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Testing of Pacific Halibut Bycatch Reduction Devices in Two US West Coast Bottom Trawl Fisheries

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Abstract

The US West Coast limited entry (LE) groundfish trawl fishery is managed under an Individual Fishing Quota (IFQ) program that establishes annual catch limits and IFQs for over 60 groundfish species, and individual bycatch quotas (IBQs) for Pacific halibut, a prohibited species. For many fishermen participating in the bottom trawl components of this fishery, bycatch of Pacific halibut can be a concern because limited IBQ is available. Individual fishermen could reach their Pacific halibut IBQ before reaching their catch share quota of other stocks, thereby ending their fishing season or forcing them to purchase limited and potentially expensive quota. In separate studies, we examined two industry-designed Pacific halibut flexible sorting grid bycatch reduction devices (BRDs): one developed for the Dover sole–thornyhead–sablefish (DTS) complex fishery, and a second developed for the nearshore flatfish fishery. For both BRDs, we used a recapture net to quantify fish escapement and retention (by weight). For the BRD tested in the DTS fishery, retention of marketable-sized Dover sole, shortspine thornyheads, and sablefish was 99.0%, 96.9%, and 90.0% respectively. Pacific halibut bycatch was reduced by 83.7%. In the nearshore flatfish fishery, the BRD examined retained 85.1% of marketable-sized flatfishes encountered. Retention was highest for petrale sole (93.3%), and Dover sole (89.4%). Bycatch of Pacific halibut was reduced by 93.7%, while catches of rock-

fishes and roundfishes were reduced by 72.1% and 96.5%, respectively. Results demonstrated the capability of flexible sorting grids to modify trawl selectivity in two US West Coast LE groundfish bottom trawl fisheries while maintaining relatively high catch levels for several target species.

Introduction

The US West Coast limited entry (LE) groundfish bottom trawl fishery extends from southern California to northern Washington and seaward to depths up to 1,280 m. Bottom trawling is prohibited inside of a rockfish conservation area (RCA), a time and area closure of the continental margin between lines approximating depth contours with seasonal and annual adjustments (Keller et al. 2013, NMFS 2014a). The closure was intended to maximize fishing opportunities and minimize incidental catch of overfished or rebuilding rockfishes (*Sebastes* spp.). North of 40°10′N the RCA is generally between 183 and 365 m. (Keller et al. 2013, NMFS 2014a). Seaward of the RCA, vessels target Dover sole (*Microstomus pacificus*), shortspine thornyhead (*Sebastolobus alascanus*), longspine thornyhead (*Sebastolobus altivelis*), and sablefish (*Anoplopoma fimbria*). This assemblage is also known as the Dover sole–thornyhead–sablefish (DTS) complex. Shoreward of the RCA, a nearshore flatfish fishery occurs where vessels harvest Dover sole and petrale sole (*Eopsetta jordani*), and to a lesser extent English sole (*Parophrys vetulus*), Pacific sanddab (*Citharichthys sordidus*), and rex sole (*Glyptocephalus zachirus*).

In 2011, the LE groundfish bottom trawl fishery began management under an Individual Fishing Quota (IFQ) program (PFMC and NMFS 2010). This program establishes annual catch limits and IFQs for over 60 groundfish species, and individual bycatch quotas (IBQs) for Pacific halibut (*Hippoglossus stenolepis*). Program participants are subject to full at-sea observer coverage and are held fully accountable for all IFQ species catches, whether discarded or retained, and Pacific halibut bycatch. Under mandate of the International Pacific Halibut Commission (IPHC) the retention of trawl-caught Pacific halibut is prohibited and halibut must be discarded. For many fishermen engaged in the groundfish DTS complex fishery and/or nearshore flatfish fishery, bycatch of Pacific halibut can be a concern because limited bycatch quota is available. Individual fishermen could reach their Pacific halibut IBQ, preventing additional harvest of quota species unless they can lease or purchase additional Pacific halibut bycatch quota from another quota share permit holder. Acquiring additional quota, however, can be costly and/or difficult to obtain (i.e., quota available, amount of quota needed, time of year, etc.). In the IFQ program, each Pacific halibut is assessed by an at-sea observer and assigned to a viability category of excellent, poor, or dead following IPHC (Williams and Chen 2004) and West Coast

Groundfish Observer Program (WCGOP) protocols (NWFSC 2010). From this assessment a percent mortality by weight is calculated and then deducted from the fishermen's IBQ. The IPHC has estimated mortality rates for trawl-caught Pacific halibut discarded at sea in excellent, poor, and dead condition at 20%, 55%, and 90%, respectively (Hoag 1975, Clark et al. 1992, Williams and Chen 2004). For example, a 15 kg Pacific halibut categorized as poor would result in 8.25 kg (15 kg x 55% mortality estimate) of quota deducted from the fishermen's IBQ. Hence, reducing the incidental catch of larger-sized Pacific halibut is important to fishermen as larger-sized fish can have a greater impact on their IBQ level. Since 2011, many fishermen have begun using bycatch reduction devices (BRDs) to modify trawl selectivity; however, currently there is limited scientific evaluation of the devices (i.e., ability to reduce bycatch while maintining catch levels, economic trade-offs between catch yields and bycatch reduction).

Sorting grids can be effective at reducing bycatch in trawl fisheries when morphological differences occur between the target and bycatch species. In the bottom trawl fishery, the majority of Pacific halibut caught are greater than 65 cm in length (Wallace and Hastie 2009, Jannot et al. 2011) and larger (typically >22 cm difference) than the primary target species (King et al. 2004, Hannah et al. 2005, Lomeli and Wakefield 2013). While studies examining rigid sorting grids have often found success in reducing bycatch (Broadhurst and Kennelly 1996, Broadhurst et al. 1997, Hannah et al. 2003), rigid grids are known to provide handling difficulties on vessels with restricted deck space or that use net reels for setting and hauling. Because most vessels in the LE groundfish bottom trawl fishery are less than 26 m in overall length, have limited deck space, and use net reels, flexible sorting grids are more suitable for use than rigid grids.

In separate studies, we tested two industry-designed Pacific halibut flexible sorting grid BRDs and evaluated their efficacy at reducing bycatch and maintaining catch levels: one developed for the DTS complex fishery, and a second developed for the nearshore flatfish fishery.

Methods and Materials

Bycatch reduction device design for two bottom trawl fisheries

1. Dover sole–thornyhead–sablefish complex fishery

The BRD developed for use in the DTS complex fishery is similar in concept to the Pacific halibut BRD tested by Lomeli and Wakefield (2013) in the groundfish bottom trawl fishery, but utilizes different sorting panel configurations. Although different in design, the BRDs examined in the

present study (in the DTS fishery) and by Lomeli and Wakefield (2013) are both designed for harvesting roundfishes and flatfishes.

