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

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Abstract

This study evaluated how illuminating the headrope of a selective flatfish trawl could affect catches of groundfishes and Pacific halibut 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. Lights were grouped into clusters of three, with each cluster attached ca. 1.35 m apart along the 40.3 m long headrope. Catch comparisons and ratios were compared between tows conducted with (*treatment*) and without (*control*) LED lights attached along the trawl headrope. Catches of rex sole, arrowtooth flounder, greenstriped rockfish, and lingcod were lower in the *treatment* compared to the *control* trawl, however, not at a significant level. Bycatch of Pacific halibut 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. As for Dover sole and sablefish, significantly fewer fish were caught in the *treatment* than the *control* trawl. Compared to the *control*, the *treatment* trawl on average caught more rockfishes (with the exception of greenstriped rockfish), English sole, and petrale sole, but not at a significant level. Findings show that illuminating the headrope of a selective flatfish trawl can affect the catch comparisons and ratios of several groundfish species and Pacific halibut, and depending on the target or avoidance species, the effect can be positive or negative.

Introduction

The U.S. West Coast limited entry (LE) groundfish bottom trawl fishery operates under a catch share program that allocates individual fishing quotas (IFQ) and establishes annual catch limits (ACLs) for 29 groundfish managed units (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., 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 by stocks with restrictive harvest limits (i.e., darkblotched rockfish [*S. crameri*, a rebuilding stock], 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 catches of constraining species allowing for increased utilization of catch share quota 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 non-target 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^{o} 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 ca. 1.3 m (Hannah et al. 2005; King et al. 2004), 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 (Hannah et al. 2015; Lomeli and Wakefield 2012, 2016; Ryer and Barnett 2006; Ryer and

Olla 2000; Walsh and Hickey 1993) and that vision is the primary sense affecting fish behavior in relation to trawl gear (Glass and Wardle 1989; Kim and Wardle 1998, 2003; Olla et al. 1997, 2000; 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 437 Chinook salmon were made with 266 individuals noted to exit out the BRD at trawl depths. Of these Chinook salmon to escape, 230 (86.4%) exited out a window that was illuminated (Lomeli and Wakefield 2016). 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% for darkblotched rockfish and 56% 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 evaluated how illuminating the headrope of the selective flatfish trawl could affect catches of groundfishes and Pacific halibut in the West Coast LE groundfish bottom trawl fishery.

Methods

Sea Trials and Sampling

Sea trials occurred aboard the F/V *Miss Sue*, a 24.7 m long, 640 horsepower trawler out of Newport, Oregon. Tows were conducted off central Oregon between 44° 10′ and 44° 59′ N and between 124° 17′ and 124° 58′ W in May 2016. Towing occurred over the continental shelf and shelf break during daylight hours, between 0600 and 1700 Pacific daylight time, at bottom fishing depths from 95 to 402 m. 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*) LED lights in an alternate tow randomized block design. After each tow, all fish were identified to species and weighed using a motion compensated platform scale. Flatfishes and lingcod were measured to the nearest cm total length, while sablefish and rockfishes were measured to the nearest cm fork length. Subsampling was avoided when possible, however, time constraints and relatively large catches often required subsampling for length measurements. All Pacific halibut caught were measured.

Trawl design

The trawl used for this study was a two-seam Eastern 400 low-rise selective flatfish trawl with a cutback headrope (Hannah et al. 2005; King et al. 2004). 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.

LED Lights

Green LED fishing lights (Lindgren-Pitman Electralume®, centered on 540 nm, ≥0.5-2.0 lx) were used to illuminate the trawl's headrope and adjacent area. The lights were grouped into clusters of three (Fig. 1), with each cluster of lights attached ca. 1.35 m apart on center along the length of the headrope. A total of 29 light clusters were used with the LEDs facing port and starboard along the headrope (Fig. 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 upon deployment and then removed upon retrieval to avoid damaging them when winding the trawl onto the net reel. Attachment points were marked with orange twine along the headrope to assure that the haul-to-haul 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 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. Both MK9 tags had similar responses to the calibration. Therefore, the tag values were pooled and one calibration function was generated. The calibration function used to convert the MK9 relative light units to irradiance units was:

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

where x is the relative light unit from the MK9 and y is the corresponding irradiance unit in μmol photons m^{-2} s^{-1}. The R^2 value for the calibration function used to convert the MK9 relative light units to irradiance units was 0.9867.

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).

Catch comparison –A catch comparison analysis was performed using a polynomial model to evaluate if mean fish catches of length class *l* differ between the *treatment* (with LEDs) and *control* (without LED) trawl. All tows and length classes caught were used in the analysis. The catch comparison (CC) model used the following equation:

$$CC(l, \boldsymbol{v}) = \frac{\exp(f(l, q_0 \ldots q_k))}{1 + \exp(f(l, q_0 \ldots q_k))}$$

where CC(l,v) expresses the likelihood of catching a fish of length class *l* in the *treatment* given that it is caught in one of the two trawl types. Values range from 0 to 1. A value above 0.5 would indicate that more fish of length class *l* were caught in *treatment*, whereas a value below 0.5 would indicate that more fish of length class *l* were caught in the *control* trawl. The term *f* refers to a polynomial of order *k* with coefficients $q_0 – q_k$, so that $v = (q_0,…., q_k)$. The polynomial model considered *f* up to an order of four with parameters q_0, q_1, q_2, q_3, and q_4. Removing one or more of the q parameters at a time resulted in 31 additional models that were considered candidate models to describe CC(l,v) between the *treatment* and *control* trawl. Based on the full set of models, multimodel inference was applied to examine how the individual models compared to one another. The resulting model was termed the pooled model. In this model, the individual models were weighted and ranked based on Akaike information criterion (AIC) (Akaike 1974) values corrected for finite sample sizes (AIC_c). Models with AIC_c values within 10 of the model with the lowest AIC_c value were considered to contribute to the pooled CC(l,v) model. Fit statistics to evaluate if the pooled model can adequately describe the experimental data are p-values >0.05, and deviance not to exceed degrees of freedom by approximately two times. Finally, Efron percentile 95%

confidence intervals (CIs) (Efron 1982) for the catch comparison curves were estimated from 1,000 bootstrap repetitions, with 2,000 repeated runs, using a double bootstrapping method implemented in SELNET to account for both within-tow and between-tow variation.

