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The Efficacy of Illumination to Reduce Bycatch of Eulachon and Groundfishes Before Trawl Capture in the Eastern North Pacific Ocean Shrimp Fishery

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Abstract

This study examined the extent that eulachon (*Thaleichthys pacificus*) and groundfishes escape trawl entrainment in response to artificial illumination along an ocean shrimp (*Pandalus jordani*) trawl fishing line. Using a double-rigged trawler, we compared the catch efficiencies for ocean shrimp, eulachon, and groundfishes between an unilluminated trawl and a trawl illuminated with 5 green LEDs along its fishing line. Results showed a significant reduction in the bycatch of eulachon and yellowtail rockfish (*Sebastes flavidus*) in the presence of illumination. As eulachon are an Endangered Species Act listed species, this finding provides valuable information for fishery managers implementing recovery plans and evaluating potential fishery impacts on their recovery and conservation. For other rockfishes (*Sebastes* spp.) and flatfishes, however, we did not see the same effect as the illuminated trawl caught similarly or significantly more fishes than the unilluminated trawl. Prior to this research, the extent that eulachon and groundfishes escape trawl capture in response to illumination along an ocean shrimp trawl fishing line was unclear. Our study has provided results to fill that data gap.

1. Introduction

The ocean shrimp (*Pandalus jordani*) fishery is one of the largest trawl fisheries by ex-vessel value off the U.S. West Coast (PacFIN 2018). Semi-pelagic trawls and otter trawls equipped with small mesh codends (35 mm between knots [BK]) are used to harvest ocean shrimp over mud and mud-sand bottom habitats (Hannah et al. 2013). Since 2003, trawls outfitted with sorting grids, similar to the Nordmøre grid, have been required to minimize bycatch of groundfishes such as Pacific hake (*Merluccius productus*), darkblotched rockfish, (*Sebastes crameri*), canary rockfish, (*S. pinniger*), and Pacific halibut (*Hippoglossus stenolepis*). In 2012, sorting grids of 19.1 mm maximum bar spacing became required off Oregon and Washington to reduce eulachon (*Thaleichthys pacificus*) bycatch (Hannah et al. 2011). Prior to this regulation, fishers were using sorting grids with bar spacing ranging from 22.2 to 28.6 mm. In 2018, additional regulations were implemented requiring fishers landing ocean shrimp in Oregon and Washington to use lighting devices (e.g., LEDs) near the trawl fishing line to further reduce eulachon bycatch (ODFW 2018; Lomeli et al. 2018a; WDFW 2018).

In the ocean shrimp trawl fishery, bycatch of eulachon (an anadromous smelt species endemic to the eastern North Pacific) has been an issue facing the fishery as the species' southern Distinct Population Segment (DPS) was listed as "threatened" under the US Endangered Species Act (ESA) in 2010 (DOC 2011; Gustafson et al. 2012). Use of sorting grids with 19.1 mm bar spacing have been shown to be effective at minimizing catches of larger-sized eulachon (>13 cm in length) and adult groundfishes. However, the devices have been less effective at reducing bycatch of smaller-sized eulachon and juvenile groundfishes which can pass through the bar spacings (Hannah et al. 2011). When smaller-sized eulachon are abundant, their bycatch can occur in considerable quantities (Hannah et al. 2105) and impact fishing operations (e.g., sorting time). Consequently, techniques to reduce the bycatch of eulachon and groundfishes such as use of LEDs to illuminate escape areas around the trawls leading edge have recently been tested (Hannah et al. 2015; Lomeli et al. 2018a).

Use of artificial illumination to minimize fish bycatch in trawl fisheries has received considerable attention in recent years. Research has primarily used illumination as a method to enhance fishes' visual perception of trawl gear components and escape areas (Hannah et al. 2015; Larsen et al. 2017, 2018; Lomeli et al. 2018ab; Melli et al. 2018; Lomeli and Wakefield 2019), but also in efforts to startle fish towards selective mesh panels (Grimaldo et al. 2018a). In the ocean shrimp trawl fishery, work has demonstrated that illuminating the trawl fishing line can reduce bycatch of eulachon, and some other fishes, without impacting ocean shrimp catches. Hannah et al. (2015) placed 10 LEDs along the center section of an ocean shrimp trawl fishing line and observed a 91% reduction by weight of eulachon. Significant bycatch reductions of rockfishes (*Sebastes* spp.) and flatfishes were also noted. Following their study, Lomeli et al. (2018a) evaluated how catches of eulachon and other fishes could be affected by altering the quantity of LEDs (e.g., 5 vs 10 vs 20 LEDs) along the fishing line. Results showed each LED configuration caught significantly fewer eulachon than the unilluminated trawl and that the catch ratio of eulachon did not differ significantly from each other between the three LED configurations tested. Rockfish and flatfish catches were significantly reduced across each LED configuration as well. These results guided to fishery managers implementation of an effective footrope lighting regulation in Oregon and Washington (ODFW 2018; WFDW 2018). Although substantial catch reductions were noted in the Hannah et al. (2015) and Lomeli et al. (2018a) studies, data was collected from the residual bycatch of trawls fished with sorting grids with 19.1 mm bar spacing and hindered the authors ability to determine the degree that eulachon across all length classes (and other fishes) are escaping trawl entrainment in response to the illumination. Thus, determining the overall efficacy of LEDs placed along ocean shrimp trawl fishing lines and knowing the degree that eulachon and other fishes escape (or do not escape) trawl entrainment in response to illumination is essential for understanding potential trawl catch impacts (e.g., physical contact with the sorting grids and/or netting, post-release and unobserved mortality, etc.) on non-target species.

The objective of this study was to determine the degree to which eulachon, and other fishes, escape trawl entrainment in response to artificial illumination along an ocean shrimp trawl fishing line.

2. Materials and Methods

2.1. Sea trials and sampling

Sea trials occurred during daylight hours off Oregon (Fig. 1) in 2018 aboard the double-rigged ocean shrimp trawler *F/V Ms. Julie*, a 22.9 m, 400 HP vessel. Our study site (Fig. 1) was selected as it is an area where ocean shrimp are typically fished and eulachon often co-occur. Tow durations were set to 60 min. to avoid catches too large for sorting, weighing, and measuring. In this fishery, commercial tow durations often range between 30 and 180 min.

We used the trawl gear components of the *F/V Ms. Julie* for this study. The port and starboard gear components were identical in material and design. Wood and steel combination doors, 2.4 x 2.7 m (length x height), were used to spread each trawl. The trawl bridles were 19 mm steel cable and totaled 6.1 m in length and connected directly to the trawl doors. The headropes and fishing lines were 27.4 m in length (Fig. 2). Drop chains measuring 0.4 m in length attached the fishing line to the chain ground line at 0.9 m separations. The center 7.3 m section of the trawl groundgear consisted of only drop chains. Both trawls had a codend mesh size of 35 mm BK.

Five Lindgren-Pitman Electralume® green LED fishing lights, centered on a wavelength of 519 nm (Nguyen et al. 2017), were used to illuminate the central trawl fishing line area. While the spectral sensitivity has not been empirically determined for all the species examined in this study, the species that have been examined possess maximal sensitivity to blue-green light, expectedly, as this is the predominant spectral component of coastal waters (Jerlov, 1976; Bowmaker 1990; Britt 2009). Therefore, we selected green LEDs for two reasons: (1) to allow for a comparison of results with the Lomeli et al. (2018a) and Hannah et al. (2015) studies, and (2) this color best matches the ambient light environment encountered in our study area and transmits well through coastal and continental shelf waters. The LEDs were attached to the trawl fishing line using zip ties, with the diodes pointing progressively forward moving towards the trawl wing tips. The LEDs were switched between the port and starboard trawl throughout the study, with one trawl serving as the illuminated and the other as the unilluminated, to control for any trawl specific differences that may occur in the selectivity between the two trawls (Hannah et al. 2011, 2015; Lomeli et al. 2018a). Lastly, fishing occurred with the sorting grids removed from the trawls.