The DTS complex BRD was constructed within a four-seam tube of 116 mm diamond netting (stretched measurements between knots) that was 50 meshes deep (fore to aft) by 88 meshes in circumference (22 meshes per seam), excluding meshes in each selvedge (Fig. 1, Table 1). The BRD was inserted between the intermediate section of the trawl and the codend. The design utilizes a 1.77 m oblique sorting panel (grid) that tapers downward (1 mesh, 3 bar taper) over the distance of 12 meshes deep to connect to a 3.37 m horizontal sorting panel that crowds fish and directs large fish toward an escape opening out of the bottom of the trawl (Fig. 1). The sorting panels have rectangular openings (14.0 x 15.2 cm, height x length). The panels were built of 0.95 cm diameter Spectra® line placed through 1.55 cm inside diameter (2.13 cm outside diameter) schedule 40 PVC pipe to create a semirigid grid. The principle of this design is that fish smaller than the panel openings will pass through and move aft toward the codend, whereas fish larger

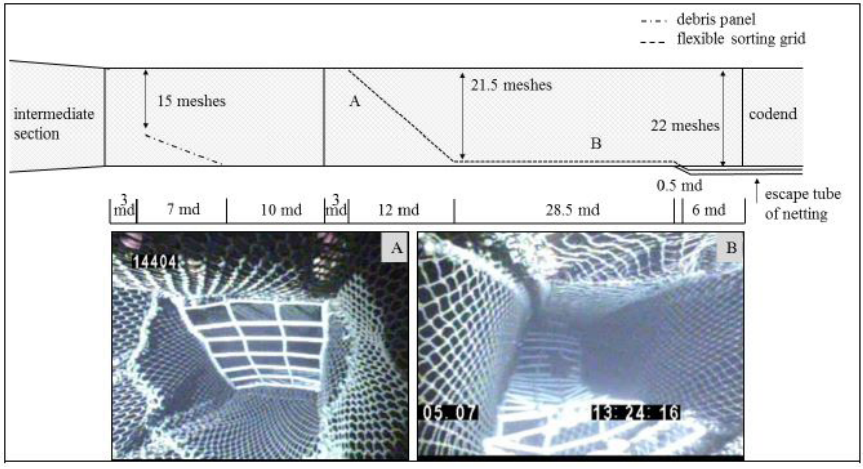

Figure 1. Top: schematic diagram of the debris panel and Pacific halibut BRD tested in the DTS complex fishery; bottom: aft view of the BRD showing the oblique sorting grid (image A); forward view of the BRD showing the oblique and horizontal sections of the sorting grid (image B). Note: images A and B are not from the BRD tested in this study. These images were provided by a groundfish bottom trawl vessel examining the same BRD design examined in the current study, but with a 25.4 x 25.4 cm grid size. The schematic diagram is not drawn to scale. md = meshes deep.

Table 1. Specifications of the gear tested. Mesh sizes (mm) are stretched measurements between knots. DM = diamond mesh; dbl. = double twine; LL = long link. * = does not account for meshes gored in each selvedge.

	Pacific halibut BRD design tested			
	(a) DTS complex fishery	(b) Near-shore flat-fish fishery	Recapture net	Trawl codend
Netting	116 mm DM	116 mm DM	116 mm DM	116 mm DM
Twine size	4 mm single (top and side panels); 5 mm dbl. (bottom panel)	4 mm single (top and side panels); 5 mm dbl. (bottom panel)	6 mm dbl.	5 mm dbl.
Circumfer-ence*	88	100	70	100
Meshes deep	50	80	50	75
Top riblines	32 mm Blue Steel™ poly rope, hung at 6%	32 mm Blue Steel™ poly rope, hung at 6%	None, selvedges sufficed as riblines	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%	None, selvedges sufficed as riblines	32 mm Blue Steel™ poly rope, hung at 6%

than the panel openings will be excluded and released out the bottom of the trawl through a four-seam "escape" tube of netting that is 12 meshes deep by 70 meshes in circumference, excluding meshes in each selvedge. Where fish transition from the BRD to the escape tube, they pass through an opening that is 0.5 meshes deep by 22 meshes long.

2. Nearshore flatfish fishery

The concept of the BRD developed for use in the nearshore flatfish fishery and the use of vertical sorting panels are similar to the Pacific halibut BRD tested by Lomeli and Wakefield (2013); however, this BRD uses different grid dimensions and openings that are designed for harvesting flatfishes.

The BRD developed for use in the nearshore flatfish fishery was constructed within a four-seam tube of 116 mm diamond netting (stretched measurements between knots) that was 80 meshes deep (fore to aft) and

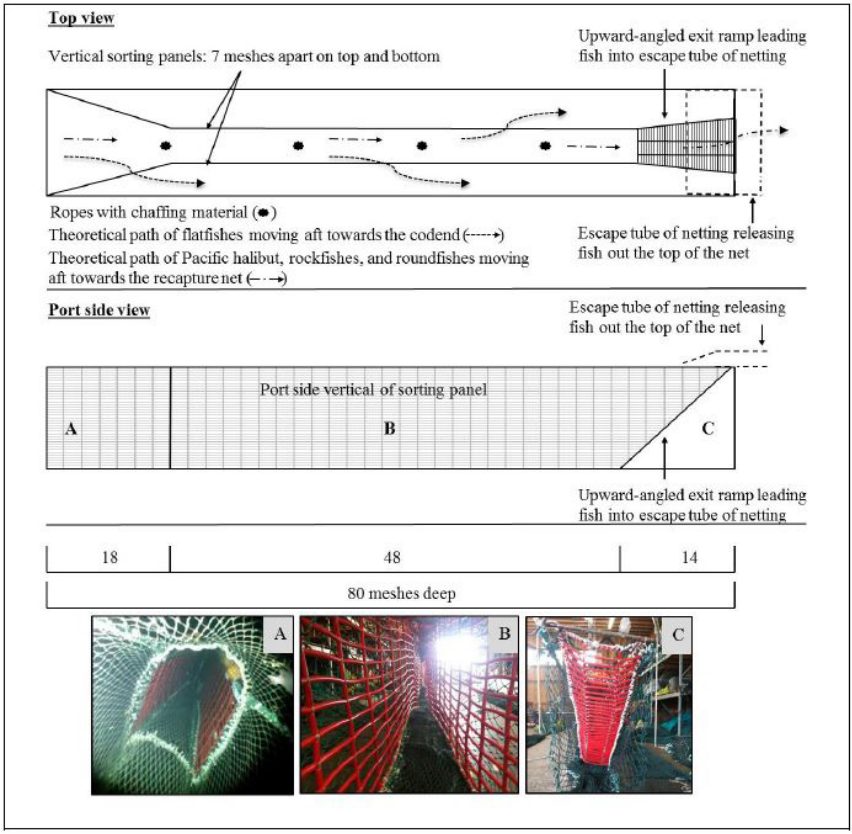

Figure 2. Schematic diagram of the Pacific halibut BRD tested in the nearshore flatfish fishery (top). Image A: aft view of the forward portion of the BRD where fish enter and encounter the device. Image B: aft view of the "hallway" section of the BRD being built. Image C: forward view of the upward–angled exit ramp. Note: the schematic diagram is not drawn to scale.