Catch ratio – The following formula was used to express the mean catch ratio (i.e., catch efficiency) that fish of length class *l* would be caught between the *treatment* and *control* trawl:

$$CR(l, \boldsymbol{v}) = \frac{CC(l, \boldsymbol{v})}{1 - CC(l, \boldsymbol{v})}$$

A value of 1.0 indicates that the catch efficiency between the *treatment* and *control* trawl does not differ. A value of 1.50, would indicate that the *treatment* catches 50% more fish of length class *l* than the *control* trawl, whereas a value of 0.50 would indicate the opposite.

For additional catch comparison and ratio model details see Sistiaga et al. (2015), Herrmann et al. (2016), and Notti et al. (2016).

Results

We completed 48 tows (12 blocks). The combined catch of English sole, rex sole (*Glyptocephalus zachirus*), arrowtooth flounder (*Atheresthes stomias*), Dover sole, and petrale sole ranged from 52 to 2,063 kg per tow in the *treatment* and 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 0 to 604 kg in the *control* trawl (Table 1). Catch of rockfishes (11 species combined) ranged from 0 to 145 kg per tow in the *treatment* and 0 to 87 kg per tow in the *control* trawl. Darkblotched, greenstriped, and canary (*S. pinniger*) rockfishes were the most frequently encountered rockfishes. Sablefish catches per tow ranged from 0 to 127 kg in the *treatment* and 0 to 441 kg in the *control* trawl. Catches of lingcod per tow ranged from 0 to 485 kg in the treatment and 0 to 477 kg in the control trawl (Table 2).

Flatfishes – Catch comparisons and ratios of flatfishes between the *treatment* and *control* trawl 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 (Fig. 2). These catch differences, however, were not significant as the mean CC(l,v) and CR(l,v) 95% CIs for these species extend above and below the CC(l,v) rate of 0.50 and CR(l,v) ratio of 1 (Figs. 3 and 4). For Dover sole, the *treatment* trawl caught significantly fewer fish of 31 cm to 44 cm in length than the *control* trawl. Over this size class range, the *treatment* trawl on average caught only 40 to 44% of the number of Dover sole compared to the *control* trawl. Bycatch of Pacific halibut was substantially lower in the *treatment*, 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 where observed in the CC(l,v) models for flatfishes which required further assessment to determine if the models were adequately describing the experimental data for these species (Table 3). Inspecting the fit between the experimental catch comparison data and the modeled mean curve for these species indicated the p-values <0.05 were due to overdispersion of the data rather than the models inability to adequately describe the data.

Roundfishes – Catch comparisons and ratios of roundfishes between the *treatment* and *control* trawls varied across length classes. In general, the *treatment* trawl on average showed increased catches for rockfishes, with the exception of greenstriped rockfish (*S. elongatus*) where catches were slightly decreased, compared to the *control* trawl. Between the two trawls, mean catches of lingcod were lower in the *treatment* trawl (Fig. 2). These catch differences for rockfishes and lingcod, however, were not significant as the mean CC(l,v) and CR(l,v) 95% CIs for these species extend above and below the CC(l,v) rate of 0.50 and CR(l,v) ratio of 1 (Figs. 5 and 6). The large 95% CIs for these selectivity curves was partially a factor of small sample sizes within length classes. For sablefish, the *treatment* trawl caught significantly fewer fish of 42 cm to 64 cm and 78 cm to 82 cm in length than the *control* trawl. Over these size classes, the *treatment* trawl on average caught only 7 to 14% of the number of sablefish compared to the *control* trawl. CC(l,v) model p-values <0.05 where noted for darkblotched rockfish, rockfishes combined, and lingcod (Table 3). As was observed in the flatfish CC(l,v) models, this result was due to overdispersion of the data rather than the models inability to adequately describe the experimental data.

Light levels and Temperature – The mud cloud created from the footrope contacting the seafloor was often detected in the MK9 tag data. Within each block, mean light levels at the headrope were substantially higher than at the trawl belly in both the *treatment* and *control* trawl. 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 4, Fig. 7). The most reasonable explanation for this result is the mud cloud obstructing the MK9 tags ability to detect the LED lights. Bottom temperatures ranged from 5.4 – 8.0^{o}C, however, the majority of temperature readings occurred between 5.5 – 7^{o}C.

Discussion

Illuminating the headrope of the selective flatfish trawl affected the catch rates of several groundfish species and Pacific halibut. Depending on the assemblage of species targeted, or avoided, illuminating the headrope of the selective flatfish trawl could have positive or negative effects. While differences in the catch rates and catch efficiencies were not significant, there was a general trend of catching fewer rex sole, arrowtooth flounder, greenstriped rockfish, and lingcod when the headrope was illuminated. Bycatch of Pacific halibut was also reduced, with an average of 57% less Pacific halibut caught when the headrope was illuminated. The opposite trend was observed for darkblotched rockfish, canary rockfish, English sole, and petrale sole with mean catches increasing when the headrope was illuminated. Further data collection would improve the model's ability to detect significant differences as alternate tow comparison designs often require large numbers of tows and length samples to detect significant effects.