In each trawl, two Wildlife Computers TDR-MK9 archival tags were used to measure the amount of light available and water temperature. The tags were attached to the underside of the net five meshes (35 mm nominal mesh size) behind the midpoint of the fishing line with the light sensor positioned horizontally and looking forward. See Lomeli et al. (2018a) for the calibration function used to convert the MK9 relative light units to irradiance units.

A Sea-Bird Scientific ECO Scattering Sensor (set to a scattering wavelength of 650 nm) was centered on the starboard trawl headrope to measure the amount of backscatter present during our study. This scattering wavelength provides a measurement of the amount of turbid material from non-organic matter in the water. The backscatter value increases with increased turbidity levels. Further, this wavelength was selected as absorption by dissolved organic material is negligible at longer wavelengths such as 650 nm (Pegau et al. 1997). The calibration function used to convert the scattering sensor relative units to meter per steradian ($m^{-1}\ sr^{-1}$) units was:

$$m^{-1}\ sr^{-1} = \textit{scale factor} * (\textit{output} - \textit{dark counts}) \quad (1)$$

where *scale factor* is $3.586e^{-06}$ ($m^{-1}\ sr^{-1}$)/counts, *output* is the relative scattering sensor value, and *dark counts* is 40. The MK9 tags and ECO Scattering Sensor were used to capture the conditions that this study was conducted under. Collecting this data is recommended by the International Council for the Exploration of the Sea to improve comparability of results between light studies (ICES 2018).

Fishing line height (FLH) was measured using Star-Oddi DST tilt sensors (0.05° tilt resolution, ±3° tilt accuracy) attached to the center of the fishing line of each trawl to ensure uniformity between the trawls. Each tag was placed in a customized aluminum bracket outfitted with a rod that extended from the fishing line to the seabed (Lomeli et al. 2018a). The mean tilt angle for the x-axis was converted to height using the following formula:

$$\text{FLH} = y \times \text{SIN}(x) \qquad (2)$$

where y is the length of the bracket (86.4 cm, Lomeli et al. 2018a) and x is the mean tilt angle in the vertical plane perpendicular to the fishing line. Tows where the mean FLH value between the two trawls differed >8.5 cm were not included in the analysis. The vessel was not equipped to measure wing spread or door spread, but we assumed any differences that may occur in these measurements would be minimal and not affect our results as identical trawl components were used.

Overall, 47 paired tows were completed. Five tows were excluded from the analyses due to mean FLH differences of >8.5 cm. After each tow, the catch from the illuminated and unilluminated trawls were dumped into a divided hopper where fish catches were then separately sorted to species as they came across the hopper conveyor belt, weighed, and then measured. Eulachon and rockfishes were measured to fork length, while flatfishes were measured to total length. For ocean shrimp, catches were collected in baskets and then a basket(s) was randomly selected to obtain length samples. From the selected basket(s), a 9.5 L plastic bag was filled with ocean shrimp and frozen for measurement at a laboratory. From this subsample, 100 individuals per net per tow were randomly selected for carapace length measurement.

2.2. Modeling the relative catch efficiency between illuminated and unilluminated trawls

We used the statistical analysis software SELNET (SELection in trawl NETting) to analyze the catch data (Sistiaga et al. 2010; Herrmann et al. 2012, 2016) and conducted length-dependent catch comparison and catch ratio analyses (Lomeli et al. 2018ab, 2019).

Using the catch information (Table 1) we wanted to determine whether there was a significant difference in catch efficiency between the unilluminated and illuminated trawl. We also wanted to determine if a potential difference between the trawls could be related to the size of ocean shrimp or a given species of fish. Specifically, to assess the relative length-dependent catch efficiency effect of changing from unilluminated to illuminated trawl, we used the method described in Herrmann et al. (2017) based on comparing the catch data between the two trawls. This method models the length-dependent catch comparison rate (CC_l) summed over tows:

$$CC_l = \frac{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}+\frac{nc_{lj}}{qc_j}\right\}} \quad (3)$$

where nc_{lj} and nt_{lj} are the numbers of ocean shrimp or a given species of fish measured in each length class l for the unilluminated and illuminated trawl in tow j, respectively. Parameters qc_j and qt_j are the related subsampling factors (fraction of the ocean shrimp or a given species of fish caught being length measured), and m is the number of tows carried out with the unilluminated and illuminated trawl. As is common practice for fishing gear catch comparison investigations a functional form $CC(l,\mathbf{v})$ for the catch comparison rate was estimated from the experimental data (Grimaldo et al. 2018b; Karlsen et al. 2018; Lomeli et al. 2018a). The functional form provides a smooth curve for length dependency that is less influenced by the observation error for individual length classes than the experimental being expressed by equation 3 and it enables to interpolate over length classes with no experimental observations. The functional form of the catch comparison rate was obtained using maximum likelihood estimation by minimizing the following equation:

$$-\sum_{l}\left\{\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j}\times ln[1.0-CC(l,\boldsymbol{v})]\right\}+\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\times ln[CC(l,\boldsymbol{v})]\right\}\right\} \qquad (4)$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\boldsymbol{v})$. The outer summation in the equation is the summation over the length classes l. When the catch efficiency of the unilluminated and illuminated trawl are equal, the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge if there is a difference in catch efficiency between the two trawls. The experimental CC_l was modeled by the function $CC(l,\boldsymbol{v})$, on the following form:

$$CC(l,\boldsymbol{v})=\frac{exp[f(l,v_0,\ldots,v_k)]}{1+exp[f(l,v_0,\ldots,v_k)]} \qquad (5)$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\boldsymbol{v}$ describing $CC(l,\boldsymbol{v})$ are estimated by minimizing equation 4, which is equivalent to maximizing the likelihood of the experimental data. We considered f of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4 as our experience from former studies including Krag et al. (2015) Santos et al. (2016) and Sistiaga et al. (2018) have shown that this provides a model that is sufficiently flexible to describe the catch comparison curves between fishing gears well in the cases examined. 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 $CC(l,\boldsymbol{v})$. 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). Specifically, the models were ranked and weighed in the estimation according to their AICc values (Burnham and Anderson 2002). The AICc is calculated as the AIC (Akaike, 1974), but it includes a correction for finite sample sizes in the data. Models that resulted in AICc values within +10 of the value of the model with lowest AICc value ($AICc_{min}$) were considered for the estimation of *cc(l,**v**)* following the procedure described in Katsanevakis (2006) and in Herrmann et al. (2015). We use the name combined model for the result of this multi-model averaging and calculated it by:

$$cc(l,\boldsymbol{v}) = \sum_i w_i \times cc(l,\boldsymbol{v}_i) \quad with \quad w_i = \frac{exp(0.5 \times (AICc_i - AICc_{min}))}{\sum_j exp(0.5 \times (AICc_j - AICc_{min}))} \qquad (6)$$

where the summations are over the models with an AICc value within +10 of $AICc_{min}$.

