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ARTICLE

Illuminating the Headrope of a Selective Flatfish Trawl: Effect on Catches of Groundfishes, Including Pacific Halibut

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Abstract

This study evaluated how illuminating the headrope of a selective flatfish trawl can affect catches of groundfishes, including Pacific Halibut *Hippoglossus stenolepis*, in the U.S. West Coast limited-entry (LE) groundfish bottom trawl fishery. Over the continental shelf, fishermen engaged in the LE bottom trawl fishery target a variety of flatfishes, roundfishes, and skates. Green LED fishing lights (Lindgren-Pitman Electralume) were used to illuminate the headrope. The lights were grouped into clusters of three, with each cluster attached ~1.3 m apart along the 40.3-m-long headrope. Catch comparisons and ratios of mean fish length classes were compared between tows conducted with (treatment) and without (control) LEDs attached along the trawl headrope. Fewer Rex Sole *Glyptocephalus zaphirus*, Arrowtooth Flounder *Atheresthes stomias*, and Lingcod *Ophiodon elongatus* were caught in the treatment than in the control trawl, though not at a significant level. Pacific Halibut catches differed between the two trawls, with the treatment trawl catching an average of 57% less Pacific Halibut. However, this outcome was not significant due to a small sample size. For Dover Sole *Microstomus pacificus* 31–44 cm in length and Sablefish *Anoplopoma fimbria* 43–61 cm in length, significantly fewer fish were caught in the treatment than in the control trawl. On average, the treatment trawl caught more rockfishes *Sebastes* spp., English Sole *Parophrys vetulus*, and Petrale Sole *Eopsetta jordani*, but not at a significant level. These findings show that illuminating the headrope of a selective flatfish trawl can affect the catch comparisons and ratios of groundfishes, and depending on fish length and species the effect can be positive or negative.

The U.S. West Coast limited-entry (LE) groundfish bottom trawl fishery operates under a catch share program that allocates individual fishing quotas (IFQs) and establishes annual catch limits (ACLs) for 29 managed units of groundfish (stocks, stock complexes, and geographical subdivisions of stocks; PFMC and NMFS 2011, 2015). Over the continental shelf, fishermen engaged in the LE bottom trawl fishery target a variety of flatfishes (e.g.,

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English Sole *Parophrys vetulus*, Dover Sole *Microstomus pacificus*, Petrale Sole *Eopsetta jordani*), roundfishes (e.g., Yellowtail Rockfish *Sebastes flavidus*, Sablefish *Anoplopoma fimbria*, Lingcod *Ophiodon elongatus*), and skates (Rajidae). Fully utilizing the ACL for many of these groundfishes, however, have been affected in recent years by stocks with restrictive harvest limits (i.e., Darkblotched Rockfish *S. crameri*, and Yelloweye Rockfish *S. ruberrimus* [an overfished stock]), and bycatch of Pacific Halibut *Hippoglossus stenolepis* (a prohibited species). Hence, it is increasingly important for fishermen and managers to develop techniques that minimize the catches of constraining species, allowing for increased utilization of the catch share quotas of healthier fish stocks.

Low-rise trawls with either a cut back headrope or a top panel constructed of large mesh are often used in flatfish fisheries (King et al. 2004; Madsen et al. 2006; Krag and Madsen 2010). These trawls are designed to allow nontarget species that tend to rise when encountered an opportunity to escape before trawl entrainment. In the LE groundfish bottom trawl fishery, fishermen are required under current regulations to use a two-seam low-rise selective flatfish trawl when fishing north of 40°10′N latitude in bottom depths less than 183 m to reduce catches of overfished and rebuilding rockfishes (NOAA 2014). This trawl, with a mean headrope height of ~1.3 m (King et al. 2004; Hannah et al. 2005), is effective at reducing catches for many benthopelagic groundfishes, but has been less effective at reducing catches of some of the more benthic groundfishes, such as Darkblotched Rockfish, and smaller-sized Pacific Halibut (King et al. 2004).

Studies have demonstrated that light can affect the behavior of fish in and around trawl gear (Walsh and Hickey 1993; Ryer and Olla 2000; Ryer and Barnett 2006; Lomeli and Wakefield 2012; Hannah et al. 2015) and that vision is the primary sense affecting fish behavior in relation to trawl gear (Glass and Wardle 1989; Olla et al. 1997, 2000; Kim and Wardle 1998, 2003; Ryer et al. 2010). Using a Pacific Hake *Merluccius productus* midwater trawl, research tested whether artificial illumination could attract Chinook Salmon *Oncorhynchus tshawytscha* to specific escape windows of a bycatch reduction device (BRD) equipped with multiple escape windows. Video observations of 438 Chinook Salmon were made, with 299 individuals being observed to exit out the BRD. Of the Chinook Salmon that escaped, 243 (81.3%) exited out a window that was illuminated (Pacific States Marine Fisheries Commission, unpublished data). This result was highly significant ($P < 0.0001$). On an ocean shrimp *Pandalus jordani* trawl, Hannah et al. (2015) examined whether placing artificial illumination along the trawl fishing line could reduce Eulachon *Thaleichthys pacificus* bycatch by illuminating escape openings between the groundline contacting the seafloor and the fishing line. Eulachon bycatch was reduced 91% by weight. This work also noted catch reductions of 82% by weight for Darkblotched Rockfish and 56% by weight for other juvenile rockfishes. In the LE groundfish bottom trawl fishery, where species such as Darkblotched Rockfish and Pacific Halibut are affecting some fishermen's ability to maximize their IFQs of healthier groundfish stocks, enhancing the visibility of the selective flatfish trawls low-rise headrope using artificial illumination could prove effective at reducing bycatch and improving trawl selectivity.

The objective of this study was to evaluate how illuminating the headrope of a selective flatfish trawl could affect catches of groundfishes, including Pacific Halibut, in the West Coast LE groundfish bottom trawl fishery.

METHODS

Sea trials and sampling.— Sea trials occurred aboard the FV *Miss Sue*, a 24.7-m-long, 640-hp (1 hp = 746 W) trawler out of Newport, Oregon. Tows were conducted off central Oregon between 44°10′N and 44°59′N and between 124°17′W and 124°58′W in May 2016. Towing occurred over the continental shelf and shelf break during daylight hours at bottom fishing depths from 95 to 402 m (Table 1). The average bottom fishing depth was 203 m. Towing speed over ground ranged from 2.2 to 2.6 knots. Tow durations were set to 1 h. The trawl was fished using the vessel's forward net reel. The trawl was fished with (treatment) and without (control) LEDs in an alternate-tow randomized block design with the tows in each block occurring next to each other and in the same direction (but without overlapping their trawl paths). After each tow, all fish were identified to species and weighed using a motion-compensated platform scale. Total length (cm) was used to measure flatfish and Lingcod, while fork length (cm) was used for Sablefish and rockfishes.