Catches of Dover sole and sablefish differed significantly between the two treatments, with fewer Dover sole and sablefish caught when the headrope was illuminated. While it is unclear if these species are avoiding trawl entrainment by passing under the footrope or rising over the low-rise headrope, presence of artificial illumination appears to enhance their optomotor response to the approaching trawl gear and their ability to escape capture. In a laboratory study exposing juvenile Pacific halibut, English sole, and northern rock sole (*Lepidopsetta polyxystra*) to a simulated trawl footrope under dark and light conditions, Ryer and Barnett (2006) found these species exhibited a dominant "run" response (from four behavioral responses evaluated [hop, rise, run, 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 they were most likely diving under the fishing line in response to the illumination and passing under the trawl through restricted openings (spaces of ca. 35-70 cm in height) made visible between the drop chains connecting the groundline to the fishing line. In the present study, where we evaluated how illuminating the headrope of a selective flatfish trawl could affect fish catches, there was a general trend of catching more darkblotched and canary rockfishes when the headrope was illuminated. Coupled with Hannah et al. (2015), these results suggest these rockfishes may exhibit a diving behavior in response to artificial illumination. While illuminating the headrope of the selective flatfish trawl did not reduce darkblotched rockfish catches, findings from this study provide useful information on behavioral response to illumination that could prove beneficial for developing selective fishing gear to reduce their catches.

In summary, this study shows that illuminating the headrope of the selective flatfish trawl can affect the catch rates of several groundfish species and Pacific halibut and the effect varies by species. For example, fishermen concerned with Pacific halibut bycatch while targeting English sole and petrale sole, could potentially benefit from an illuminated headrope, whereas fishermen seeking to target Dover sole and/or sablefish, but avoid darkblotched rockfish, would not benefit from an illuminated headrope. As fishermen in west coast and Alaska fisheries experiment with artificial illumination in efforts to improve gear selectivity, better understanding 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.

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Table 1. Catch data by weight (kg) for flatfishes per each 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 2. Catch data by weight (kg) for rockfishes, sablefish, and lingcod per each experimental block. CTRL = control (without LEDs); TRMT = treatment (with LEDs); RF = rockfish; * = species include rougheye (*S. aleutianus*), redbanded (*S. babcocki*), darkblotched, greenstriped, widow (*S. entomelas*), yellowtail, canary, and yelloweye rockfishes, and Pacific ocean perch (*S. alutus*), chilipepper (*S. goodei*), and bocaccio (*S. paucispinis*).

	Darkblotched RF		Greenstriped RF		Canary RF		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	82.2	76.4	72.1	20.1	15.4	6.6
2	3.6	0.5	10.2	9.5	3.0	0	17.2	10.7	72.4	2.9	10.6	0
3	0	0	48.2	3.5	11.4	57.0	70.0	82.0	3.8	0	44.2	12.3
4	0	0	36.3	41.4	29.8	3.1	73.7	51.0	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	11.0	79.7	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	21.3	86.7	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	1.3	0	0	0	6.7	23.5
11	0	0	0	0.3	0.8	2.4	0.8	2.7	0.5	0	7.4	14.6
12	0.3	0	0	0	0	0	0.3	0.8	0.2	0	22.4	11.4
13	0	0	0	0.8	3.8	1.4	7.0	2.2	0.8	3.3	120.8	81.4
14	0	0	0.5	0	9.3	4.9	11.2	11.5	0.8	0	158.2	392.5
15	0	0	14.2	10.9	44.9	105.9	59.1	116.8	0	6.0	476.8	484.3
16	6.5	137.4	0.4	0	0	1.7	6.9	144.7	164.1	30.0	0	4.9
17	0	0.4	2.2	12.4	2.1	0	4.3	12.8	4.0	4.4	43.5	141.2
18	19.4	12.9	1.3	0	0	0	21.4	13.9	132.7	56.3	12.7	8.6
19	0	1.6	0	0	0	0	0	1.6	59.4	82.7	0	0
20	1.0	36.9	0.6	0	7.7	0	13.2	42.3	376.5	50.5	70.9	15.7
21	79.4	24.3	0	0	0	0	86.9	24.9	392.2	12.7	5.3	0
22	4.3	13.0	0	0	0	0	4.3	13.9	22.0	38.5	0	3.7
23	3.0	22.7	0	0	0	0	4.8	24.5	153.5	27.3	34.9	40.3
24	0.7	0	3.3	3.6	2.3	5.4	7.7	11.6	441.0	22.6	10.3	5.3
Total	189.5	319.3	118.8	83.3	139.7	234.8	504.6	810.7	1,939.0	488.8	1,384.8	1,333.7

Table 3. Catch comparison curve fit statistics. df = degrees of freedom; * = species include rougheye, redbanded, darkblotched, greenstriped, widow, yellowtail, canary, and yelloweye rockfishes, and Pacific ocean perch, chilipepper, and bocaccio.

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	0.035	45.5	30
Darkblotched rockfish	<0.001	47.9	18
Greenstriped rockfish	0.194	19.5	15
Canary rockfish	0.198	21.7	17
Rockfishes*	0.044	46.8	32
Sablefish	0.334	38.0	35
Lingcod	0.043	61.4	44

Table 4. Mean light levels per tow at the center of trawl belly and headrope. * = Treatment trawl (with LEDs).