100 meshes in circumference (25 meshes per seam), excluding meshes in each selvedge (Fig. 2, Table 1). The BRD was inserted between the intermediate section of the trawl and the codend. The design utilizes two vertical panels with 4.4 x 21.6 cm (height x length) rectangular slot openings to crowd fish and direct larger fish toward an upward-angled exit ramp. The vertical panels were built of 0.95 cm Spectra® line (running vertically) and 0.79 cm (7 x 19 strand core) galvanized steel cable (running horizontally) placed through 1.21 cm inside diameter (1.59 cm

outside diameter) AQUAPEX® tubing to create a semirigid grid. The exit ramp was constructed of Spectra® line placed through AQUAPEX® tubing. The vertical panels are 7.8 m in length and stand approximately 0.9 m high and extend longitudinally down the tube of netting 66 meshes deep before connecting to an exit ramp that is 1.6 m in length. Over this distance, the two panels gradually angle inward over 18 meshes deep (1 point, 2 bar taper) then straighten to create a narrow "hallway" that extends aft 48 meshes deep (Fig. 2). Within the "hallway" section of the excluder, four ropes with chafing material wedged through them were installed to stimulate fish to interact with the vertical panels by creating a partial obstruction to fish moving aft. These ropes were positioned vertically (attached to the bottom and top panel of the tube of netting) and placed approximately every 10 meshes deep within the "hallway" section of the excluder. At the end of the "hallway," the top portion of the vertical panels gradually angle outward to become 14 meshes apart, to allow for integration of the exit ramp and the associated "escape" tube of netting. Fish that do not pass through the panel openings are guided by the exit ramp and exit out the top of the trawl through a four seam "escape" tube of netting that is 12 meshes deep and 70 meshes in circumference, excluding meshes in each selvedge. To offset the weight created by the sorting panels, 16 floats (20.3 cm center-hole, 3.1 kg buoyance) were placed above each vertical panel over the length of the BRD.

Trawl design

We used the chartered vessel's four-seam Aberdeen trawl (a typical design used in the LE groundfish bottom trawl fishery). The headrope was 26.8 m in length and utilized 27.9 cm deepwater floats for lift. The footrope was 20.7 m in length, covered with rubber disks (15.2 cm), and outfitted with rockhopper discs (40.6 cm) placed approximately every 61.0 cm over this length. The port and starboard footrope extensions were each 6.1 m in length and covered with 15.2 cm rubber discs.

Sea trials

Sea trials occurred aboard the F/V *Miss Sue*, a 24.7 m long, 640 horsepower trawler out of Newport, Oregon, USA. Tests were completed off Oregon between 44°19′ and 45°02′N and between 124°53′ and 124°49′W during June 2013. Towing speed over ground ranged from 2.2 to 2.6 knots. Although tow durations exceeding 1-3 h are common commercial practice in the LE groundfish bottom trawl fishery, tow durations in these projects were set to 45 min to avoid large catches that could not be completely weighed. For the BRD examined in the DTS fishery, a total of 23 tows were completed. Towing primarily occurred over the upper continental slope between 191 and 440 m depth. Average bottom fishing depth was 301 m. For the BRD tested in the nearshore flatfish

fishery, a total of 15 tows were made. Nearshore towing occurred over the continental shelf between 119 and 188 m depth. Average bottom fishing depth was 159 m.

Sampling and analysis

For both BRDs, we used a recapture net to quantify fish escapement and retention. The recapture net was a four-seam tube of netting that was 50 meshes deep and 70 meshes in circumference (25 meshes on the top and bottom panel, 10 meshes on the side panels), excluding meshes in each selvedge (Table 1). The recapture net was attached over the BRD's "escape" tube to capture excluded fish.

To prevent large debris (i.e., rocks, logs, crab pots, fish traps, etc.) from contacting and potentially clogging or damaging the BRDs, a "debris panel" built of diamond netting (40.6 cm between knots, single 5 mm twine, 5 meshes deep by 5 meshes long) was rotated into a square mesh configuration and laced into a tube of netting (20 meshes deep) that was inserted forward of each BRD when tested. The debris panel was laced at a downward angle (all bar taper) along the lower seven meshes of the trawl side panels and across the entire bottom panel (Fig. 1). To access debris caught by the panel, a zipper line, running port to starboard along the bottom of the trawl was placed just forward of where the panel attached to the bottom of the trawl.

After each tow, all fish caught in the trawl and recapture net were identified to species and weighed using a motion compensated platform scale. To examine size selectivity, subsamples of commercially important species were randomly selected for individual measurements. Up to 100 fish of each species for the trawl and recapture net were selected per tow and measured to the nearest cm fork length. All Pacific halibut caught were weighed, measured, and assigned to a viability category of excellent, poor, or dead.

Percent retention by weight [trawl / (trawl + recapture net)] in kg was calculated per tow for each species. To determine if mean lengths differed significantly between fish caught in the trawl and recapture net, we used either an equal variance two-sample *t*-test, Mann-Whitney *U* test, or a Kolmogorov-Smirnov test depending on the variance and normality test results for the species being analyzed.

Results

Bycatch reduction device for the Dover sole–thornyhead–sablefish complex fishery

Catch data from 23 tows employing the DTS complex BRD are summarized in Table 2. Catch per tow ranged from 120 to 3,270 kg for the trawl and 11 to 392 kg for the recapture net. In descending order, sablefish,

Table 2. Catch data by weight (kg), per tow, for the Pacific halibut BRD tested in the DTS complex fishery. # = numbers of Pacific halibut; TR = trawl; RN = recapture net; %R = percent retention.

	Pacific halibut (#)			Pacific halibut			Rex sole			Arrowtooth flounder		
Tow	TR	RN	%R	TR	RN	%R	TR	RN	%R	TR	RN	%R
1	0	1	0.0	0	32.50	0.0	22.55	1.40	94.2	27.00	2.30	92.2
2	2	5	28.6	14.00	36.45	27.8	28.50	1.05	96.5	267.25	21.55	92.5
3	2	5	28.6	12.40	49.70	20.0	38.30	2.15	94.7	203.75	16.65	92.5
4	0	2	0.0	0	12.80	0.0	14.90	0.40	97.4	189.55	8.75	95.6
5	1	4	20.0	4.70	38.35	10.9	15.00	0.25	98.4	209.45	8.70	96.0
6	0	1	0.0	0	10.95	0.0	9.75	0	100.0	72.70	2.55	96.6
7	0	0	–	0	0	–	43.50	0	100.0	66.20	2.70	96.1
8	1	1	50.0	3.15	15.65	16.8	24.90	0.45	98.2	100.00	8.85	91.9
9	0	1	0.0	0	7.80	0.0	6.00	0	100.0	96.30	12.05	88.9
10	1	1	50.0	4.85	10.00	32.7	19.15	0.70	96.5	162.30	16.40	90.8
11	0	0	–	0	0	–	6.95	0.95	88.0	66.90	19.90	77.1
12	0	2	0.0	0	29.20	0.0	67.50	2.95	95.8	241.40	20.95	92.0
13	0	0	–	0	0	–	44.90	2.45	94.8	145.55	20.60	87.6
14	0	1	0.0	0	8.65	0.0	3.15	0	100.0	24.05	0	100.0
15	0	3	0.0	0	34.20	0.0	6.05	0.30	95.3	132.35	5.15	96.3
16	3	5	37.5	14.70	50.60	22.5	32.60	0.85	97.5	989.50	63.85	93.9
17	3	5	37.5	15.75	40.45	28.0	6.55	0.45	93.6	98.10	4.65	95.5
18	2	4	33.3	11.80	27.05	30.4	0.50	0.10	83.3	35.95	0.80	97.8
19	0	4	0.0	0	30.65	0.0	2.25	0	100.0	45.80	0.60	98.7
20	2	4	33.3	9.55	28.20	25.3	4.35	0.50	89.7	55.00	2.05	96.4
21	0	1	0.0	0	9.10	0.0	6.65	0	100.0	83.55	0.10	99.9
22	0	1	0.0	0	9.30	0.0	0.95	0	100.0	7.70	0	100.0
23	1	1	50.0	4.10	5.05	44.8	0.90	0	100.0	25.20	0	100.0
Total	**18**	**52**		**95.00**	**486.65**		**405.85**	**14.95**		**3,345.55**	**239.15**	
Mean	**0.78**	**2.26**	**25.7**	**4.13**	**21.16**	**16.3**	**17.65**	**0.65**	**96.4**	**145.46**	**10.40**	**93.3**
SE	**0.22**	**0.38**	**0.07**	**1.20**	**3.35**	**0.04**	**3.70**	**0.18**	**7.83**	**41.39**	**2.92**	**4.66**