The trawl used for this study was a two-seam Eastern 400 low-rise selective flatfish trawl with a cutback headrope (King et al. 2004; Hannah et al. 2005). The headrope was 40.3 m in length, and the chain footrope was 31.2 m in length. The chain footrope was covered with rubber discs 20.3 cm in diameter and outfitted with rubber rockhopper discs 35.6 cm in diameter placed approximately every 58.4 cm over the footrope length. This trawl also lacks floats along the central portion of the headrope to reduce any diving behavior by fish in reaction to floats. The trawl cod end was a four-seam tube of 116-mm diamond netting (6.0-mm double twine) that was 88 meshes in circumference, excluding the meshes in each selvedge.

Green LED fishing lights (Lindgren-Pitman Electralume, centered on 540 nm; ≥0.5–2.0 lx) were used to illuminate the trawl's headrope. The lights were grouped into clusters of three (Figure 1), with each cluster of lights

TABLE 1. Mean ambient and artificial light levels per tow at the center of the trawl belly and headrope. Asterisks denote treatment trawls (with LEDs); time = Pacific standard time.

Tow	Block	Date	Time (hours)	Depth (m)	Light level (μmol photons m^{-2} s^{-1})	
					Belly	Headrope
1	1	May 10	0618	256	7.85×10^{-9}	
2	1*	May 10	1020	256	2.44×10^{-6}	
3	2*	May 10	1327	220	2.72×10^{-4}	
4	2	May 10	1525	220	7.14×10^{-8}	
5	3*	May 10	0611	155	4.40×10^{-6}	
6	3	May 11	0851	155	1.43×10^{-5}	
7	4*	May 11	1144	154	4.01×10^{-5}	
8	4	May 11	1338	155	4.64×10^{-5}	
9	5	May 12	0600	117	3.15×10^{-4}	
10	5*	May 12	0743	117	1.37×10^{-3}	
11	6*	May 12	0933	146	3.65×10^{-4}	
12	6	May 12	1319	154	3.15×10^{-4}	
13	7	May 13	0606	402	1.41×10^{-8}	
14	7*	May 13	0810	402	1.49×10^{-7}	
15	8*	May 13	1113	187	3.11×10^{-7}	
16	8	May 13	1330	187	2.95×10^{-8}	
17	9*	May 17	0745	95	5.44×10^{-2}	
18	9	May 17	1001	95	6.64×10^{-1}	
19	10	May 17	1310	135	1.30×10^{-4}	1.20
20	10*	May 17	1615	135	8.37×10^{-5}	6.64×10^{-1}
21	11*	May 18	0645	130	1.43×10^{-5}	1.18×10^{-3}
22	11	May 18	0900	130	2.99×10^{-5}	5.16×10^{-3}
23	12*	May 18	1120	143	1.43×10^{-5}	3.32×10^{-3}
24	12	May 18	1330	143	4.40×10^{-6}	1.84×10^{-3}
25	13	May 18	1515	146	2.58×10^{-5}	3.32×10^{-3}
26	13*	May 18	1652	148	7.94×10^{-6}	1.37×10^{-3}
27	14	May 19	0646	150	3.28×10^{-6}	4.89×10^{-4}
28	14*	May 19	0937	150	2.58×10^{-5}	1.45×10^{-2}
29	15*	May 19	1227	176	1.43×10^{-5}	2.13×10^{-3}
30	15	May 19	1504	176	4.40×10^{-6}	3.65×10^{-4}
31	16*	May 20	0625	238	9.59×10^{-8}	7.61×10^{-4}
32	16	May 20	0825	238	1.29×10^{-7}	1.07×10^{-5}
33	17	May 20	1037	192	4.40×10^{-6}	3.65×10^{-4}
34	17*	May 20	1149	192	4.41×10^{-6}	4.22×10^{-4}
35	18*	May 24	0901	256	5.32×10^{-8}	1.30×10^{-4}
36	18	May 24	1106	256	3.42×10^{-8}	1.01×10^{-6}
37	19	May 24	1328	329	1.41×10^{-8}	2.95×10^{-8}
38	19*	May 24	1532	329	1.42×10^{-8}	1.51×10^{-4}
39	20	May 25	0706	238	1.41×10^{-8}	8.28×10^{-8}
40	20*	May 25	1025	238	1.36×10^{-6}	2.34×10^{-4}
41	21	May 25	1305	311	7.14×10^{-8}	7.53×10^{-7}
42	21*	May 25	1555	311	7.94×10^{-6}	1.75×10^{-4}
43	22*	May 26	0658	338	1.82×10^{-6}	3.15×10^{-4}
44	22	May 26	0917	338	9.10×10^{-9}	3.42×10^{-8}
45	23*	May 26	1311	274	2.44×10^{-6}	1.37×10^{-3}
46	23	May 26	1516	274	3.96×10^{-8}	4.84×10^{-7}
47	24*	May 27	0600	229	2.32×10^{-7}	2.34×10^{-4}
48	24	May 27	0749	229	1.90×10^{-8}	1.01×10^{-6}

attached ~1.3 m apart on center along the length of the headrope. A total of 29 light clusters were used, with the LEDs facing port or starboard depending on the side of the trawl they were placed (Figure 1). Given the catenary shape of the trawl headrope, the LEDs faced increasingly forward moving along the headrope from its apex toward the leading edge of the wings. The lights were attached to the trawl on deployment and then removed on retrieval to avoid damaging them when winding the trawl onto the net reel. Attachment points were marked with twine along the headrope to assure that the tow-to-tow attachment point of each cluster was at the same location. A Wildlife Computers TDR-MK9 archival tag was attached, facing upward, to the middle of the trawl belly to measure the ambient and artificial light levels and temperature in the net on all tows. After tow 18, an additional MK9 tag was attached, facing upward, to the center of the headrope to collect further light data. Prior to field sampling, the MK9 tags were calibrated using an International Light IL1700 light meter and PAR sensor. The calibration function used to convert the MK9 relative light units to irradiance units was

$$y = 1 \times 10^{-9} e^{0.1472x} \qquad (1)$$

where x is the relative light unit from the MK9 and y is the corresponding irradiance unit in μmol photons m^{-2} s^{-1}.

Statistical analysis.— We used the statistical analysis software SELNET (SELection in trawl NETting) to analyze the data (Sistiaga et al. 2010; Herrmann et al. 2012, 2016) and conducted a length-dependent catch comparison and catch ratio analyses. Table 2 summaries the data that was used in each analysis. The analysis was conducted separately by species following the procedure described below.

Using the catch information (numbers and sizes of fish for each of the tows), we wanted to determine whether there was a significant difference in catch efficiency between the control trawl (without LEDs) and the treatment trawl (with LEDs). We also wanted to determine whether a difference between the trawls could be related to the size of the fish. Specifically, to assess the relative length-dependent catch efficiency effect of changing from the control trawl to treatment trawl, we used the method described in Herrmann et al. (2017) based on comparing

FIGURE 1. Images of an LED cluster attached **(A)** near the center of the trawl headrope on the starboard side and **(B)** along the wing tip on the port side, and their orientations.