			Light level (μmol photons $m^{-2} s^{-1}$)					Light level (μmol photons $m^{-2} s^{-1}$)	
Tow	Block	Depth (m)	Belly	Headrope	Tow	Block	Depth (m)	Belly	Headrope
1	1	256	7.85E-09	-	25	13	146	2.58E-05	3.32E-03
2	1*	256	2.44E-06	-	26	13*	148	7.94E-06	1.37E-03
3	2*	220	2.72E-04	-	27	14	150	3.28E-06	4.89E-04
4	2	220	7.14E-08	-	28	14*	150	2.58E-05	1.45E-02
5	3*	155	4.40E-06	-	29	15*	176	1.43E-05	2.13E-03
6	3	155	1.43E-05	-	30	15	176	4.40E-06	3.65E-04
7	4*	154	4.01E-05	-	31	16*	238	9.59E-08	7.61E-04
8	4	155	4.64E-05	-	32	16	238	1.29E-07	1.07E-05
9	5	117	3.15E-04	-	33	17	192	4.40E-06	3.65E-04
10	5*	117	1.37E-03	-	34	17*	192	4.41E-06	4.22E-04
11	6*	146	3.65E-04	-	35	18*	256	5.32E-08	1.30E-04
12	6	154	3.15E-04	-	36	18	256	3.42E-08	1.01E-06
13	7	402	1.41E-08	-	37	19	329	1.41E-08	2.95E-08
14	7*	402	1.49E-07	-	38	19*	329	1.42E-08	1.51E-04
15	8*	187	3.11E-07	-	39	20	238	1.41E-08	8.28E-08
16	8	187	2.95E-08	-	40	20*	238	1.36E-06	2.34E-04
17	9*	95	5.44E-02	-	41	21	311	7.14E-08	7.53E-07
18	9	95	6.64E-01	-	42	21*	311	7.94E-06	1.75E-04
19	10	135	1.30E-04	1.20E+00	43	22*	338	1.82E-06	3.15E-04
20	10*	135	8.37E-05	6.64E-01	44	22	338	9.10E-09	3.42E-08
21	11*	130	1.43E-05	1.18E-03	45	23*	274	2.44E-06	1.37E-03
22	11	130	2.99E-05	5.16E-03	46	23	274	3.96E-08	4.84E-07
23	12*	143	1.43E-05	3.32E-03	47	24*	229	2.32E-07	2.34E-04
24	12	143	4.40E-06	1.84E-03	48	24	229	1.90E-08	1.01E-06

Figure 1. Image of an LED cluster attached near the center of the trawl headrope (A, starboard-side) and wing tip (B, port-side) and their orientation.