arrowtooth flounder (*Atheresthes stomias)*, Dover sole, and shortspine thornyhead made up 77% of the total catch composition. The remaining 23% of the total catch consisted of 31 species and included marketable species (rockfishes, lingcod [*Ophiodon elongatus*], rex sole, petrale sole, and skates [Rajidae]), juvenile and unmarketable-sized groundfishes, noncommercial species, and Pacific halibut bycatch.

Overall, 93.5% of the marketable-sized flatfishes and roundfishes targeted were retained. The mean retention of Pacific halibut was 16.3% (SE ±0.04), an 83.7% reduction in bycatch (Table 3). Mean retention by

Table 2. (continued) Catch data by weight (kg), per tow, for the Pacific halibut BRD tested in the DTS complex fishery. # = numbers of Pacific halibut; TR = trawl; RN = recapture net; %R = percent retention.

	Dover sole			Petrale sole			Shortspine thornyhead			Rougheye rockfish		
Tow	TR	RN	%R	TR	RN	%R	TR	RN	%R	TR	RN	%R
1	24.95	0	100.0	0	0	–	29.15	0.80	97.3	82.25	6.50	92.7
2	54.45	1.45	97.4	0	0	–	54.40	1.85	96.7	5.80	5.95	49.4
3	64.65	0.55	99.2	1.10	0	100.0	101.60	1.10	98.9	0	0	–
4	36.30	0.65	98.2	1.25	0	100.0	20.35	0.35	98.3	0	0	–
5	28.45	0	100.0	0	0	–	37.00	2.05	94.8	25.75	0	100.0
6	85.45	0.60	99.3	0	0	–	59.55	2.55	95.9	3.80	0	100.0
7	93.60	0.75	99.2	0	0	–	80.40	4.45	94.8	0	0	–
8	283.90	7.05	97.6	0	0	–	104.60	3.95	96.4	0	0	–
9	307.15	0.65	99.8	0	0	–	76.50	0.30	99.6	0	0	–
10	114.05	0.60	99.5	0.90	0	100.0	46.40	3.45	93.1	0	0	–
11	488.65	2.40	99.5	0	0	–	37.00	2.20	94.4	0	0	–
12	226.25	4.30	98.1	0	0	–	2.05	0	100.0	0	0	–
13	218.95	1.95	99.1	0	0	–	10.50	0	100.0	1.85	0	100.0
14	57.85	0	100.0	0	0	–	20.30	0.60	97.1	0	0	–
15	31.40	0	100.0	0	0	–	34.45	1.90	94.8	31.70	9.95	76.1
16	63.40	1.80	97.2	0	0	–	69.55	1.55	97.8	11.95	0	100.0
17	3.65	0	100.0	69.30	2.15	97.0	0	0	–	0	0	–
18	27.40	0	100.0	81.40	2.30	97.3	0	0	–	0	0	–
19	50.50	0	100.0	28.25	2.10	93.1	0	0	–	0	0	–
20	40.95	0	100.0	27.35	0	100.0	0	0	–	0	0	–
21	59.65	0.10	99.8	14.90	0	100.0	0.35	0	100.0	0	0	–
22	56.70	0	100.0	111.75	1.95	98.3	0	0	–	0	0	–
23	32.15	0	100.0	83.30	4.40	95.0	0	0	–	0	0	–
Total	**2,450.45**	**22.85**		**419.50**	**12.90**		**784.15**	**27.10**		**163.10**	**22.40**	
Mean	**106.54**	**0.99**	**99.1**	**18.24**	**0.56**	**97.0**	**34.10**	**1.18**	**96.7**	**7.10**	**0.97**	**87.9**
SE	**24.83**	**0.35**	**33.68**	**7.03**	**0.24**	**13.92**	**7.18**	**0.29**	**8.39**	**3.84**	**0.55**	**3.89**

weight of marketable-sized arrowtooth flounder, Dover sole, and petrale sole was 93.3% (SE ±4.66), 99.0% (SE ±33.08), and 96.9% (SE ±13.80), respectively. The mean percentage retained by weight of marketable-sized shortspine thornyhead and sablefish was 96.9% (SE ±8.67) and 90.0% (SE ±4.07), respectively. Sablefish larger than 79 cm were caught in the recapture net in a higher proportion (by numbers) than in the trawl and accounted for nearly 5% of the total loss observed (Fig. 3). Big (*Raja binoculata)* and longnose skates (*R. rhina*), secondary target species, were retained in low numbers.

Table 2. (continued)