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 (D) and the degrees of freedom (DF), should be >0.05. Specifically, D has approximate χ^2 distribution when the model is correct and the p-value is therefore calculated for a χ^2 distribution with D and DF as parameters (Wileman et al. 1996). For DF we use the number of length classes in the experimental data minus the number of parameters $\boldsymbol{v}$ in the model $cc(l,\boldsymbol{v})$. However, lack of fit as indicated by large D compared to DF which corresponds to p-value < 0.05 does not necessarily imply that the fitted combined catch comparison curve is not a good model for the length dependent catch comparison data (Wileman et al. 1996). If a plot of deviance residuals D_l versus length l shows no clear structure then the lack of fit can be assumed to be due to over-dispersion in the data (McCullagh and Nelder 1989). Therefore, in case of p-value < 0.05 we checked deviance residuals which for individual length classes is calculated by:

$$D_l = 2 \times sign(y_l - ym_l) \times \sum_l \left\{ nt_l \times ln\left(\frac{y_l}{ym_l}\right) + nc_l \times ln\left(\frac{1-y_l}{1-ym_l}\right) \right\} \quad (7),$$

where

$$
\begin{aligned}
y_l &= \frac{nt_l}{nt_l + nc_l} \\
ym_l &= \frac{qt_l \times cc(l,\boldsymbol{v})}{qt_l \times cc(l,\boldsymbol{v}) + qc_l \times (1 - cc(l,\boldsymbol{v}))} \\
nt_l &= \sum_{j=1}^{m} nt_{lj} \\
nc_l &= \sum_{j=1}^{m} nc_{lj} \\
qt_l &= \frac{nt_l}{\sum_{j=1}^{m} \left\{ \frac{nt_{lj}}{qt_j} \right\}} \\
qc_l &= \frac{nc_l}{\sum_{j=1}^{m} \left\{ \frac{nc_{lj}}{qc_j} \right\}}
\end{aligned} \qquad (8)
$$

The model deviance is based on equation 7 calculated by (Wileman et al 1996):

$$D = \sum_l D_l^2 \qquad (9)$$

Based on the estimated combined catch comparison function *CC(l,**v**)*, we obtained the relative catch ratio *CR(l,**v**)* between fishing with the two trawls by the general relationship:

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{[1 - CC(l,\boldsymbol{v})]} \qquad (10)$$

The catch ratio provides a direct relative value of the catch efficiency between fishing with and without illumination. Thus, if the catch efficiency of both trawls is equal, *CR(l,**v**)* should always be 1.0.

The 95% confidence interval (CI) limits for the catch comparison and catch ratio curves were estimated using a double bootstrapping method for paired trawl catch data in SELNET. The bootstrapping method accounts for uncertainty due to between haul variation by selecting *m* hauls with replacement from the *m* hauls available during each bootstrap repetition (equation 4). Within each resampled haul, the data for each length class were resampled in an inner bootstrap to account for the uncertainty in estimation of the catch comparison and catch ratio rates in the haul resulting from that only a limited number of ocean shrimp or a given species of fish were caught, and length measured in the specific haul. The inner resampling of the data in each length class were performed prior to the raising of the data with subsampling factors qc_j and qt_j to account for the additional uncertainty due to the subsampling (Eigaard et al. 2012). The resulting data set obtained from each bootstrap repetition was analyzed as described above and therefore also accounted for uncertainty in model selection and model averaging because the multimodel inference was included (Grimaldo et al. 2018a). Based on the bootstrap results we estimated the Efron percentile 95% confidence intervals (Efron 1982) for both the catch comparison and catch ratio curve. We performed 1,000 bootstrap repetitions.

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

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \left\{ \frac{nt_{lj}}{qt_j} \right\}}{\sum_l \sum_{j=1}^{m} \left\{ \frac{nc_{lj}}{qc_{lj}} \right\}} \qquad (11)$$

where the outer summation covers the length classes in the catch during the experimental fishing period. Based on equation 11, the percent change in average catch efficiency between fishing with the unilluminated trawl to the illuminated trawl was estimated by:

$$\Delta CR_{average} = 100 \times (CR_{average} - 1.0) \qquad (12)$$

We used $\Delta CR_{average}$ to provide a length-averaged value for the effect of changing from unilluminated to illuminated trawl on the catch efficiency. When the percent change in catch efficiency of both trawls is equal, the expected value would be zero. The uncertainties for $CR_{average}$ and $\Delta CR_{average}$ were obtained by including their calculation according to equation 11 and 12 into the bootstrap procedure described above.

2.3. *Modeling the effect of artificial illumination level and backscatter value on catch comparison*

We performed regression analyses on tow data using the statistical software JMP® (version 14.2.0) to examine if $CC_{average}$ changed linearly with level of artificial illumination and degree of backscatter for ocean shrimp or a given species of fish. Linear regression was used to model level of artificial illumination and degree of backscatter against $CC_{average}$ as single model parameters, while a multiple regression model was used with level of artificial illumination and degree of backscatter as combined model parameters. Light level and backscatter values were log-transformed to achieve normality of model residuals. Because the regression analyses were performed on tow data, we were unable to use $CR_{average}$ as the response variable as some tows had zero catch in the control trawl (unilluminated trawl).

3. Results

3.1. *Sampling conditions*

Towing occurred at bottom fishing depths averaging 166 m (SE ±1.4). Towing speed ranged from 3.3 to 3.5 km h^{-1} (1.8–1.9 knots). The mean ambient light level measured in the unilluminated trawl was $2.4e^{-05}$ ($\pm 1.0e^{-06}$) µmol photons m^{-2} s^{-1}. In the illuminated trawl, the mean light level measured increased to $3.2e^{-02}$ ($\pm 8.4e^{-04}$) µmol photons m^{-2} s^{-1}. Mean light levels per tow for the unilluminated and illuminated trawl are shown in Figure 3. The mean temperature was 8.4^{o}C (±0.02) and ranged from 8.0-8.7^{o}C. The mean backscatter value was $1.66e^{-03}$ (SE $\pm 9.13e^{-06}$) m^{-1} sr^{-1}. Figure S1 in the Supplementary material shows the mean backscatter value per tow. The mean FLH for the port trawl was 25.8 cm (SE ±0.10) while the starboard trawl was 27.6 cm (±0.09). The mean FLH for the illuminated trawl was 26.1 cm (±0.09) while the unilluminated trawl was 27.2 cm (±0.09). Figure S2 in the Supplementary material shows the mean FLH per tow for the port and starboard trawl.

3.2. *Relative catch efficiency between illuminated and unilluminated trawls*

The change in average catch efficiency of ocean shrimp did not differ significantly between the illuminated and unilluminated trawl (Fig. 4). Further, the catch comparison and catch ratio analyses detected no significant length-dependent catch efficiency effect of changing from unilluminated to illuminated trawl for ocean shrimp as indicated by the mean $CC(l,\mathbf{v})$ and $CR(l,\mathbf{v})$ 95% CIs extended above and below the $CC(l,\mathbf{v})$ rate of 0.5 and $CR(l,\mathbf{v})$ ratio of 1.0. (Figs. 5 and S3).

Eulachon 12.5-16.5 cm in length comprised 94% of the total eulachon catch by numbers. Over this size range, a significant difference in catch efficiency occurred (Fig. 5) with the illuminated trawl catching on average only 33% of the number of eulachon compared to the unilluminated trawl (Fig. S3). For yellowtail rockfish (*S. flavidus*), a similar effect was observed with the illuminated trawl catching significantly fewer fish 43.5-61.5 cm in length than to the unilluminated trawl (Fig. 6). Over these lengths, the illuminated trawl caught on average only 37% of the number of yellowtail rockfish compared to the unilluminated trawl (Fig. S4). In terms of change in average catch efficiency, results show the unilluminated trawl caught significantly more eulachon (66%) than the illuminated trawl (Fig. 4). For yellowtail rockfish, the change in average catch efficiency showed the illuminated trawl caught on average 51% more fish than the unilluminated trawl. This result was significant, however, moderate in effect as the mean $\Delta CR_{average}$ 95% CIs nearly extended above and below the $\Delta CR_{average}$ ratio of zero (Fig. 4).