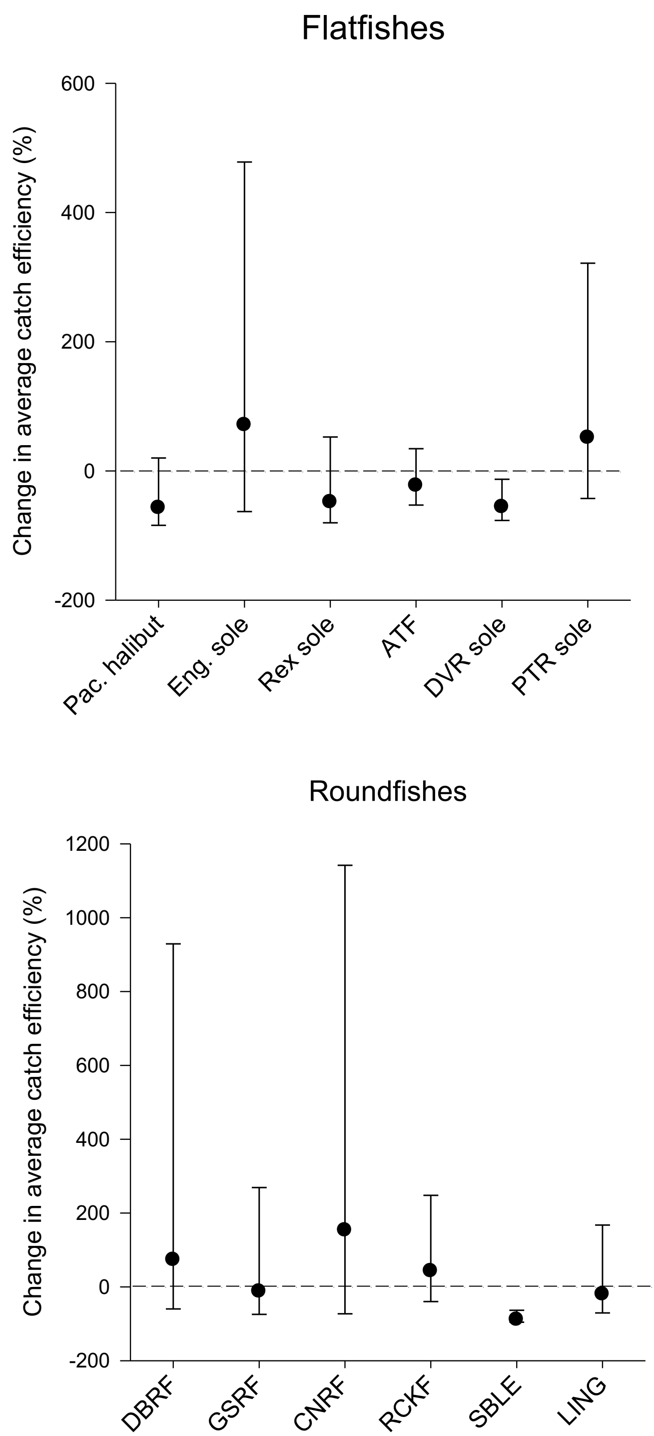

Figure 2. Change in average catch efficiency (%) between the *treatment* and *control* trawl. Values below zero indicate more fish were caught in the *control* trawl, and vice versa for values above zero. Eng. = English; ATF = arrowtooth flounder; DVR = Dover; PTR = petrale; DBRF = darkblotched rockfish; GSRF = greenstriped rockfish; CNRF = canary rockfish; RCKF = rockfishes combined (species include rougheye, redbanded, darkblotched, greenstriped, widow, yellowtail, canary, and yelloweye rockfishes, and Pacific ocean perch, chilipepper, and bocaccio); SBLE = sablefish; LING = lingcod.

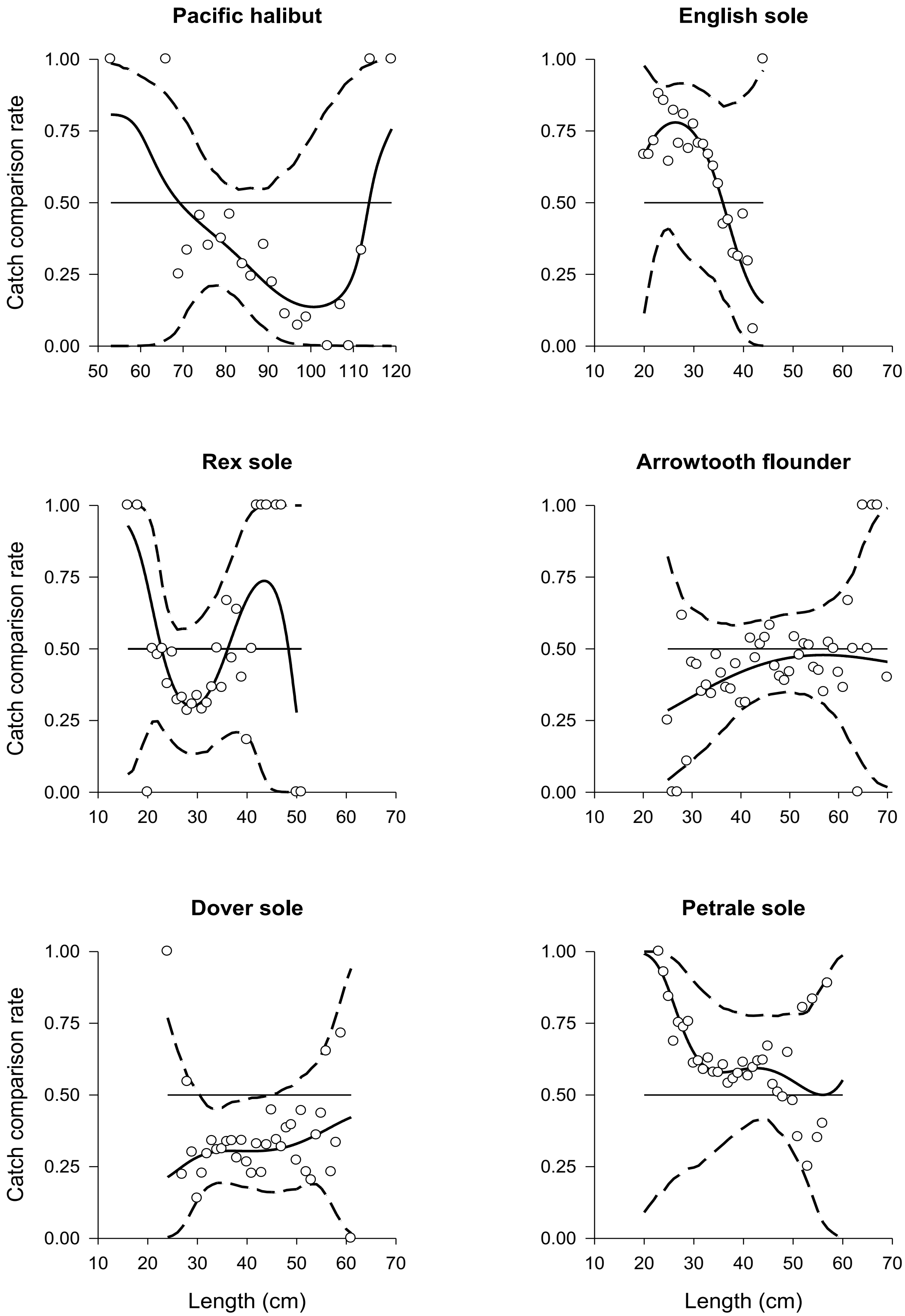

Figure 3. Mean catch comparison rate curves for flatfishes per size class. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% confidence interval limits; straight lines depict the baseline catch comparison rate of 0.50 indicating equal catch rates between the *treatment* and *control* trawl.