	Sablefish			Lingcod			Big skate			Longnose skate		
Tow	**TR**	**RN**	**%R**	**TR**	**RN**	**%R**	**TR**	**RN**	**%R**	**TR**	**RN**	**%R**
1	155.30	8.85	94.6	0	0	–	0	0	–	21.40	20.35	51.3
2	173.55	10.15	94.5	0	0	–	0	0	–	0	37.55	0.0
3	42.45	6.25	87.2	9.20	0	100.0	0	0	–	0	22.20	0.0
4	17.50	0	100.0	4.15	0	100.0	0	11.60	0.0	0	41.00	0.0
5	197.30	3.55	98.2	0	0	–	0	0	–	10.10	29.55	25.5
6	124.35	20.35	85.9	0	0	–	0	0	–	30.55	28.45	51.8
7	155.80	0	100.0	0	0	–	0	0	–	0	0	–
8	779.95	92.30	89.4	0	0	–	0	0	–	0	5.20	0.0
9	2,777.05	372.45	88.2	0	0	–	0	0	–	1.00	6.45	13.4
10	23.60	0	100.0	5.20	0	100.0	0	0	–	0	1.40	0.0
11	1,662.40	199.40	89.3	0	0	–	0	0	–	0.85	16.30	5.0
12	138.75	4.70	96.7	0	0	–	0	0	–	0	103.35	0.0
13	154.55	17.60	89.8	0	0	–	0	0	–	0	70.60	0.0
14	7.35	0	100.0	0	0	–	0	0	–	0	9.45	0.0
15	154.25	10.45	93.7	0	0	–	0	0	–	3.40	23.75	12.5
16	143.40	1.55	98.9	2.40	0	100.0	0	0	–	0	41.75	0.0
17	0	0	–	23.30	0	100.0	0	37.95	0.0	0	39.55	0.0
18	0	0	–	17.70	2.55	87.4	0	77.40	0.0	0	10.30	0.0
19	0	0	–	5.75	0	100.0	0	0	–	0	5.35	0.0
20	0	0	–	6.65	0	100.0	0	0	–	0	0	–
21	0	0	–	3.65	12.30	22.9	0	0	–	0	15.05	0.0
22	0	0	–	112.15	2.95	97.4	0	0	–	0	7.10	0.0
23	0	0	–	51.90	4.25	92.4	0	7.35	0.0	0	6.40	–
Total	**6,707.55**	**747.60**		**242.05**	**22.05**		**0**	**134.30**		**67.30**	**541.10**	
Mean	**291.63**	**32.50**	**90.0**	**10.52**	**0.96**	**91.6**	**0**	**5.84**	**0.0**	**2.93**	**23.53**	**11.1**
SE	**135.94**	**17.99**	**4.07**	**5.22**	**0.57**	**5.73**	**0**	**3.68**	**n/a**	**1.61**	**5.14**	**0.07**

Pacific halibut ranged from 2.75 to 32.5 kg (mean 8.31 kg, SE ±0.6 kg) in weight and 64 to 141 cm (mean 87 cm, SE ±1.6 cm) in length. The BRD was most effective at reducing the bycatch of larger-sized Pacific halibut (Fig. 4). Bycatch of Pacific halibut less than 5 kg, 5 to 8 kg, and greater than 8 kg was reduced by 25%, 70%, and 100%, respectively. Size selection excluding larger fish was observed for sablefish, rougheye rockfish (*Sebastes aleutianus)*, and arrowtooth flounder (Table 4). No biologically meaningful difference in mean length was shown for short-spine thornyhead between retained and excluded individuals.

Table 3. Percent retention of Pacific halibut and target species by total weight (kg) and total weight of marketable-sized fish caught for the Pacific halibut BRD tested in the DTS complex fishery. Values in parentheses represent the number of Pacific halibut captured. n/a* = prohibited species.

	Total weight			Total weight of marketable-sized fish		
Species	**Recapture net**	**Trawl**	**Retention (%)**	**Recapture net**	**Trawl**	**Retention (%)**
Pacific halibut	486.65 (52)	95.00 (18)	16.3 (25.7)	n/a*	n/a*	n/a*
Rex sole	14.95	405.85	96.4	7.48	251.16	97.1
Arrowtooth flounder	239.15	3,345.55	93.3	237.71	3,318.90	93.3
Dover sole	22.85	2,450.45	99.1	22.22	2,304.65	99.0
Petrale sole	12.90	419.50	97.0	11.73	365.34	96.9
Rougheye rockfish	22.40	163.10	87.9	22.40	163.10	87.9
Shortspine thornyhead	27.10	784.15	96.7	24.13	753.24	96.9
Sablefish	747.60	6,707.55	90.0	747.60	6,707.55	90.0
Lingcod	22.05	242.05	91.6	22.05	201.71	90.1

With the exception of one individual, all Pacific halibut caught in the recapture net were assigned to the "excellent" viability category (Table 5). For Pacific halibut caught in the trawl, the majority of fish were categorized as excellent with only a few fish being categorized as poor or dead. One Pacific halibut (73 cm, 6.5 kg) was wedged in a sorting grid opening of the BRD. This was the only wedging incident observed of the 70 Pacific halibut encountered. Although viability was assessed only for Pacific halibut, when brought on deck most fish caught in the recapture net appeared lively and in good condition (with the exception of rockfishes, which suffered from barotrauma).

The debris panel positioned forward of the BRD was effective at preventing debris from contacting the excluder. This panel caught debris on six of the 23 tows conducted and included small logs, a television set, a hagfish (*Eptatretus* spp.) pot, and a sablefish trap. The only fish retained by the debris panel were two big and three longnose skates.

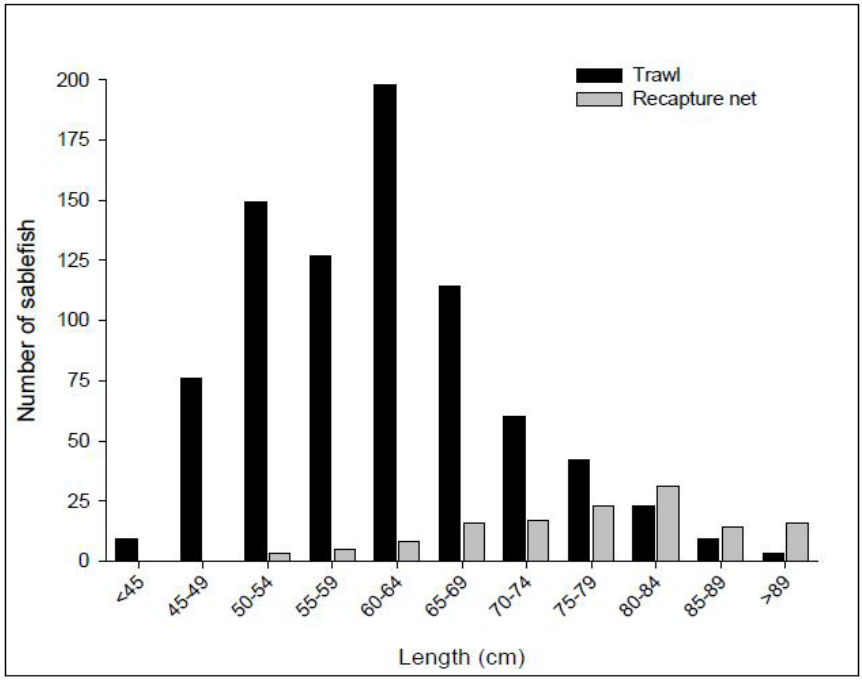

Figure 3. Comparison of sablefish caught in the trawl and recapture net by size class for the Pacific halibut BRD tested in the DTS complex fishery.

Bycatch reduction device for the nearshore flatfish fishery

Catch data from the 15 tows employing the BRD for the nearshore flatfish fishery are summarized in Table 6. Catch per tow ranged from 17 to 232 kg for the trawl and 14 to 439 kg for the recapture net. Flatfishes, not including Pacific halibut, made up 53.1% of the total catch composition with arrowtooth flounder, Dover sole, and petrale sole (in descending order) accounting for 85.7% of the total flatfish catch. Rockfishes (12 species), roundfishes (7 species), skates (3 species), and Pacific halibut (34 fish) made up the remaining 46.9% of the total catch composition.