In contrast to eulachon and yellowtail rockfish, the catch comparison and catch ratio analysis show the illuminated trawl caught significantly more stripetail rockfish (*S. saxicola*) (8.5-16.5 cm in length), other rockfishes (11.5-34.5 cm in length), arrowtooth flounder (*Atheresthes stomias*) (across all lengths), slender sole (*Lyopsetta exilis*) (13.5-27.5 cm in length), and other flatfishes (8.5-37.5 cm in length) than the unilluminated trawl (Figs. 6 and 7). Over these size classes, the illuminated trawl on average caught 3.6, 3.5, 2.8, 4.4, and 2.7 times more stripetail rockfish, other rockfishes, arrowtooth flounder, slender sole, and other flatfishes, respectively, than the unilluminated trawl (Figs. S4-S5). When evaluating the change in average catch efficiency (a length-averaged value), the same effect was noted with the illuminated trawl catching significantly more stripetail rockfish and flatfishes than to the unilluminated trawl (Fig. 4). For other rockfishes, the illuminated trawl on average caught 59% more fish than the unilluminated trawl, however, this change in average catch efficiency did not differ significantly from the unilluminated trawl (Fig. 4). The catch efficiency analyses (e.g., $CC(l,\mathbf{v})$, $CR(l,\mathbf{v})$, and $\Delta CR_{average}$) for darkblotched rockfish detected no significant difference in catch efficiencies between the illuminated and unilluminated trawl (Figs. 6 and S4).

With the exception to ocean shrimp, the combined $CC(l,\mathbf{v})$ models described the experimental data well for the species we evaluated as demonstrated by the fit statistics *p*-values >0.05 and the deviances within times of the degrees of freedom values (Table 2). For ocean shrimp, inspecting the fit between the experimental catch comparison data and the modeled mean curve for these species indicated the poor fit statistics were due to overdispersion of the data rather than the model's inability to adequately describe the data.

3.3. *Effect of artificial illumination level and backscatter value on catch comparison*

The regression analyses results showed $CC_{average}$ did not changed linearly with level of artificial illumination for ocean shrimp or a given species of fish (Table 3, Fig. 8, Supplementary Figs. S6-S9). For the degree of backscatter, the linear regression analysis showed this parameter effected the $CC_{average}$ for only ocean shrimp and arrowtooth flounder (Table 3, Supplementary Figs. S6-S9) with $CC_{average}$ decreasing as the degree of backscatter increased (Fig. 8). However, these results were moderate in effect. In the multiple regression analysis, results showed the degree of backscatter effected the $CC_{average}$ for only ocean shrimp (Table 4). This result was also moderate in effect.

4. Discussion

To determine the extent that eulachon and other fishes escape trawl entrainment in response to illumination along the trawl fishing line, we compared the catch efficiency between two simultaneously fished ocean shrimp trawls (one illuminated and the other unilluminated) without sorting grids installed. Our analyses showed eulachon (and yellowtail rockfish) escaped trawl capture in significant numbers when the fishing line was illuminated. As eulachon are an ESA-listed species, this finding provides critical information for fishery managers implementing ESA recovery plans and evaluating potential fishery impacts on their recovery and conservation (NMFS 2017). The clear reduction in eulachon bycatch before trawl capture in trawls outfitted with LEDs translates to significantly fewer fish exposed to capture-escape processes within the trawl. These processes can cause physiological stress, fatigue, injuries (from contact with sorting grids, webbing, and/or other fishes, etc.) and lead to unobserved and unaccounted post-release mortality (Chopin and Arimoto 1995; Davis and Olla 2001, 2002; Ryer 2004; Davis 2005). Depending on its magnitude, a reduction in eulachon bycatch mortality could have significant conservation benefits.

We found using illumination along the trawl fishing line significantly affected the catch rates of eulachon and several groundfishes, without impacting ocean shrimp catches. However, the effect was not consistent across species. Our data continues to support the hypothesis that there is a significant reduction in eulachon bycatch when artificial illumination is present. Research has shown that vision plays a major role in how fish respond to trawl gear (under conditions without artificial illumination present) (Glass and Wardle 1989; Olla et al. 1997, 2000; Kim and Wardle 1998, 2003; Ryer et al. 2000, 2010; Ryer and Barnett, 2006; Arimoto et al. 2010). However, it remains unknown whether eulachon's response is positive (moving towards), negative (moving away), or neutral (the presence of illumination simply allows them to perceive the trawl gear components and escape capture). Research on phototaxis and visual cues in eulachon is required to understand the behavioral response affecting their catch rates. For rockfishes and flatfishes, our results suggest their ability to escape trawl entrainment in response to illumination along the fishing line is not as strong as previously indicated (Hannah et al. 2015; Lomeli et al. 2018a). Compared to the unilluminated trawl, we found the illuminated trawl caught significantly more stripetail rockfish and flatfishes. The illuminated trawl also caught more darkblotched rockfish and other rockfishes (except yellowtail rockfish), but not at a significant level. These results differ from prior studies (which included the use of sorting grids) that demonstrated the ability to significantly reduce bycatch of those same species with the addition of illumination along the fishing line (Hannah et al. 2015; Lomeli et al. 2018a). It should also be mentioned, that the trawls used in the current study differed from the prior studies in that the central portion of the groundgear consisted of just drop chains as opposed to a continuous ground line (Hannah et al. 2011). This complicates our ability to further understand the efficacy of illumination along trawl fishing lines as trawls with central ground line sections removed have been shown to reduce the overall level of bycatch compared to trawls with continuous ground lines (Hannah and Jones, 2003; Hannah et al., 2011). In the ocean shrimp fishery, both groundgear configurations described above are commonly used. Further research investigating how changes in groundgear configuration may affect the efficacy of illumination along ocean shrimp trawl fishing lines is needed.

While the presence of artificial illumination was found to have a significant effect on the catch efficiency for eulachon, yellowtail and stripetail rockfishes, arrowtooth flounder, slender sole, and other flatfishes, our regression analyses showed the level of artificial illumination itself had no effect on the average catch comparison rate for ocean shrimp or a given species of fish. However, the linear regression analysis did show that degree of backscatter had a moderate effect (p=0.04) on the average catch comparison rate for ocean shrimp and arrowtooth flounder. For these two species, the catch efficiency analyses showed the illuminated trawl caught more individuals than the unilluminated trawl. This result was significant for arrowtooth flounder (across all size classes), but not significant for ocean shrimp. In the linear regression analysis, results showed the average catch comparison rate for ocean shrimp and arrowtooth flounder decreased towards 0.5 (which would indicate equal catch efficiency between the two trawls) as degree of backscatter increased towards 3.0 m^{-1} sr^{-1}. These findings make logical sense in terms that increased levels of backscatter (e.g., increased turbidity) would reduce the attenuation of light and either hinder a fishes or shrimps ability to perceive the illumination itself or the distance that a fish or shrimp can perceive and respond to the illumination; which could influence the effectiveness of the illumination. Why this result was only noted for ocean shrimp and arrowtooth flounder is unclear, but differences in their spectral sensitivity compared to the other species could be one plausible explanation. Lastly, as this research occurred under conditions representative of conditions fished by ocean shrimp fishers, our catch efficiency results reflect what would occur under normal fishing conditions with LEDs attached along the trawl fishing line.