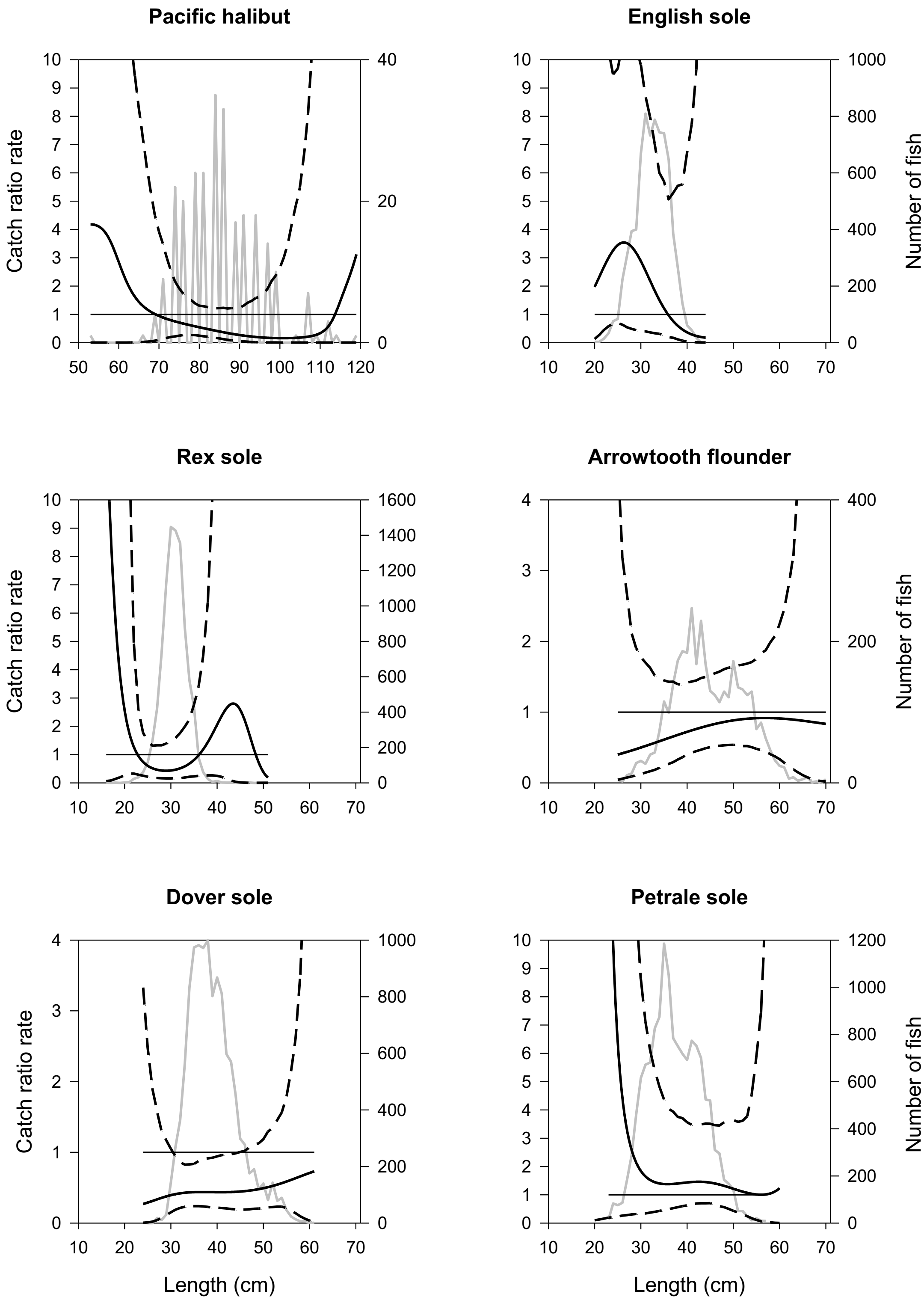

Figure 4. Mean catch ratio rate curves for flatfishes per size class. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% confidence interval limits; grey lines are number of fish caught; straight lines depict the baseline catch ratio rate of 1.0 indicating equal catch efficiencies between the *treatment* and *control* trawl.