Pacific halibut ranged from 2.6 to 19.8 kg (mean 6.8 kg, SE ±0.8 kg) in weight and 62 to 111 cm (mean 80 cm, SE ±2.3 cm) in length. Over this size range, a mean retention of 6.3% (SE ±0.03) was noted, a bycatch reduction of 93.7% (Table 7). Pacific halibut over 75 cm were caught exclusively in the recapture net (Fig. 4). Only four Pacific halibut less

Table 4. Comparison of mean lengths (cm) between target species and Pacific halibut caught in the recapture net and the trawl for the Pacific halibut BRD tested in the DTS complex fishery. nr = the number of fish that were measured from the recapture net; nt = the number of fish that were measured from the trawl. * = subsample lengths taken from a larger species catch.

Species	Recapture net, mean total length (SE)	n_r	Trawl, mean total length (SE)	n_t	*P*-value
	Flatfishes				
Pacific halibut	90 (1.9)	52	76 (1.6)	18	<0.0001
Rex sole	31 (0.4)	67	32 (0.0)	976*	0.1760
Arrowtooth flounder	52 (0.7)	166	49 (0.2)	1,130*	<0.0001
Dover sole	40 (0.8)	36	40 (0.2)	1,042*	0.9978
Petrale sole	40 (2.1)	11	38 (0.2)	426*	0.3605
	Rockfishes				
Darkblotched rockfish (*Sebastes crameri*)	30 (–)	1	33 (0.3)	305	0.8758
Rougheye rockfish	57 (0.9)	7	50 (0.8)	69	0.0008
	Roundfishes				
Shortspine thornyhead	27 (0.8)	82	28 (0.2)	1,091*	<0.0165
Sablefish	77 (0.9)	133	61 (0.3)	807*	<0.0001
Lingcod	72 (0.7)	5	61 (0.8)	96*	0.3323

than 75 cm were retained in the trawl. With the exception of Pacific halibut, no meaningful differences in mean length were found for flatfishes caught in the trawl versus the recapture net (Table 8). For most rockfishes and roundfishes, however, length data showed larger-sized fish were excluded from the trawl with only the smaller-sized individuals retained.

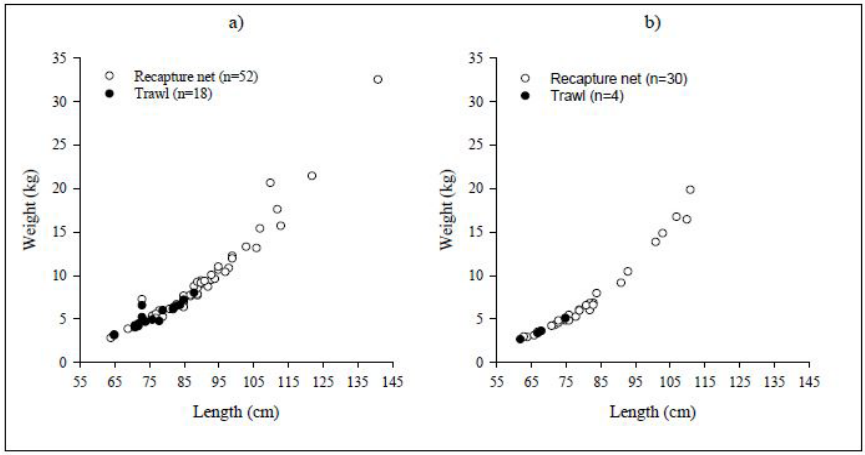

Figure 4. Length–weight scatter plot of Pacific halibut caught during these studies. (a) = Pacific halibut BRD tested in the DTS complex fishery. (b) = Pacific halibut BRD tested in the nearshore flatfish fishery.

The retention of marketable-sized flatfishes ranged from 74.8% to 93.3% with retention being highest for petrale sole (93.3%, SE ±2.3), Dover sole (89.4%, SE ±2.98), and English sole (87.9%, SE ±2.03) (Table 7). Arrowtooth flounder, the lowest valued flatfish, displayed the lowest percent retention, 74.8% (SE ±0.90). Compared to the other flatfishes encountered, arrowtooth flounder were larger in size (in both body thickness and length) than the other flatfishes caught, likely explaining why this species exhibited the lowest percent retention. The escapement of rockfishes was greatest for fish measuring greater than 36 cm. Of the rockfishes encountered measuring 36 cm or greater, 94.6% were caught in the recapture net, whereas only 46.5% of rockfishes measuring less than 36 cm were caught in the recapture net. Lingcod and sablefish exhibited escapement rates of 92.6% (SE ±0.02) and 99.0% (SE ±0.04), respectively. Nearly all skates encountered were caught in the recapture net. Overall, 84.6% of the flatfishes encountered were retained, whereas only 27.9% of rockfishes, 3.5% of roundfishes, and 6.3% of Pacific halibut encountered were retained by the trawl (Tables 6 and 7).

Pacific halibut caught in the trawl and recapture net were scored in excellent condition. Although viability was assessed only for Pacific halibut, when brought on deck most fish caught in the recapture net appeared lively and in good condition (with the exception of rockfishes, which suffered from barotrauma).

No debris or fish were noted in the debris panel.

Table 5. Viability assigned to Pacific halibut caught in the trawl and recapture net for the Pacific halibut BRD tested in the DTS complex fishery.

	Viability category			% Excellent condition
	Excellent	Poor	Dead	
Trawl	13	1	4	72.2
Recapture net	51	0	1	98.0
Total	64	1	5	91.4

Table 6. Catch by weight (kg), per tow, for Pacific halibut, flatfishes, rockfishes, roundfishes, and skates for the Pacific halibut BRD tested in the nearshore flatfish fishery. TR = trawl; RN = recapture net; %R = percent retention.