In the U.S. West Coast groundfish bottom trawl fishery, Lomeli et al. (2018b) found illuminating the headrope of a low-rise selective flatfish trawl with LEDs tended to increase rockfish catches (i.e., darkblotched, greenstriped [*S. elongatus*], and canary rockfishes). For flatfishes, catch trends varied between species with the illuminated trawl catching on average more English sole (*Parophrys vetulus*) and petrale sole (*Eopsetta jordani*), but fewer rex sole (*Glyptocephalus zachirus*), arrowtooth flounder, and Dover sole (*Microstomus pacificus*). Catch trends from that previous study have some similarities to our current results. While our work and the prior studies presented above are not directly comparable to each other, they collectively present that specific species behavioral response to illumination stimuli can be widely variable (with perhaps the exception to eulachon). Results from our study suggest that factors beyond vision (i.e., size [Melli et al. 2018], innate behavior [Grimaldo et al. 2018a], fish density, fatigue, stress, time of day, placement of illumination [Hannah et al. 2015], groundgear configuration, etc.) may have a considerable effect on how some fishes respond to illumination on trawl gear. How these factors influence fishes behavioral response to illumination, however, is not well understood and requires further research.

Bycatch reduction research and implementation of findings have been key to the success of ocean shrimp management. In 2003, ocean shrimp trawls outfitted with sorting grids became mandatory to reduce canary rockfish bycatch (a stock declared overfished at that time). In 2016, the canary rockfish stock was declared fully rebuilt, and had been since 2006 (Thorson and Wetzel 2016). Further, because earlier studies (Hannah et al. 2015; Lomeli et al. 2018a) in the fishery have shown use of illumination along the trawl fishing line can result in codend catches comprised mainly of ocean shrimp, some may question whether the sorting grid requirement is still necessary (due to handling and safety concerns, loss of target catch that can occur at times, and the recovery of canary rockfish). Results from our study clearly demonstrate that sorting grids are still necessary as our study noted the illuminated trawl caught several size classes of fishes that the sorting grids would have released if present.

Prior to this study, the degree that fishes escaped trawl capture in response to illumination along an ocean shrimp trawl fishing line was unclear. Our research has provided results to help fill that data gap. For eulachon and yellowtail rockfish, we found they escaped trawl entrainment in significant numbers in response to illumination along the fishing line. As conservation of ESA-listed eulachon is an ongoing management priority, our research contributes new data on the efficacy of footrope illumination to reduce their bycatch before trawl capture. For other species, however, we did not see the same effect as the illuminated trawl caught similarly or significantly more fishes than the unilluminated trawl. These findings demonstrate that some fishes ability to escape trawl entrainment in response to illumination along the fishing line is not as strong as previous research (which included sorting grids) has suggested and that the combined use of footrope illumination and sorting grids (as is required in Oregon and Washington fisheries) is the most effective means for reducing bycatch across a larger suite of species and sizes. Further, our research shows that use of footrope illumination to reduce bycatch is a much more complex process than simply enhancing fishes' visual perception of trawl gear components and escape areas. Lastly, while our results have regional impacts, our study findings could provide useful information to other shrimp/prawn trawl fisheries internationally; for example, the ocean shrimp trawl fishery off British Columbia, Canada where fishers have requested management to allow use of illumination to reduce eulachon bycatch (DFO 2018), and northern prawn (*P. borealis*) trawl fisheries in the Northern Atlantic where illumination has been tested as a bycatch reduction technique for marine fishes (Larsen et al. 2017, 2018).

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Table 1. Length data used for the catch comparison and catch ratio analyses. Values in parentheses are the length measurement subsample ratio from the total catch. Other rockfishes include widow (*Sebastes entomelas*, n=2), shortbelly (*S. jordani*, n=7), greenstriped (*S. elongatus*, n=114), splitnose (*S. diploproa*, n=62), redstripe (*S. proriger*, n=1), and canary (*S. pinniger*, n=140) rockfishes, chilipepper (*S. goodei*, n=5) and cowcod (*S. levis*, n=4); Other flatfishes include Pacific sanddab (*Citharichthys sordidus,* n=4), rex sole (*Glyptocephalus zachirus,* n=195), Dover sole (*Microstomus pacificus*, n=127), flathead sole (*Hippoglossoides elassodon*, n=49), petrale sole (*Eopsetta jordani*, n=7).

	No. measured	
Species	Illuminated trawl	Unilluminated trawl
Ocean shrimp	4,000 (0.002)	4,000 (0.002)
Eulachon	119 (1.0)	358 (1.0)
Darkblotched rockfish	182 (1.0)	167 (1.0)
Yellowtail rockfish	176 (1.0)	270 (0.75)
Stripetail rockfish	560 (1.0)	191 (1.0)
Other rockfishes	206 (1.0)	129 (1.0)
Arrowtooth flounder	664 (1.0)	236 (1.0)
Slender sole	492 (0.86)	147 (1.0)
Other flatfishes	253 (1.0)	129 (1.0)

Table 2. Catch comparison curve fit statistics. See Table 1 for the species included in other rockfishes and other flatfishes.

Species	*p*-value	Deviance	Degrees of freedom
Ocean shrimp	< 0.0001	76.0	9
Eulachon	0.3740	10.8	10
Darkblotched rockfish	0.2295	26.5	22
Yellowtail rockfish	0.3257	21.2	19
Stripetail rockfish	0.8762	9.0	15
Other rockfishes	0.1246	63.9	52
Arrowtooth flounder	0.4695	38.0	38
Slender sole	0.7170	12.4	16
Other flatfishes	0.3403	31.5	29

Table 3. Fit statistics for linear regression model ($CC_{average} = \beta_0 + \beta_1 x_1 + e$) examining if $CC_{average}$ changed linearly with level of artificial illumination or degree of backscatter as single model effects. See Table 1 for the species included in other rockfishes and other flatfishes.

	Model parameter: Level of artificial illumination			Model parameter: Degree of backscatter		
Species	Estimate (95% CIs)	*p*-value	R^2	Estimate (95% CIs)	*p*-value	R^2
Ocean shrimp	0.0079 (-0.0142 – 0.0301)	0.4718	0.01	-0.2098 (-0.4083 - -0.0114)	0.0388	0.11
Eulachon	0.0069 (-0.0737 – 0.0877)	0.8585	<0.01	-0.1201 (-1.0393 – 0.7990)	0.7879	<0.01
Darkblotched rockfish	0.0014 (-0.0844 – 0.0871)	0.9746	<0.01	0.0741 (-0.7427 – 0.8909)	0.8550	<0.01
Yellowtail rockfish	0.1179 (-0.2215 – 0.4573)	0.4127	0.14	-1.5314 (-3.2733 – 0.2105)	0.0734	0.51
Stripetail rockfish	0.0550 (-0.0320 – 0.1420	0.2026	0.08	-0.7045 (-1.5715 – 0.1625)	0.1059	0.12
Other rockfishes	0.0772 (-0.0470 – 0.2015)	0.2038	0.11	0.1343 (-1.3149 – 1.5835)	0.8453	<0.01
Arrowtooth flounder	0.0234 (-0.0172 – 0.6400)	0.2503	0.03	-0.4172 (-0.8037 - -0.0307)	0.0351	0.11
Slender sole	0.0151 (-0.0723 – 0.1024)	0.7262	<0.01	0.0701 (-0.7858 – 0.9260)	0.8678	<0.01
Other flatfishes	-0.0021 (-0.0665 – 0.0622)	0.9459	<0.01	-0.4211 (-1.0898 – 0.2476)	0.2069	0.06

Table 4. Fit statistics for the multiple regression model ($CC_{average} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + e$) examining if $CC_{average}$ changed linearly with level of artificial illumination and degree of backscatter and model parameters. See Table 1 for the species included in other rockfishes and other flatfishes.