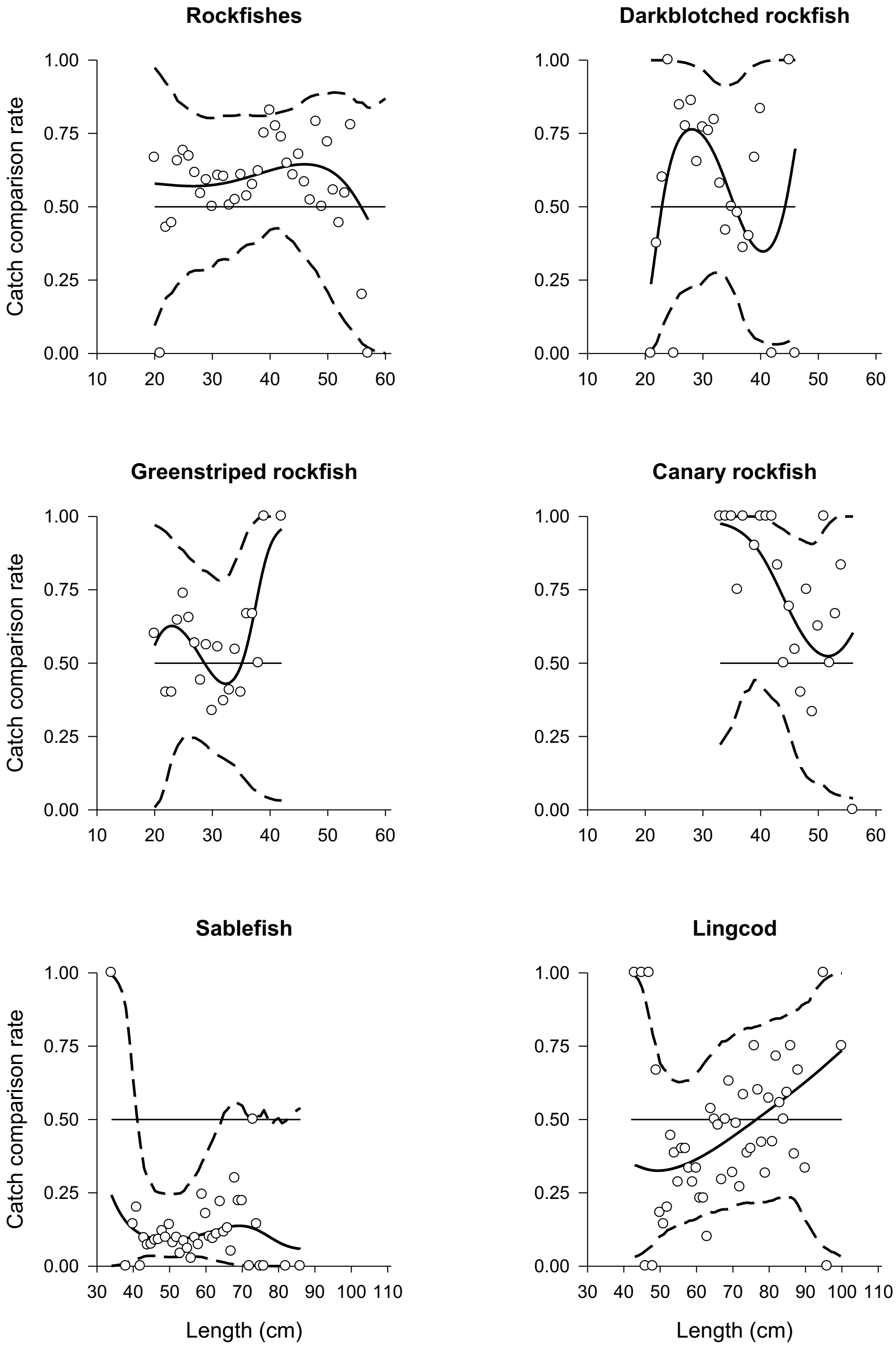

Figure 5. Mean catch comparison rate curves for rockfishes combined (species include rougheye, redbanded, darkblotched, greenstriped, widow, yellowtail, canary, and yelloweye rockfishes, and Pacific ocean perch, chilipepper, and bocaccio), sablefish, and lingcod per size class. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% confidence interval limits; straight lines depict the baseline catch comparison rate of 0.50 indicating equal catch rates between the *treatment* and *control* trawl.