TABLE 2. Length data used for the catch comparison and catch ratio analyses. The values in parentheses are the percentages of the total catch that were sampled for length measurements. Rockfishes* includes Rougheye *Sebastes aleutianus*, Redbanded *S. babcocki*, Widow *S. entomelas*, Yellowtail *S. flavidus*, and Yelloweye rockfishes, Pacific Ocean Perch *S. alutus*, Chilipepper *S. goodei*, and Bocaccio *S. paucispinis*.

	Control		Treatment	
Species	No. measured	Length range (cm)	No. measured	Length range (cm)
Pacific Halibut	185 (1.0)	69–112	79 (1)	53–119
English Sole	1,096 (0.39)	20–42	1,276 (0.27)	20–44
Rex Sole *Glyptocephalus zachirus*	1,614 (0.27)	20–51	1,484 (0.48)	16–47
Arrowtooth Flounder *Atheresthes stomias*	1,145 (0.55)	25–70	1,050 (0.66)	25–70
Dover Sole	2,468 (0.30)	27–61	1,961 (0.54)	24–59
Petrale Sole	2,298 (0.36)	23–57	2,335 (0.26)	23–57
Darkblotched Rockfish	242 (1.0)	21–46	404 (1.0)	22–45
Greenstriped Rockfish	281 (0.77)	20–38	317 (1.0)	20–42
Canary Rockfish	82 (1.0)	34–57	130 (0.90)	33–56
Rockfishes*	148 (1.0)	24–53	144 (1.0)	25–53
Sablefish	593 (.038)	38–86	276 (1.0)	34–90
Lingcod	285 (0.69)	43–100	208 (0.61)	45–100

the catch data for tows with the control and treatment trawls. This method models the length-dependent catch comparison rate (CC_l) summed over tows, namely,

$$CC_l = \frac{\sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{i=1}^{mc}\left\{\frac{nc_{li}}{qc_i}\right\} + \sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\right\}} \tag{2}$$

where nc_{li} and nt_{lj} are the numbers of fish measured in each length class l for the control and treatment trawls, respectively, in tows i and j, qc_i and qt_j are the related subsampling factors (fractions of the caught fish measured for length), while mc and mt are the numbers of tows carried out with the control and treatment trawls. The functional form catch comparison rate $CC(l,\mathbf{v})$ (the experimental being expressed by equation 2) was obtained using maximum likelihood estimation by minimizing the following equation:

$$-\sum_l \left\{ \begin{array}{c} \sum_{i=1}^{mc}\left\{\frac{nc_{li}}{qc_i} \times \ln(1.0 - CC(l,\mathbf{v}))\right\} \\ + \sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j} \times \ln(\mathrm{CC}(1,\mathbf{v}))\right\} \end{array} \right\} \tag{3}$$

where $\mathbf{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\mathbf{v})$. The outer summation in the equation is the summation over the length classes l. When both the catch efficiency of the control and treatment trawls and the number of tows are equal ($mc = mt$), the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge whether or not there is a difference in catch efficiency between the two trawls. The experimental CC_l was modelled by the function $CC(l,\mathbf{v})$, on the following form:

$$CC(l,\mathbf{v}) = \frac{\exp(f(l, v_0, \ldots, v_k))}{1 + \exp(f(l, v_0, \ldots, v_k))} \tag{4}$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\mathbf{v}$ describing $CC(l,\mathbf{v})$ are estimated by minimizing equation (3), which is equivalent to maximizing the likelihood of the observed data. We considered f s of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison $CC(l,\mathbf{v})$. Among these models, estimations of the catch comparison rate were made using multimodel inference to obtain a combined model (Burnham and Anderson 2002; Herrmann et al. 2017).

The ability of the combined model to describe the experimental data was evaluated based on the P-value, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct. Therefore, this P-value, which was calculated based on the model deviance and the degrees of freedom, should not be <0.05 for the combined model to describe the experimental data sufficiently well except in cases in which the data are overdispersed (Wileman et al. 1996; Herrmann et al. 2017). Based the estimated catch comparison function $CC(l,\mathbf{v})$, we obtained the relative catch efficiency (also called the catch ratio) $CR(l,\mathbf{v})$ between fishing with the two trawls by the general relationship

$$CR(l,\mathbf{v}) = \frac{mc \times CC(l,\mathbf{v})}{mt \times (1 - CC(l,\mathbf{v}))} \tag{5}$$

The catch ratio provides a direct relative value of the catch efficiency between fishing with the control and treatment trawls. If the catch efficiency of both trawls is equal, $CR(l,\mathbf{v})$ would be 1.0. Thus, $CR(l,\mathbf{v}) = 1.5$ would mean that the treatment trawl is catching (on average) 50% more fish with length l than the control trawl. In contrast, $CR(l,\mathbf{v}) = 0.8$ would mean that the treatment trawl is only catching 80% of the fish with length l that the control trawl is catching.

The confidence limits for the catch comparison curve and catch ratio curve were estimated using a double bootstrapping method (Herrmann et al. 2017). This bootstrapping method accounts for the uncertainty in the estimation resulting from tows' variation in catch efficiency and the availability of fish as well as uncertainty about the size structure of the catch for the individual tows. By employing multimodel inference in each bootstrap iteration, the method also accounts for the uncertainty due to uncertainty in model selection. We performed 1,000 bootstrap repetitions and calculated the Efron 95% (Efron 1982) confidence limits. To identify sizes of fish with significant differences in catch efficiency, we checked for length classes in which the confidence limits for the catch ratio curve did not contain 1.0.

A length-integrated average value for the catch ratio was also estimated directly from the experimental catch data by means of the equation

$$CR_{average} = \frac{\frac{1}{mt}\sum_{l}\sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\frac{1}{mc}\sum_{l}\sum_{i=1}^{mc}\left\{\frac{nc_{li}}{qc_i}\right\}} \tag{6}$$

where the outer summation covers the length classes in the catch during the experimental fishing period.

Based on equation (6), the percentage change in average catch efficiency by shifting from the control trawl to the treatment trawl was estimated by

$$\Delta CR_{average} = 100 \times \left(CR_{average} - 1.0\right) \tag{7}$$

By incorporating $\Delta CR_{average}$ into each of the bootstrap iterations described above, we were able to assess the 95% confidence limits for $\Delta CR_{average}$. We used $\Delta CR_{average}$ to provide a length-averaged value for the effect of changing from the control to the treatment trawl on the catch efficiency. In contrast to the length-dependent evaluation of the catch ratio, $\Delta CR_{average}$ is specific for the population structure encountered during the experimental sea trials. Therefore, its value is specific for the size structure in the fishery at the time the trials were carried out, and it cannot be extrapolated to other scenarios in which the size structure of the fish population may be different.