	Model parameters				Whole model	
	Level of illumination		Degree of backscatter			
Species	Estimate (95% CIs)	*p*-value	Estimate (95% CIs)	*p*-value	R^2	Model *p*-value
Ocean shrimp	-0.0077 (-0.0338 – 0.0185)	0.5568	-0.2520 (-0.4989 - -0.0051)	0.0457	0.12	0.1023
Eulachon	0.0067 (-0.0763 – 0.0896)	0.8680	-0.1179 (-1.0638 – 0.8280)	0.7971	0.01	0.9518
Darkblotched rockfish	0.0053 (-0.0897 – 0.1004)	0.9102	0.0943 (-0.8106 – 0.9992)	0.8335	<0.01	0.9773
Yellowtail rockfish	0.1140 (-0.1531 – 0.3811)	0.3018	-1.5178 (-3.3280 – 0.2924	0.0804	0.63	0.1341
Stripetail rockfish	0.0166 (-0.0996 – 0.1328)	0.7688	-0.5922 (-1.7789 – 0.5945)	0.3103	0.12	0.2674
Other rockfishes	0.1054 (-0.0364 – 0.2473)	0.1324	0.6710 (-0.8899 – 2.2319)	0.3700	0.17	0.3029
Arrowtooth flounder	0.0054 (-0.0389 – 0.0497)	0.8071	-0.3928 (-0.8328 – 0.0472)	0.0786	0.11	0.1086
Slender sole	0.0203 (-0.0752 – 0.1158)	0.6653	0.1421 (-0.7919 – 1.0761)	0.7570	0.01	0.8968
Other flatfishes	-0.0158 (-0.0826 – 0.0509)	0.6292	-0.4737 (-1.1890 – 0.2416)	0.1847	0.07	0.4068

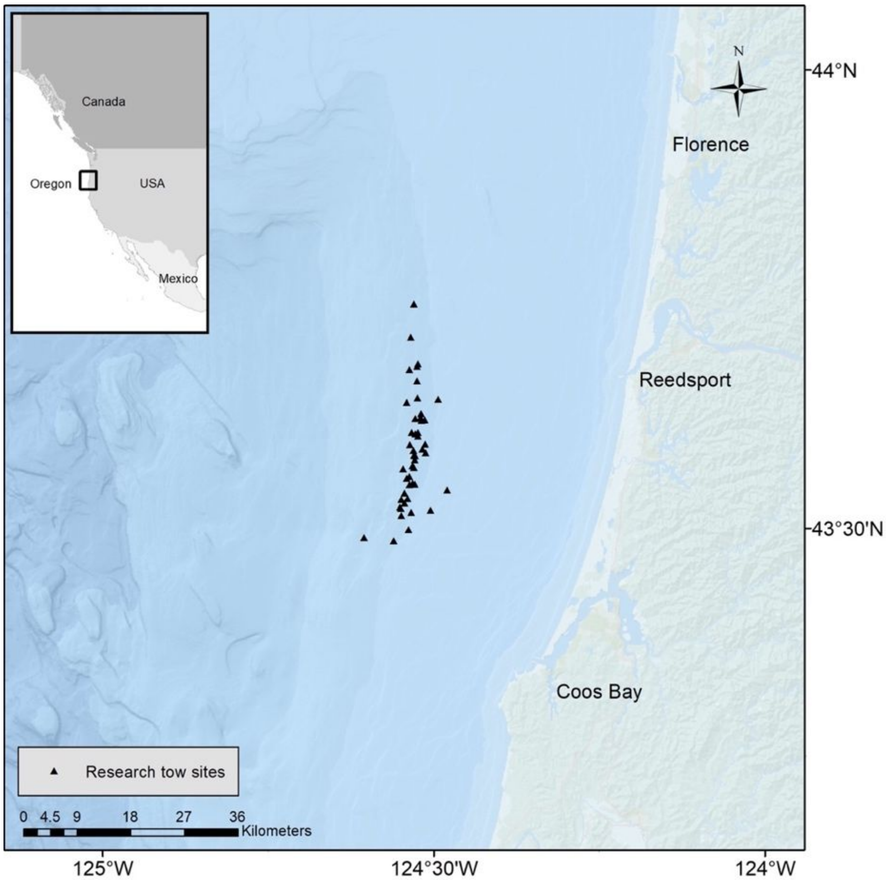

Figure 1. Map of the area off the Oregon coast where sea trials were conducted.

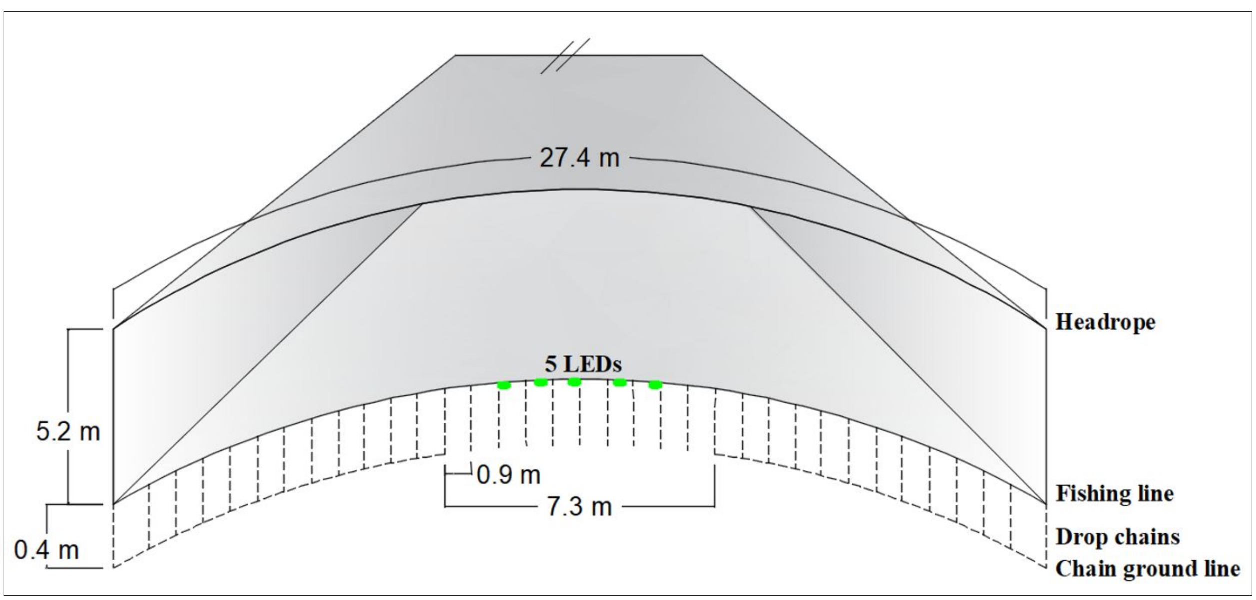

Figure 2. Schematic diagram of an ocean shrimp trawl and placement of LEDs along the trawl fishing line. Note: diagram not to scale.

