD-1. In the Gulf of Alaska, where bycatch of Pacific Halibut at times has impacted fishermen's ability to fully utilize the available resource consisting of Rex Sole, Arrowtooth Flounder, Dover Sole, and Flathead Sole *Hippoglossoides elassodon* (Rose and Gauvin 2000), application of the BRD design evaluated in the current study may prove useful for improving catch utilization in that flatfish fishery.

For sorting grids, mesh panels, modified cod ends (e.g., T90, Bacoma, square mesh, etc.), and other selective fishing devices to be effective, the probability of fish contacting the selective gear must be high. Methods to increase contact probabilities have included deflector/guiding devices (Santos et al. 2016), lifting panels (Sistiaga et al. 2010), and a reduced number of meshes in cod-end circumferences (Herrmann et al. 2007, 2013). In this study, flatfishes and roundfishes exhibited a high probability of contacting the grid systems, as indicated by the high C_{grid} mean values observed for each BRD design. These findings demonstrate that the general BRD design of using two elongated vertical sorting panels to crowd and sort fish was effective at prompting the fish to interact with the sorting grids.

In summary, the size-selection characteristics of two flexible sorting-grid BRDs designed to retain flatfishes while reducing catches of rockfishes, other roundfishes, and Pacific Halibut in the LE groundfish bottom trawl fishery were evaluated. The size-selectivity parameters for rockfishes, other roundfishes, Pacific Halibut, English Sole, and Rex Sole did not differ significantly between the two BRD designs. However, there were differences for Arrowtooth Flounder, Dover Sole, and Petrale Sole, with significantly more fish of larger size-classes caught in BRD-1 than in BRD-2. Compared to previous flatfish sorting-grid selectivity work conducted in the fishery (Lomeli and Wakefield 2015, 2016), the BRD-1 design tested here showed the ability to improve the overall retention of flatfishes while reducing catches of nontarget and constraining species.

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