RESULTS

We completed 48 tows (24 blocks; Table 1). The combined catch of English Sole, Rex Sole, Arrowtooth Flounder, Dover Sole, and Petrale Sole ranged from 52 to 2,063 kg per tow in the treatment and from 48 to 2,062 kg per tow in the control trawl. Catches of Pacific Halibut per tow ranged from 0 to 137 kg in the treatment and from 0 to 604 kg in the control trawl (Table 3). Catch of rockfishes (11 species; Table 4) overall ranged from 0 to 144 kg per tow in the treatment and from 0 to 86 kg per tow in the control trawl. Darkblotched, Greenstriped, and Canary *S. pinniger* rockfishes were the most frequently encountered rockfishes. Other rockfishes caught, but in small numbers, included Rougheye, Redbanded, Widow, Yellowtail, and Yelloweye rockfishes, and Pacific Ocean Perch, Chilipepper, and Bocaccio. Sablefish catches per tow ranged from 0 to 128 kg in the treatment and from 0 to 441 kg in the control trawl. Catches of Lingcod per tow ranged from 0 to 484 kg in the treatment and from 0 to 477 kg in the control trawl (Table 4).

Flatfishes

The catch comparisons and ratios of flatfishes between the treatment and control trawls varied across length classes. In general, the treatment trawl on average caught more English Sole and Petrale Sole but fewer Rex Sole and Arrowtooth Flounder than the control trawl (Figure 2). These catch differences, however, were not significant, as the 95% CIs for the mean $CC(l,\mathbf{v})$ and $CR(l,\mathbf{v})$ for these species extend above and below the $CC(l,\mathbf{v})$ rate of 0.5 and the $CR(l,\mathbf{v})$ ratio of 1.0 (Figures 3 and 4). For Dover Sole, the treatment trawl caught significantly fewer fish 31–44 cm in length than the control trawl. Over this size-class range, the treatment trawl on average caught only 40–44% of the Dover Sole caught by the control trawl. Catches of Pacific Halibut were substantially lower in the treatment trawl, with the control trawl catching an average of 57% more Pacific Halibut. However, this outcome was not significant due to a small sample size (264 individuals). With the exception of Pacific Halibut, P-values <0.05 were observed in the $CC(l,\mathbf{v})$ models for flatfishes, which required further assessment to determine whether the models were adequately describing the experimental data for these species

TABLE 3. Catch data (kg) for flatfishes by experimental block; CTRL = control (without LEDs), TRMT = treatment (with LEDs).

	Pacific Halibut		English Sole		Rex Sole		Arrowtooth Flounder		Dover Sole		Petrale Sole	
Block	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT
1	0	0	3.1	1.5	200.1	69.0	184.0	132.8	756.8	243.6	1.9	0
2	5.1	0	1.6	4.4	19.3	13.8	93.9	69.9	108.4	49.4	2.1	4.5
3	47.9	0	136.7	234.2	19.9	14.6	12.1	8.8	9.5	7.9	204.8	284.0
4	12.8	4.9	80.9	97.5	7.6	11.3	12.3	3.1	5.6	16.9	262.7	158.1
5	119.3	31.7	2.4	5	6.5	5.2	0	0	1.0	0.5	38.5	41.1
6	34.0	0	288.5	716.3	26.6	25.3	2.8	0.3	10.1	3.8	1,045.6	1,317.6
7	0	0	0	0	10.5	15.0	8.5	23.4	359.2	154.1	0	0
8	16.8	0	27.5	15.6	513.7	149.2	49.7	29.1	1,376.9	291.8	93.9	54.3
9	17.3	5.5	2.5	5.7	2.1	5.1	0	0	1.2	0.4	64.4	74.4
10	100.3	30.8	17.3	11.1	2.8	0.5	25.5	20.0	38.3	31.1	523.1	421.2
11	27.3	75.6	17.0	30.1	1.2	1.4	11.4	12.9	45.5	44.1	201.7	326.6
12	20.2	26.0	18.1	24.4	2.3	4.2	22.3	25.3	112.0	192.3	158.1	209.3
13	51.4	35.6	17.4	16.3	8.7	6.3	59.4	34.2	30.5	29.2	742.8	1,048.3
14	51.4	38.6	15.3	8.4	7.6	8.6	55.2	53.2	70.3	68.7	486.5	578.9
15	13.8	23.9	5.4	10.8	26.8	21.6	148.3	157.1	155.2	224.9	375.4	687.6
16	0	0	0	0	19.1	6.6	48.0	68.9	84.6	19.4	0	0
17	603.7	137.1	1.6	1.0	19.6	24.3	85.8	68.9	135.1	310.2	176.4	249.5
18	0	5.4	0.5	0	42.9	13.2	87.2	77.4	311.9	96.6	2.0	0
19	0	0	0	0	5.6	4.6	74.5	85.3	39.3	39.7	0	0
20	20.5	0	325.2	107.0	109.4	19.3	289.5	117.1	235.9	59.0	6.5	5.5
21	5.5	0	232.6	133.3	132.9	91.6	161.0	94.7	54.7	33.2	0	0
22	7.9	0	7.0	9.1	146.3	117.4	58.2	51.3	523.4	154.4	0	0
23	0	0	55.8	25	27.4	10.2	153.4	122.7	300.3	65.2	1.6	0
24	0	0	1.5	1.89	76.8	29.2	272.2	222.7	377.4	137.8	23.1	3.1
Total	1,155.2	415.1	1,257.9	1,458.6	1,435.7	667.5	1,915.2	1,479.1	5,143.1	2,274.2	4,411.1	5,464.0

(Table 5). Inspecting the fit between the experimental catch comparison data and the modeled mean curve for these species indicated *P*-values <0.05 were due to overdispersion of the data rather than the model's inability to adequately describe the data.

Roundfishes

The catch comparisons and ratios of roundfishes between the treatment and control trawls also varied across length classes. In general, the treatment trawl on average led to larger catches of rockfishes than the control trawl. Between the two trawls, mean catches of Lingcod were lower in the treatment trawl (Figure 2). These catch differences were not significant, as the 95% CIs of the mean $CC(l,\boldsymbol{v})$ and $CR(l,\boldsymbol{v})$ for these species extend above and below the $CC(l,\boldsymbol{v})$ rate of 0.5 and $CR(l,\boldsymbol{v})$ ratio of 1.0 (Figures 5 and 6). The large 95% CIs for these selectivity curves were partly a result of small sample sizes within length classes. For Sablefish, the treatment trawl caught significantly fewer fish 43–61 cm in length than the control trawl. Over these size-classes, the treatment trawl on average caught only 15–19% of the Sablefish caught by the control trawl. $CC(l,\boldsymbol{v})$ model *P*-values <0.05 were noted for Darkblotched Rockfish and Sablefish (Table 5). As was observed in the flatfish $CC(l,\boldsymbol{v})$ models, this result was due to overdispersion of the data rather than the model's inability to adequately describe the experimental data.