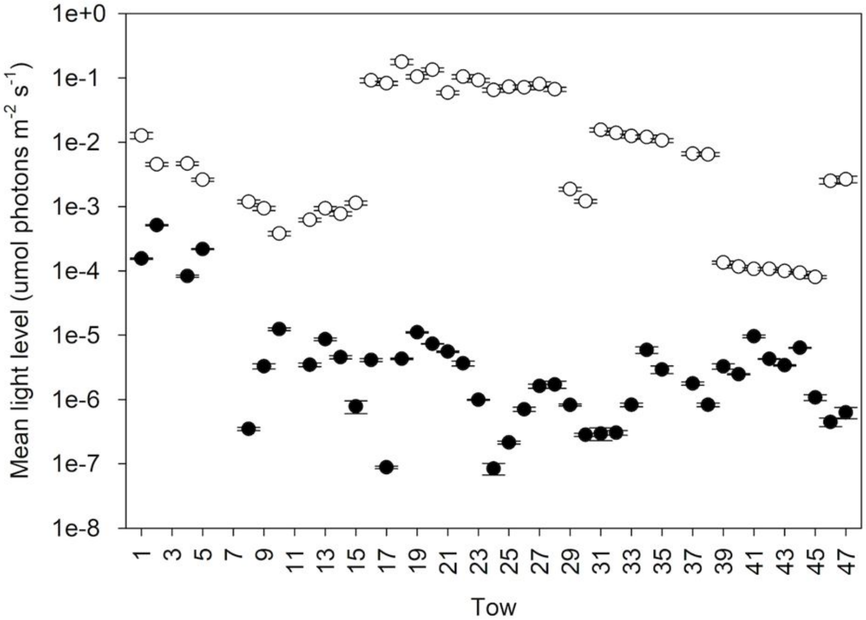

Figure 3. Mean light level measured at the center of the fishing line for the unilluminated trawl (closed circles) and illuminated trawl (open circles) per tow. ± bars are standard errors (n = 50 measurements per net per tow).

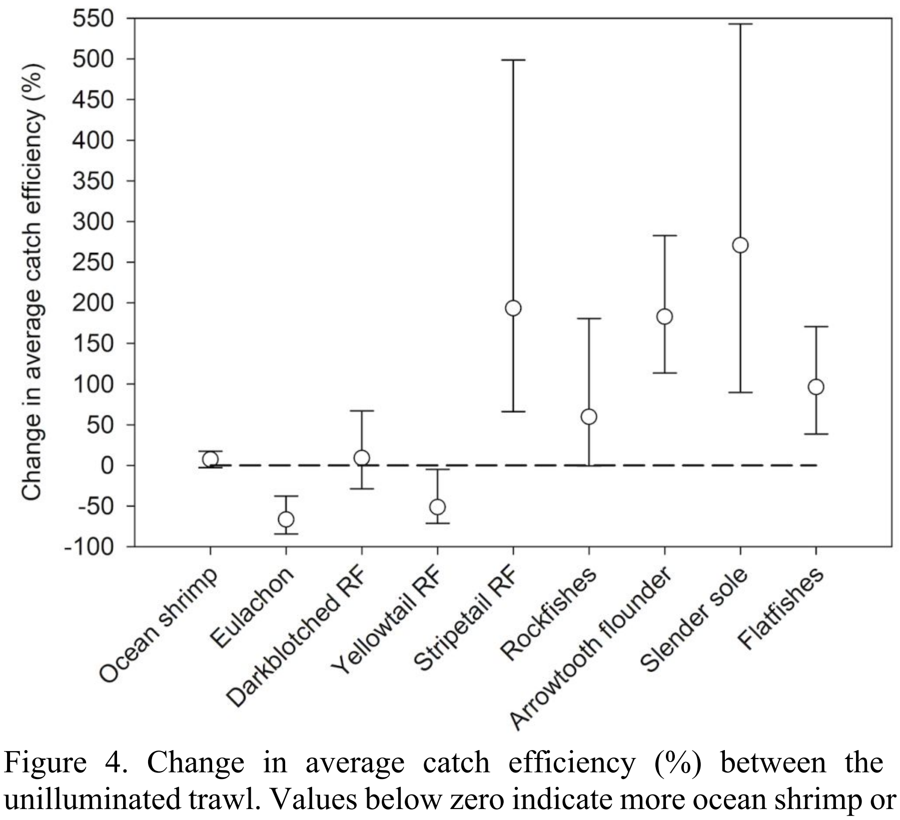

Figure 4. Change in average catch efficiency (%) between the illuminated trawl and the unilluminated trawl. Values below zero indicate more ocean shrimp or a given species of fish were caught in the unilluminated trawl, and vice versa for values above zero. ± bars are 95% CIs; RF = rockfish. See Table 1 for the species included in rockfishes and flatfishes.

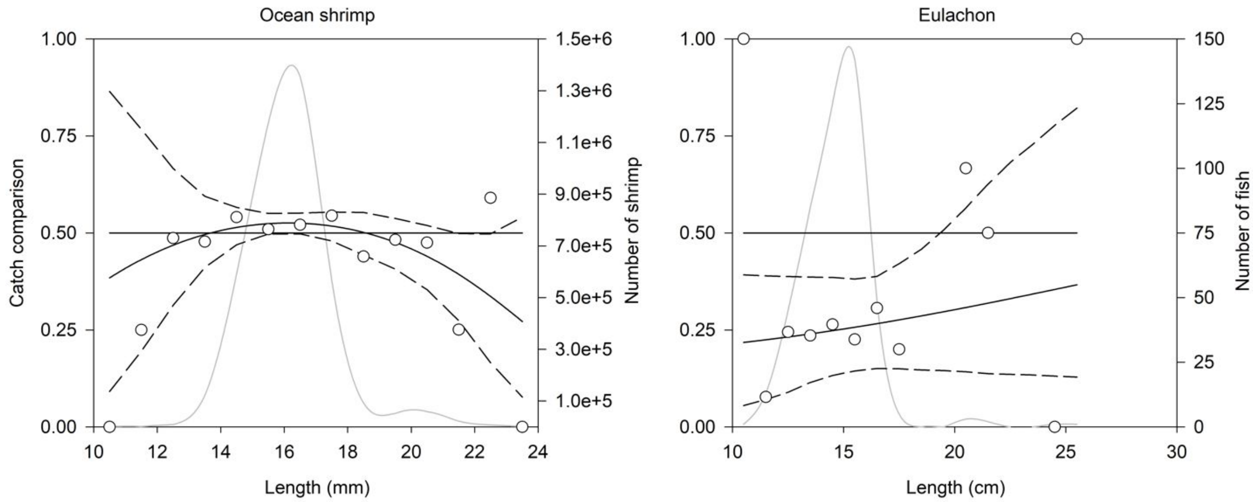

Figure 5. Mean catch comparison curves for ocean shrimp and eulachon between the unilluminated trawl and illuminated trawl. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% CIs; grey lines are number of ocean shrimp and eulachon caught; straight lines depict the baseline catch comparison rate of 0.5 indicating equal catch rates between the illuminated and unilluminated trawl.