	Pacific halibut			Flatfishes			Rockfishes			Roundfishes			Skates		
Tow	TR	RN	%R	TR	RN	%R	TR	RN	%R	TR	RN	%R	TR	RN	%R
1	0	33.60	0.0	90.25	16.40	84.6	1.25	5.50	18.5	0.90	13.15	6.4	0	40.05	0.0
2	0	25.00	0.0	88.45	24.80	78.1	0	2.00	0.0	0	22.85	0.0	0	8.10	0.0
3	0	0	–	51.40	19.85	72.1	0	2.55	0.0	0	58.45	0.0	0	19.25	0.0
4	0	0	–	78.90	16.30	82.9	0	0.25	0.0	0.15	33.05	0.5	0	19.10	0.0
5	0	0	–	226.25	57.75	79.7	0.50	2.00	20.0	3.55	43.30	7.6	1.25	32.55	3.7
6	8.35	18.50	31.1	68.25	6.60	91.2	37.75	28.35	57.1	2.50	25.65	8.9	0	28.55	0.0
7	0	16.90	0.0	45.00	5.55	89.0	25.05	29.15	46.2	0.70	34.15	2.0	1.15	3.55	24.5
8	0	0	–	39.40	4.80	89.1	1.35	4.20	24.3	0.30	6.85	4.2	0	14.10	0.0
9	0	30.70	0.0	72.20	10.75	87.0	78.80	277.05	22.1	4.15	106.65	3.8	0	13.05	0.0
10	0	13.55	0.0	37.15	3.80	90.7	7.35	5.60	56.8	0	42.90	0.0	0	5.10	0.0
11	0	4.50	0.0	188.35	9.10	95.4	5.90	37.10	13.7	1.50	27.25	5.2	0	0	–
12	0	0	–	89.20	17.30	83.8	0.15	12.55	1.2	1.05	3.30	24.1	0	5.00	0.0
13	0	4.75	0.0	40.15	12.60	76.1	1.15	3.70	23.7	1.10	10.15	9.8	0	4.70	0.0
14	0	6.55	0.0	16.25	4.60	77.9	0	2.15	0.0	0	0	–	0	0	–
15	6.15	62.75	8.9	49.80	4.75	91.3	0	0	–	0	16.95	0.0	0	4.55	0.0
Total	**14.50**	**216.80**		**1,181.00**	**214.95**		**159.25**	**412.15**		**15.90**	**444.65**		**2.40**	**197.65**	
Mean	**0.97**	**14.45**	**6.3**	**78.73**	**14.33**	**84.6**	**10.62**	**27.48**	**27.9**	**1.06**	**29.64**	**3.5**	**0.16**	**13.18**	**1.2**
SE	**0.67**	**4.58**	**0.03**	**14.75**	**3.53**	**1.22**	**5.63**	**18.09**	**0.07**	**0.35**	**6.94**	**0.008**	**0.11**	**3.20**	**0.007**

Table 7. Percent retention of Pacific halibut and groundfishes by total weight (kg) and total weight of marketable-sized fish caught for the Pacific halibut BRD tested in the nearshore flatfish fishery. n/a* = prohibited species.

	Total weight			Total weight of marketable-sized fish		
Species	**Recapture net**	**Trawl**	**% Retention**	**Recapture net**	**Trawl**	**% Retention**
Pacific halibut	216.80	14.50	6.3	n/a*	n/a*	n/a*
English sole	15.00	109.10	87.9	15.00	108.77	87.9
Arrowtooth flounder	116.25	341.65	74.6	111.02	330.38	74.8
Dover sole	40.35	339.35	89.4	39.10	328.83	89.4
Petrale sole	28.65	345.70	92.3	22.78	318.39	93.3
Other (5 species)[a]	14.70	45.20	75.5	5.99	22.72	79.1
Total	**214.95**	**1,181.00**	**84.6**	**193.89**	**1,109.09**	**85.1**
Pacific ocean perch (*Sebastes alutus*)	0	0.85	100.0	0	0.57	100.0
Darkblotched rockfish	0.30	0.80	72.7	0	0	–
Greenstriped rockfish (*S. elongatus*)	65.00	53.15	45.0	62.34	39.07	38.5
Widow rockfish (*S. entomelas*)	28.95	0	0.0	28.95	0	0.0
Chilipepper (*S. goodei*)	243.20	92.15	27.5	208.18	54.00	20.6
Bocaccio (*S. paucispinis)*	5.5	0	0.0	5.5	0	0.0
Canary rockfish (*S. pinniger*)	38.9	1.7	4.2	38.9	1.7	4.2
Other rockfishes (5 species)[b]	30.3	10.6	25.9	3.2	1.3	28.9
Total	**412.15**	**159.25**	**27.9**	**347.07**	**96.54**	**21.8**
Sablefish	41.50	3.30	7.4	41.50	3.30	7.4
Lingcod	387.05	3.95	1.0	73.54	0.0	0.0
Other (5 species)[c]	16.10	8.65	34.9	0.0	0.0	–
Total	**444.65**	**15.90**	**3.5**	**115.04**	**3.30**	**2.8**
Sandpaper skate (*Bathyraja interrupta*), big skate, longnose skate	197.65	2.40	1.2	194.09	0.0	0.0
Total	**197.65**	**2.40**	**1.2**	**194.09**	**0.0**	**0.0**

[a] Species included southern rock sole (*Lepidopsetta bilineata*), Pacific sanddab, rex sole, slender sole (*Lyopsetta exilis*), and flathead sole (*Hippoglossoides elassodon*).

[b] Species included silvergray (*Sebastes brevispinis*), yellowtail (*S. flavidus*), shortbelly (*S. jordani*), stripetail (*S. saxicola*), and sharpchin rockfishes (*S. zacentrus*).

[c] Species include spiny dogfish (*Squalus suckleyi*), spotted ratfish (*Hydrolagus colliei*), Pacific hake (*Merluccius productus*), shortspine thornyhead, and threadfin sculpin (*Icelinus filamentosus*).

Table 8. Statistical comparison of mean fork lengths (cm) for Pacific halibut and selected flatfishes, rockfishes, and roundfishes caught in the recapture net and the trawl for the Pacific halibut BRD tested in the nearshore flatfish fishery. n_r = number of fish that were measured from the recapture net; n_t = number of fish that were measured from the trawl.

Species	Recapture net mean fork length (SE)	n_r	Trawl mean fork length (SE)	n_t	*P*-value
Flatfishes					
Pacific halibut	81 (2.4)	30	68 (2.7)	4	0.0282
English sole	33 (0.5)	49	33 (0.1)	351	0.5288
Arrowtooth flounder	45 (0.7)	132	43 (0.3)	397	0.0252
Dover sole	41 (0.8)	64	42 (0.3)	327	0.2271
Petrale sole	38 (1.0)	44	39 (0.3)	315	0.2264
Rockfishes					
Pacific ocean perch	0 (–)	0	28 (1.0)	3	n/a
Silvergray rockfish	0 (–)	0	44 (–)	1	n/a
Darkblotched rockfish	26 (–)	1	23 (0.4)	4	0.4000
Greenstriped rockfish	30 (0.2)	148	28 (0.2)	166	<0.0001
Widow rockfish	45 (0.5)	21	0 (–)	0	n/a
Yellowtail rockfish	51 (0.3)	4	41 (–)	1	0.4000
Chilipepper	36 (0.6)	146	28 (0.2)	198	<0.0001
Shortbelly rockfish	0 (–)	0	21 (0.4)	5	n/a
Bocaccio	80 (–)	1	0 (–)	0	n/a
Canary rockfish	49 (1.2)	19	46 (–)	1	0.8000
Stripetail rockfish	22 (0.4)	105	23 (0.7)	40	0.4618
Sharpchin rockfish	24 (0.8)	22	26 (0.6)	3	0.1782
Roundfishes					
Sablefish	49 (0.6)	40	44 (1.3)	5	0.0152
Lingcod	61 (0.6)	184	55 (4.5)	3	0.2651

Discussion

Reducing Pacific halibut bycatch and providing opportunities to fully utilize catch share quota of groundfish stocks are increasingly important to fishermen. In this work, a Pacific halibut BRD designed to retain roundfishes and flatfishes in the DTS complex fishery was tested. A second Pacific halibut BRD was evaluated for use in the nearshore flatfish fishery where species such as Dover sole, petrale sole, and English sole are targeted. Both BRDs examined in these fisheries were shown to reduce Pacific halibut bycatch while maintaining relatively high catch levels for several target species. As efforts to improve trawl selectivity in groundfish fisheries continue, findings from these studies provide important information to industry and management.