Light Levels and Temperature

The mud cloud created by the footrope contacting the seafloor was often detected in the MK9 tag data. Within each block, the mean light levels at the headrope were substantially higher than those at the trawl belly in both the treatment and control trawls. Within most (but not all) blocks, the treatment trawl exhibited higher mean light levels than the control trawl at both the belly and headrope (Table 1). The most reasonable explanation for this is the mud cloud obstructing the MK9 tags' ability to detect the LEDs. Bottom temperatures ranged from 5.4°C to 8.0°C, though the majority of temperature readings were between 5.5°C and 7°C.

TABLE 4. Catch data (kg) for rockfishes, Sablefish, and Lingcod by each experimental block; CTRL = control (without LEDs), TRMT = treatment (with LEDs). See Table 2 for the species included in Rockfishes*.

	Darkblotched Rockfish		Greenstriped Rockfish		Canary Rockfish		Rockfishes*		Sablefish		Lingcod	
Block	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT	CTRL	TRMT
1	71.3	69.6	0	0	0	0	10.9	6.8	72.1	20.1	15.4	6.6
2	3.6	0.5	10.2	9.5	3.0	0	0.4	0.7	72.4	2.9	10.6	0
3	0	0	48.2	3.5	11.4	57.0	10.4	21.5	3.8	0	44.2	12.3
4	0	0	36.3	41.4	29.8	3.1	7.6	6.5	8.2	0	44.2	14.0
5	0	0	0	0	0	0	0	0	0	0	4.2	0
6	0	0	0	0	9.1	29.2	1.9	50.5	0	0	257.4	49.0
7	0	0	0	0	0	0	0	0	24.8	127.6	0	0
8	0	0	1.4	0.9	14.4	23.8	5.5	62.0	10	3.9	21.0	22.0
9	0	0	0	0	0	0	0	0	0	0	17.9	2.4
10	0	0	0.2	0	1.1	0	0	0	0	0	6.7	23.5
11	0	0	0	0.3	0.8	2.4	0	0	0.5	0	7.4	14.6
12	0.3	0	0	0	0	0	0	0.8	0.2	0	22.4	11.4
13	0	0	0	0.8	3.8	1.4	3.2	0	0.8	3.3	120.8	81.4
14	0	0	0.5	0	9.3	4.9	1.4	6.6	0.8	0	158.2	392.5
15	0	0	14.2	10.9	44.9	105.9	0	0	0	6.0	476.8	484.3
16	6.5	137.4	0.4	0	0	1.7	0	5.6	164.1	30.0	0	4.9
17	0	0.4	2.2	12.4	2.1	0	0	0	4.0	4.4	43.5	141.2
18	19.4	12.9	1.3	0	0	0	0.7	1.0	132.7	56.3	12.7	8.6
19	0	1.6	0	0	0	0	0	0	59.4	82.7	0	0
20	1.0	36.9	0.6	0	7.7	0	3.9	5.4	376.5	50.5	70.9	15.7
21	79.4	24.3	0	0	0	0	7.5	0.6	392.2	12.7	5.3	0
22	4.3	13.0	0	0	0	0	0	0.9	22.0	38.5	0	3.7
23	3.0	22.7	0	0	0	0	1.8	1.8	153.5	27.3	34.9	40.3
24	0.7	0	3.3	3.6	2.3	5.4	1.4	2.6	441.0	22.6	10.3	5.3
Total	189.5	319.3	118.8	83.3	139.7	234.8	56.6	173.3	1,939.0	488.8	1,384.8	1,333.7

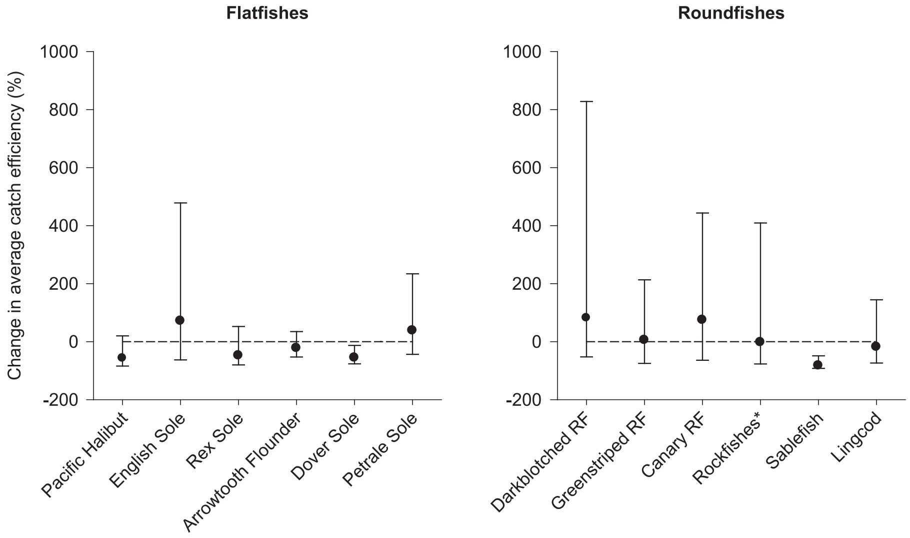

FIGURE 2. Change in average catch efficiency between the treatment and control trawls. Values below zero indicate that more fish were caught in the control trawl than in the treatment trawl, and conversely for values above zero. The abbreviation RF stands for rockfish; rockfishes* includes Rougheye, Redbanded, Widow, Yellowtail, and Yelloweye rockfishes, Pacific Ocean Perch, Chilipepper, and Bocaccio.