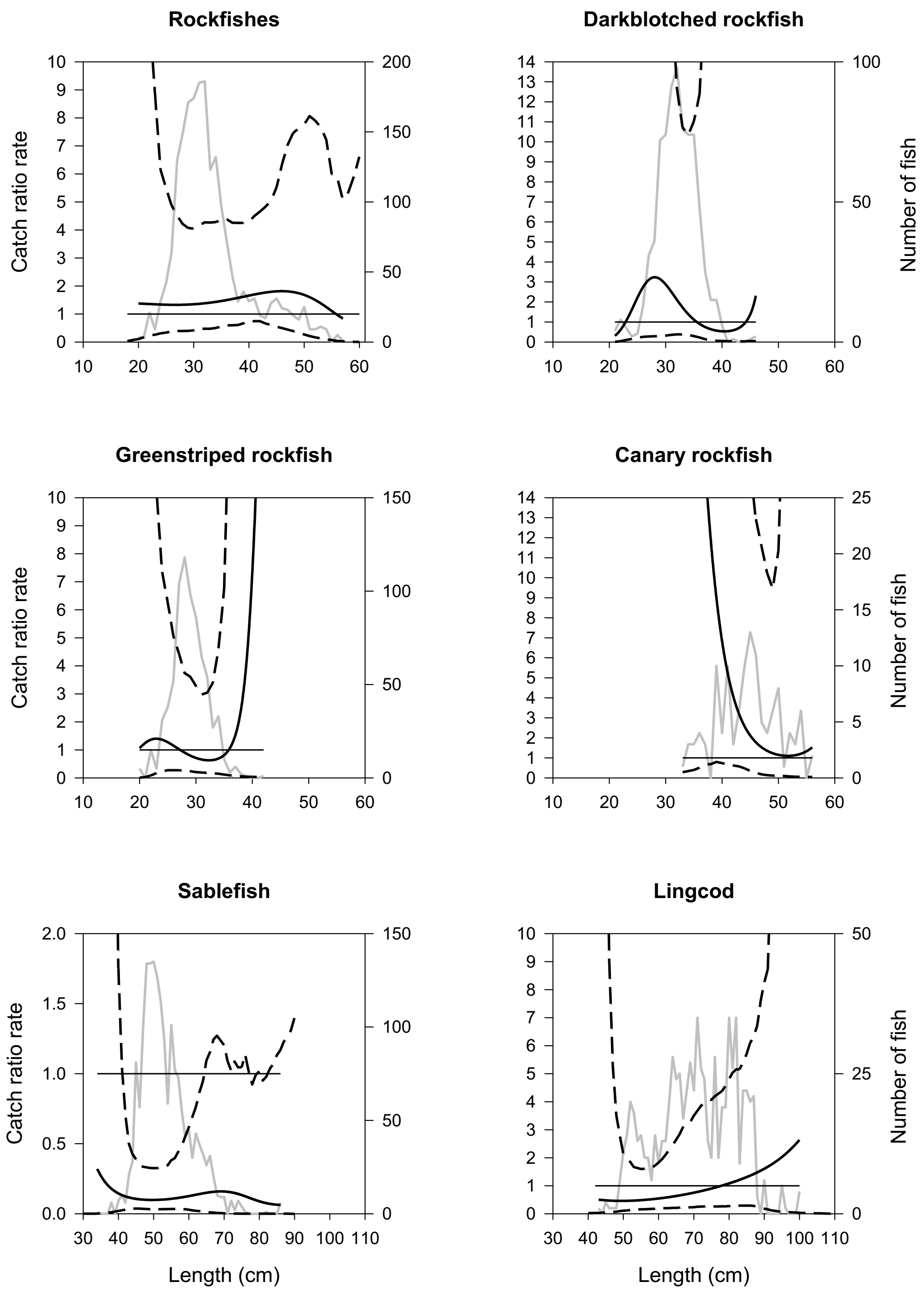

Figure 6. Mean catch ratio rate curves for rockfishes combined (species include rougheye, redbanded, darkblotched, greenstriped, widow, yellowtail, canary, and yelloweye rockfishes, and Pacific ocean perch, chilipepper, and bocaccio), sablefish, and lingcod per size class. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% confidence interval limits; grey lines are number of fish caught; straight lines depict the baseline catch ratio rate of 1.0 indicating equal catch efficiencies between the *treatment* and *control* trawl.

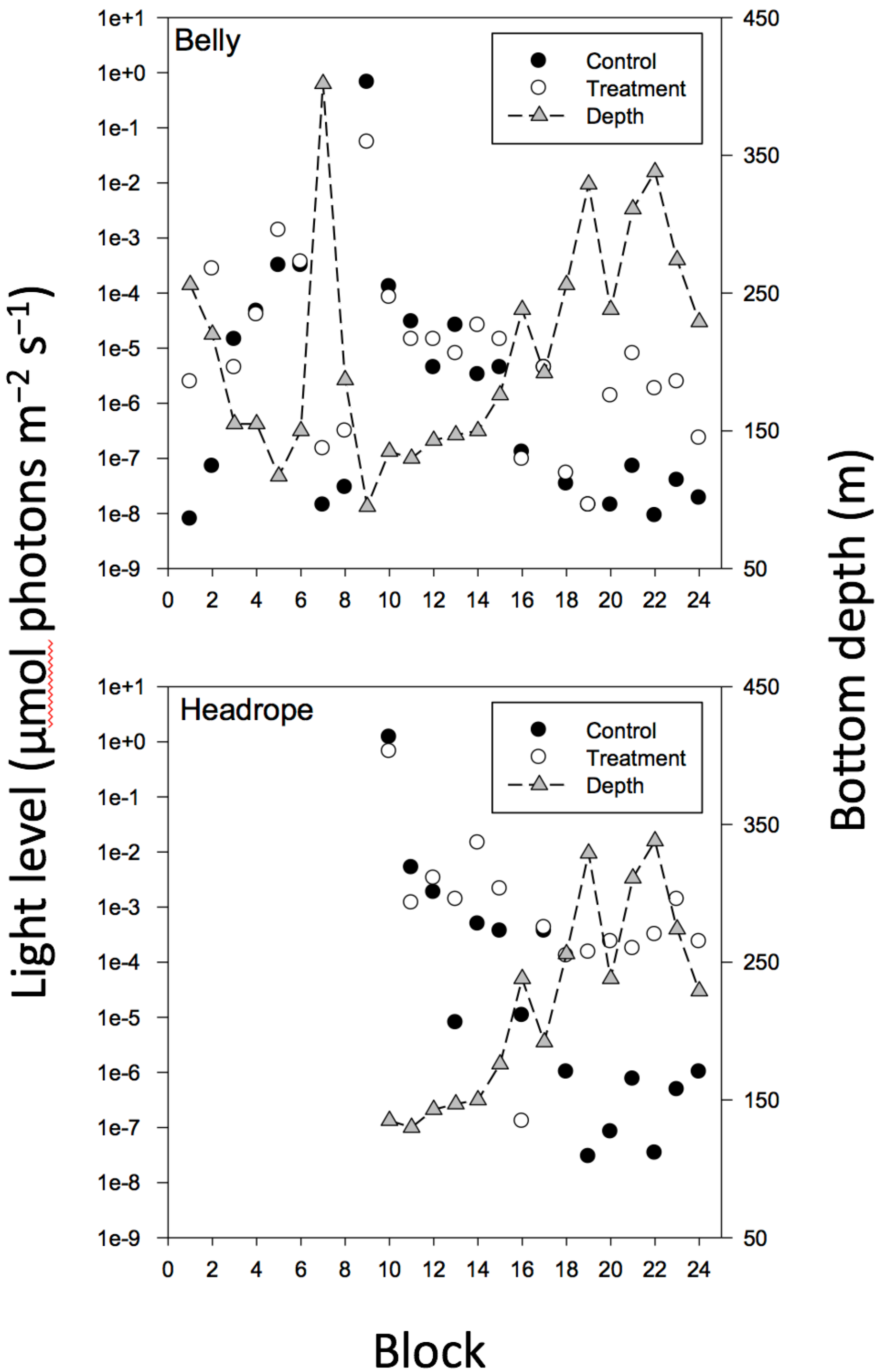

Figure 7. Mean light levels at the center of trawl belly and headrope and mean bottom fishing depths per block. Control = without LEDs; Treatment = with LEDs.