The BRD evaluated in the DTS fishery excluded larger-sized Pacific halibut. For Pacific halibut less than 5 kg, a 25.0% reduction (by weight) in bycatch was observed, whereas for fish larger than 5 kg an 84.5% reduction occurred. This finding is similar to prior work conducted in the fishery by Lomeli and Wakefield (2013), which examined a Pacific halibut flexible sorting grid excluder (with 19.1 x 19.1 cm square openings) designed for harvesting assemblages of roundfishes and flatfishes. In their study, a 48.4% reduction in Pacific halibut bycatch occurred for fish smaller than 5 kg, whereas an 85.7% reduction was shown for Pacific halibut larger than 5 kg. While the BRD evaluated by Lomeli and Wakefield (2013) demonstrated the ability to reduce Pacific halibut bycatch, a considerable loss in target catch (>10% by weight) occurred for several flatfishes and roundfishes.

Mortality rates for trawl-caught Pacific halibut discarded at sea in excellent, poor, and dead condition have been estimated at 20%, 55%, and 90%, respectively (Hoag 1975, Clark et al. 1992, Williams and Chen 2004). However, information is lacking on the condition of Pacific halibut that escape out of BRDs. In our studies, Pacific halibut excluded from the trawl were categorized as being in excellent condition, with the exception of one fish. Since Pacific halibut escaping out of these BRDs were recaptured, this work provides an estimate of the potential condition of Pacific halibut that escape out of these BRDs. The viability estimates we provide for Pacific halibut retained in the trawl suggest that the semirigid grids of these BRDs are not increasing mortality.

Sablefish are an economically important species harvested in the DTS complex fishery. Ex-vessel prices for trawl-caught sablefish range from $1.10 to $9.35 per kg (2013 ex-vessel value) and are dependent on weight, with sablefish 5.4 kg or larger exhibiting the highest ex-vessel price per kg. For the BRD evaluated in this fishery, the percentage retained by weight of marketable-sized sablefish was 90.0%. However, sablefish larger than 79 cm, fish primarily ≥5.4 kg, accounted for nearly 5% of the total loss observed. Though there may be conservation

benefits, this level of loss of larger-sized and valuable sablefish could economically impact fishermen and affect their voluntary use of this BRD. Conversely, sablefish have become a constraining species for those fishing on the slope as the 2014 sablefish shore-based trawl allocation (2,641 t) is relatively low when compared to the Dover sole allocation. Recent catches of Dover sole have been approximately 7,933 t (PacFIN 2013) even though the shore-based trawl allocation is 22,234 t (NMFS 2014b) with constraining species, such as sablefish and Pacific halibut, as the primary cause. Hence, reducing the catch rate of sablefish and Pacific halibut relative to Dover sole will allow fishermen to more fully utilize their Dover sole allocation, while still attaining but not exceeding their sablefish IFQ and staying under their Pacific halibut IBQ. Use of the BRD we tested in the DTS fishery would have trade-offs between economic yields and bycatch reduction of Pacific halibut that individual fishermen would have to assess relative to their quota mix.

The BRD examined in the nearshore flatfish fishery substantially reduced bycatch of rockfishes and roundfishes by 72.1% and 96.5%, respectively. The rockfishes and roundfishes that were retained in the trawl consisted primarily of smaller-sized fish (mean 28 cm, SE ±0.2). A simple technique to reduce this bycatch of juvenile and unmarketable-sized roundfishes would be the use of a T90 mesh codend. T90 mesh is conventional diamond mesh that has been turned 90° in orientation (Digre et al. 2010, Herrmann et al. 2013). As shown for knotless square mesh codends, this unique configuration allows the meshes over the entire codend to remain open, changing codend size selection characteristics (Madsen et al. 2012; Wienbeck et al. 2011, 2014). In contrast to knotless square mesh codends, however, the simple construction of a T90 codend results in easier repair and reduced manufacturing costs. A selective flatfish trawl, with a cutback headrope and low rise, designed to allow fish that have a tendency to rise when encountering the footrope to escape, could be used to separate some species of rockfishes and roundfishes before trawl entrainment (King et al. 2004, Hannah et al. 2005).

Dover sole and petrale sole are two economically important flatfishes targeted in the LE groundfish bottom trawl flatfish fishery. Dover sole are significant as they account for over 60% by weight of all flatfish landings (annual) with an ex-vessel value of approximately $0.99 per kg. In 2013, 7,933 t of Dover sole was landed (PacFIN 2013). Petrale sole, on the other hand, account for 16.8% of all flatfish landings, but can have an ex–vessel value of up to $3.30 per kg. Among all flatfishes, petrale sole exhibit the highest ex-vessel price per kg. In the current study, the BRD tested in the nearshore flatfish fishery was most effective at retaining Dover sole and petrale sole. Combined, 91.3% of the marketable-sized Dover sole and petrale sole were caught in the trawl with no significant difference in mean length occurring between fish caught in the trawl

and recapture net. These findings suggest that the BRD examined may prove useful for allowing fishermen to harvest Dover sole and petrale sole on fishing grounds where constraining roundfish species (i.e., overfished and rebuilding rockfishes, sablefish), and/or Pacific halibut co-occur.

While skates are considered a secondary target species by most fishermen in the LE groundfish bottom trawl fishery, skate catches can contribute substantially to the ex-vessel value of a fishing trip as they draw approximately $0.88 per kg (2013 ex-vessel value). In our studies, the BRDs were not effective at retaining skates. These results, however, were anticipated for skates of a marketable size (>3 kg) as only a small percentage pass through the sorting grids. To address this issue, some fishermen using these BRDs place a large mesh recapture bag (38.1 to 45.7 cm knot to knot) over the escape hole to retain skates. While this technique improves the retention of larger-sized skates it increases the likelihood of retaining large-sized Pacific halibut, which can have a greater impact on a fisherman's IBQ level. Currently, fishermen and gear researchers are collaborating on developing alternative techniques to address this issue.

Providing fishermen with an option of using a more selective trawl that will provide access to highly productive stocks of flatfishes and roundfishes while reducing the catch of those species with relatively low ACLs or harvest guidelines would be beneficial to the fishermen, coastal communities, management, and rebuilding or prohibited species. In our work, two BRDs were tested for two fisheries that demonstrated the capability of reducing Pacific halibut bycatch. However, these BRDs would have trade-offs between economic yields and bycatch reduction of Pacific halibut that individual fishermen would have to assess relative to their quota mix. Further evaluation of these BRDs over various fishing conditions would provide important information to better determine their true efficacy in these fisheries. While this research has regional impacts, the application of flexible sorting grids also has potential uses in other fisheries nationally and internationally.

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