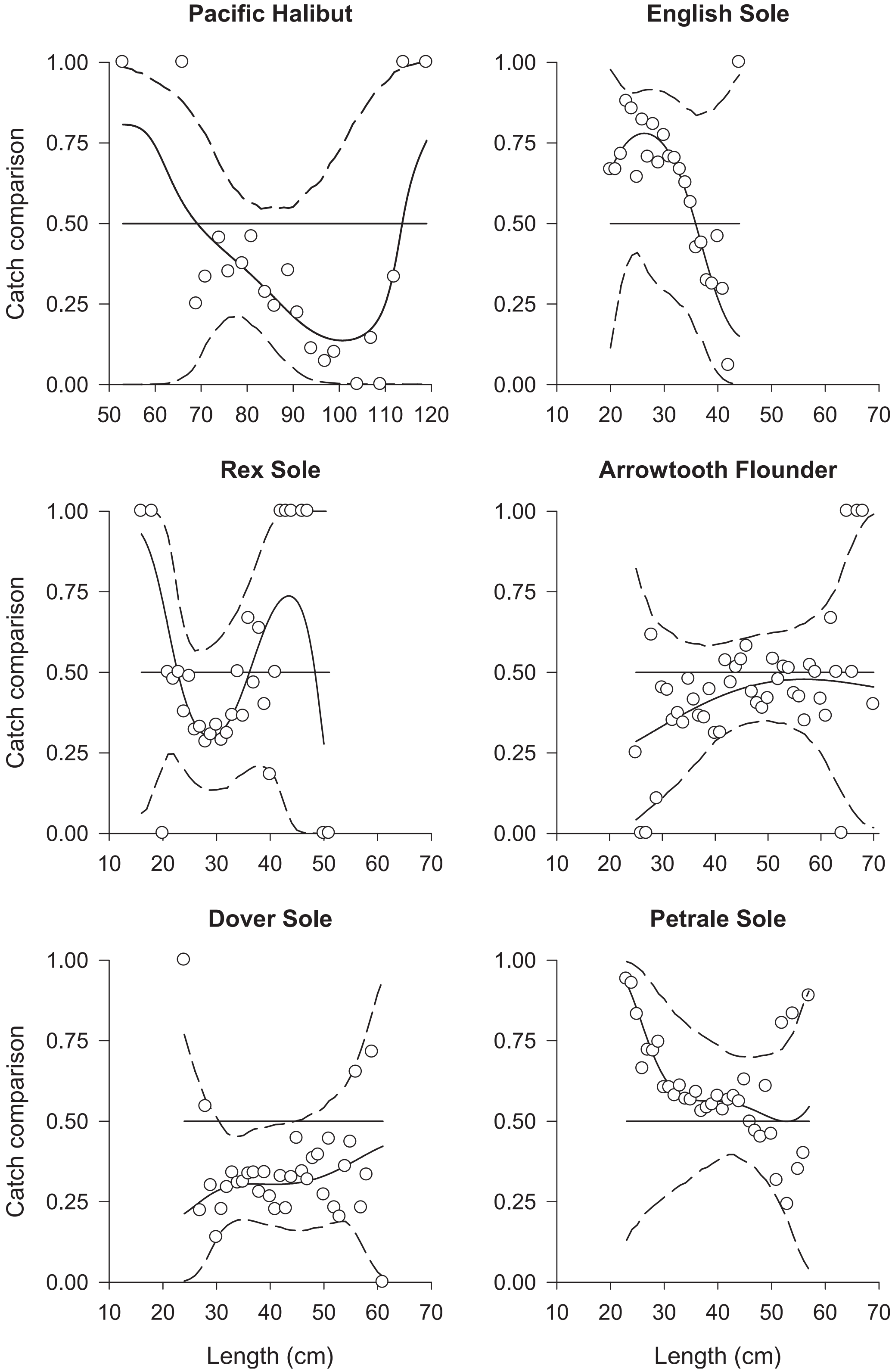

FIGURE 3. Mean catch comparison curves for flatfishes per size-class. Circles denote the experimental data; solid curves are the modeled values; dashed lines represent the 95% confidence interval limits; horizontal lines depict the baseline catch comparison rate of 0.5, indicating equal catch rates between the treatment and control trawls.

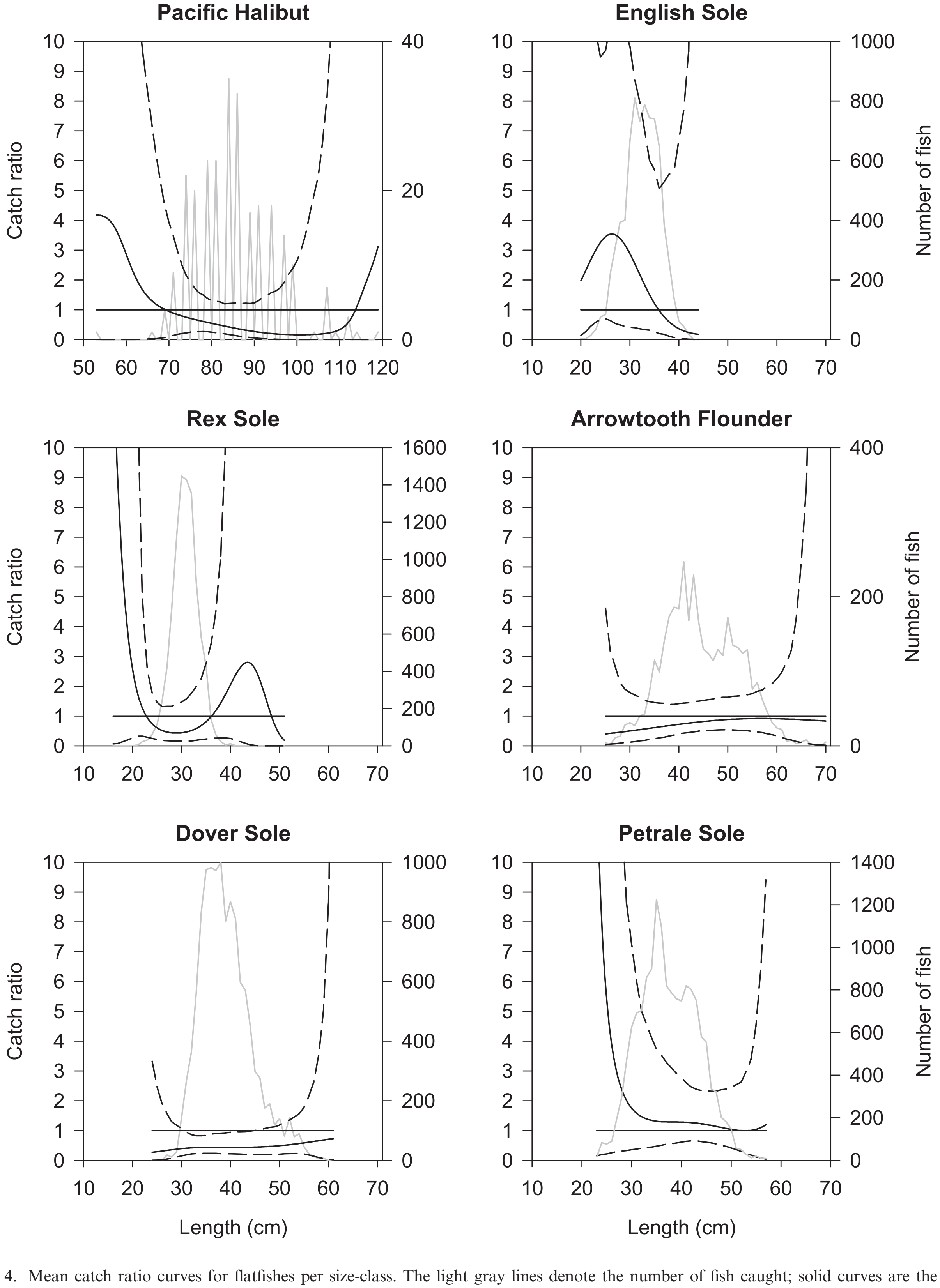

FIGURE 4. Mean catch ratio curves for flatfishes per size-class. The light gray lines denote the number of fish caught; solid curves are the modeled values; dashed lines represent the 95% confidence interval limits; horizontal lines depict the baseline catch ratio rate of 1.0, indicating equal catch efficiencies between the treatment and control trawls.