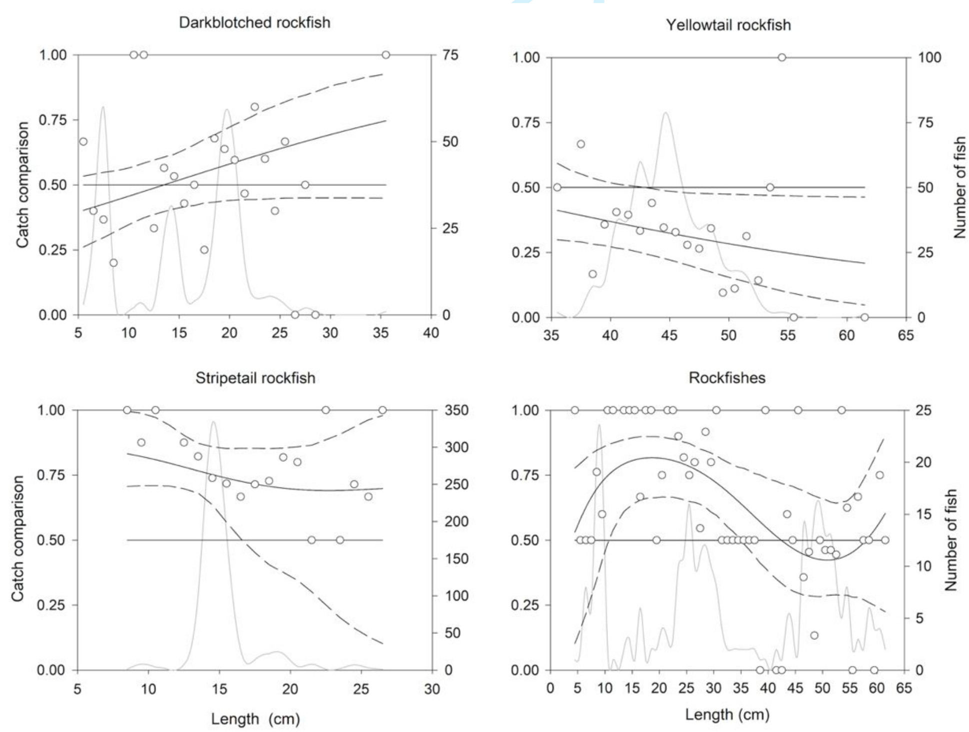

Figure 6. Mean catch comparison curves for darkblotched, yellowtail, stripetail, and other rockfishes between the unilluminated trawl and illuminated trawl. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% CIs; grey lines are number of fish caught; straight lines depict the baseline catch comparison rate of 0.5 indicating equal catch rates between the illuminated and unilluminated trawl. See Table 1 for the species included in rockfishes.

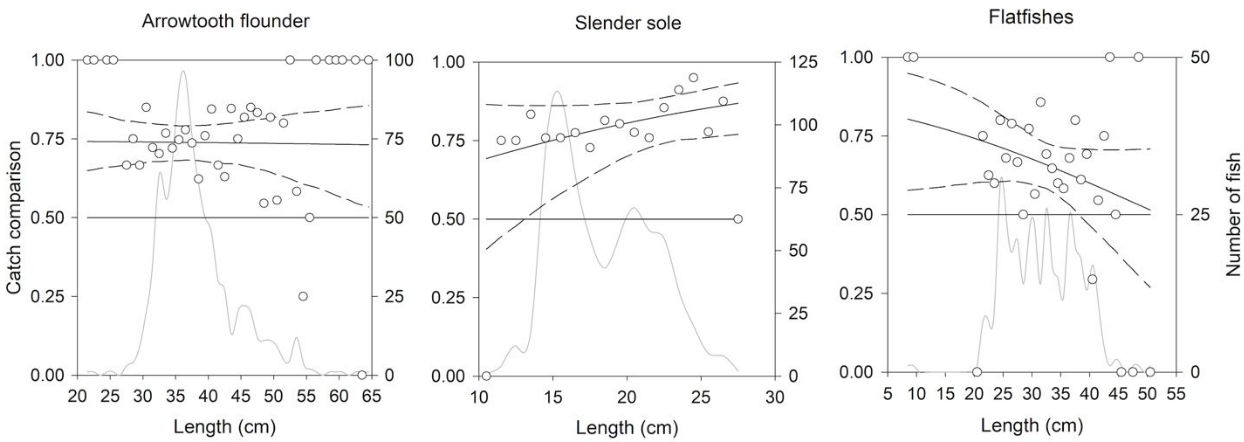

Figure 7. Mean catch comparison curves for arrowtooth flounder, slender sole, and other flatfishes between the unilluminated trawl and illuminated trawl. Circles are the experimental data; fitted lines are the modeled value; dashed lines are 95% CIs; grey lines are number of fish caught; straight lines depict the baseline catch comparison rate of 0.5 indicating equal catch rates between the illuminated and unilluminated trawl. See Table 1 for the species included in flatfishes.

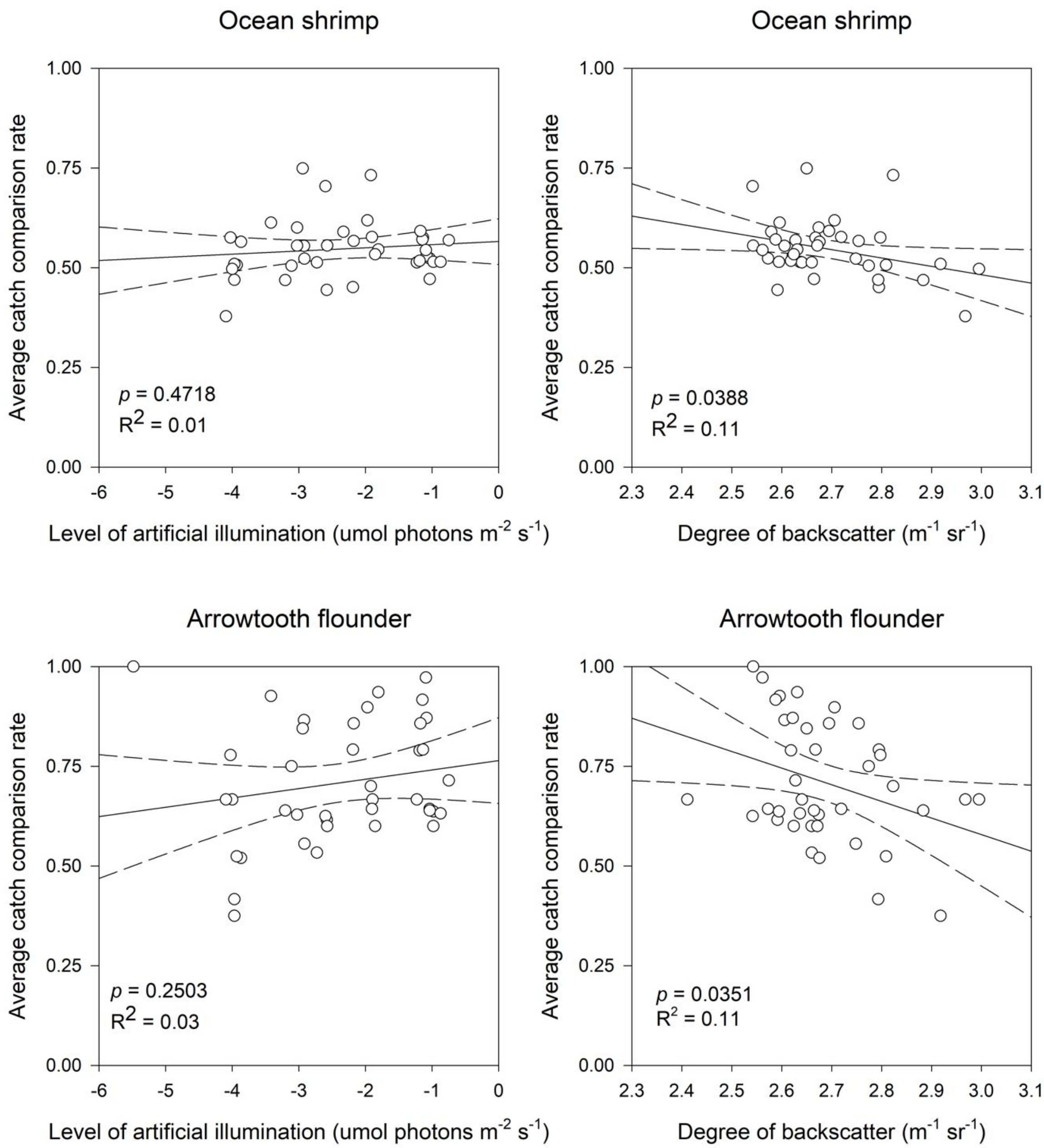

Figure 8. Linear regression model results examining if $CC_{average}$ changes linearly with level of artificial illumination or degree of backscatter for ocean shrimp and arrowtooth flounder. Circles are the experimental data; fitted lines are the regression lines; dashed lines are 95% CIs.