TABLE 5. Catch comparison curve fit statistics. See Table 2 for the species included in Rockfishes*.

Species	*P*-value	Deviance	df
Pacific Halibut	0.971	7.1	16
English Sole	0.011	36.0	19
Rex Sole	0.001	55.4	26
Arrowtooth Flounder	<0.001	77.4	40
Dover Sole	<0.001	75.3	30
Petrale Sole	0.037	45.2	30
Darkblotched Rockfish	<0.001	50.9	18
Greenstriped Rockfish	0.194	19.5	15
Canary Rockfish	0.528	17.9	19
Rockfishes*	0.278	26.5	23
Sablefish	0.043	56.6	40
Lingcod	0.056	59.8	44

DISCUSSION

Depending on the species and length of the fish, illuminating the headrope of the selective flatfish trawl could have positive or negative effects on catch. While the differences in the catch rates and catch efficiencies were not significant, there was a general tendency to catch fewer Rex Sole, Arrowtooth Flounder, and Lingcod when the headrope was illuminated. The catches of Pacific Halibut was also reduced, with an average of 57% fewer Pacific Halibut being caught when the headrope was illuminated. However, the small sample size of Pacific Halibut prevented the catch analysis models from detecting a significant difference between the treatment and control trawls. The opposite trend was observed for rockfishes, English Sole, and Petrale Sole, for which mean catches increased when the headrope was illuminated. Further data collection would improve the model's ability to detect significant differences, as comparisons of alternative tow designs often require large numbers of tows and length samples to detect significant effects.

The catches of Dover Sole and Sablefish differed significantly between the two trawls, with fewer fish being caught when the headrope was illuminated. While it is unclear whether these species avoid trawl entrainment by passing under the footrope or over the low-rise headrope, artificial illumination appears to enhance their optomotor response to the approaching trawl gear and thus their ability to escape capture. In a laboratory study in which juvenile Pacific Halibut, English Sole, and Northern Rock Sole *Lepidopsetta polyxystra* were exposed to a simulated trawl footrope under dark and light conditions, Ryer and Barnett (2006) found that these species exhibited a dominant "run" response (of four behavioral responses evaluated [hop, rise, run, and under]) when encountering the footrope under ambient light conditions. Under dark settings, the behavioral responses were more evenly distributed across the four categories, indicating a diminished optomotor response. In a midwater trawl, Olla et al. (2000) examined the swimming and orientation behaviors of Walleye Pollock *Gadus chalcogrammus* under light and dark conditions. Under lights conditions, Walleye Pollock swam actively and oriented themselves parallel to the principal axis of the trawl, whereas under dark conditions they showed little to no swimming activity and were unable to orient themselves parallel to the principal axis of the trawl. Further research using video or imaging sonar systems would identify the behavioral patterns exhibited by Dover Sole and Sablefish encountering the selective flatfish trawl.

When testing the effect of artificial illumination along the fishing line of an ocean shrimp trawl, Hannah et al. (2015) noted significant reductions in the catch of Darkblotched Rockfish when illumination was present. The authors speculated that these fish were most likely diving under the fishing line in response to the illumination and passing under the trawl through restricted openings (spaces of ~35–70 cm in height) made visible between the drop chains connecting the groundline to the fishing line. In the present study, in which we evaluated how illuminating the headrope of a selective flatfish trawl would affect fish catches, there was a general trend of catching more rockfishes, including Darkblotched Rockfish, when the headrope was illuminated. Coupled with Hannah et al. (2015), these results suggest that Darkblotched Rockfish exhibit a diving behavior in response to artificial illumination. While illuminating the headrope of the selective flatfish trawl did not reduce Darkblotched Rockfish catches, the findings from this study provide useful information on behavioral responses to illumination that could prove beneficial in developing selective fishing gear to reduce the catches of this species.

In summary, this study shows that illuminating the headrope of the selective flatfish trawl can affect the catch rates of several groundfish species, including Pacific Halibut, and that the effect varies by species and size. For example, fishermen concerned about Pacific Halibut bycatch when targeting English Sole and Petrale Sole could benefit from an illuminated headrope, whereas fishermen seeking to target Dover Sole and/or Sablefish but avoid Darkblotched Rockfish, would not. As fishermen in West Coast and Alaska fisheries experiment with artificial illumination in their efforts to improve gear selectivity, better understanding of the mechanisms affecting fish behavior in response to artificial illumination on mobile fishing gear becomes increasingly important to gear researchers, fishermen, management, and the resource.

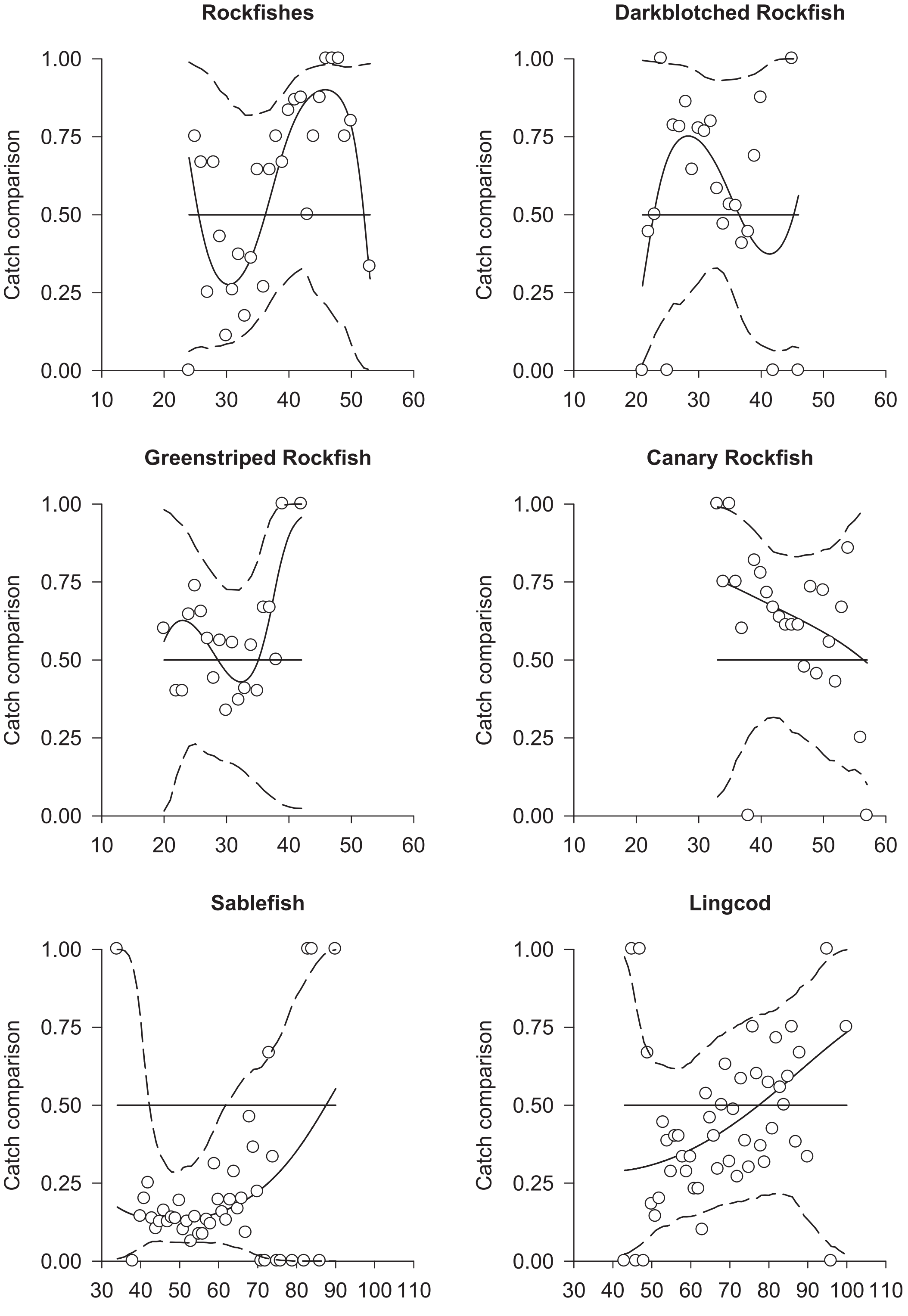

FIGURE 5. Mean catch comparison curves for rockfishes (Rougheye, Redbanded, Widow, Yellowtail, and Yelloweye rockfishes, Pacific Ocean Perch, Chilipepper, and Bocaccio), Darkblotched, Greenstriped, and Canary rockfishes, Sablefish, and Lingcod per size-class. Circles denote the experimental data; solid curves are the modeled value; dashed lines represent the 95% confidence interval limits; horizontal lines depict the baseline catch comparison rate of 0.5, indicating equal catch rates between the treatment and control trawls.

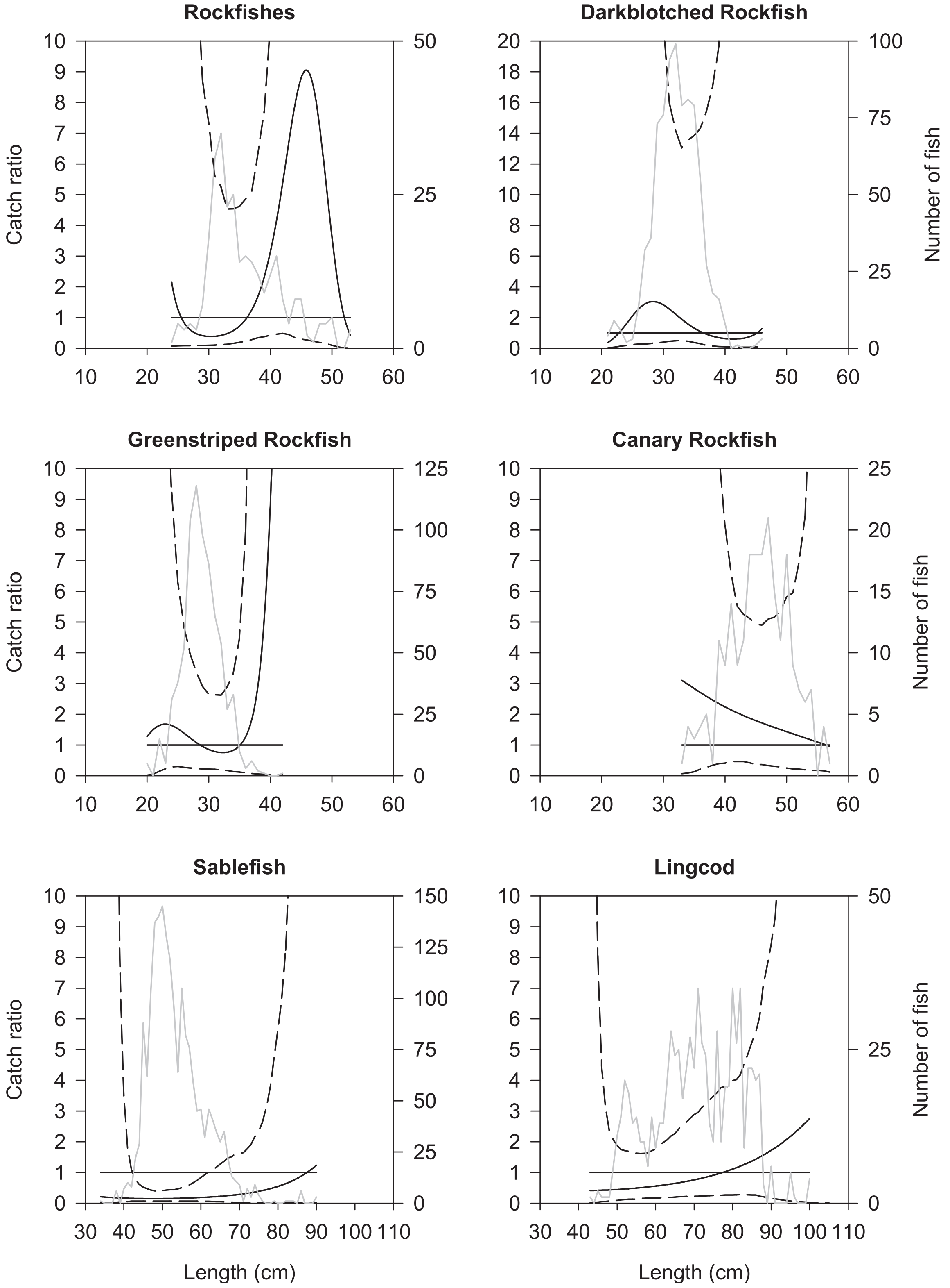

FIGURE 6. Mean catch ratio curves for rockfishes (Rougheye, Redbanded, Widow, Yellowtail, and Yelloweye rockfishes, Pacific Ocean Perch, Chilipepper, and Bocaccio), Darkblotched, Greenstriped, and Canary rockfishes, Sablefish, and Lingcod per size-class. The light gray lines denote the number of fish caught; solid curves are the modeled value; dashed lines represent the 95% confidence interval limits; horizontal lines depict the baseline catch ratio rate of 1.0, indicating equal catch efficiencies between the treatment and control trawls.

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