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Original Article

Effects on the bycatch of eulachon and juvenile groundfish by altering the level of artificial illumination along an ocean shrimp trawl fishing line

Mark J. M. Lomeli[1,*], Scott D. Groth[2], Matthew T. O. Blume[3], Bent Herrmann[4], and W. Waldo Wakefield[5]

[1]*Pacific States Marine Fisheries Commission, 2032 SE OSU Drive, Newport, OR 97365, USA*
[2]*Oregon Department of Fish and Wildlife, 63538 Boat Basin Drive, Charleston, OR 97420, USA*
[3]*Oregon Department of Fish and Wildlife, 2040 SE Marine Science Drive, Newport, OR 97365, USA*
[4]*SINTEF Fisheries and Aquaculture, Willemoesvej 2, Hirtshals DK-9850, Denmark*
[5]*Fishery Resource Analysis and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2032 SE OSU Drive, Newport, OR 97365, USA*

**Corresponding author: tel: +1 541 867 0544; e-mail: mlomeli@psmfc.org.*

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We examined how catches of ocean shrimp (*Pandalus jordani*), eulachon (*Thaleichthys pacificus*), and juvenile groundfish could be affected by altering the level of artificial illumination along the fishing line of an ocean shrimp trawl. In the ocean shrimp trawl fishery, catches of eulachon are of special concern, as the species' southern Distinct Population Segment is listed as "threatened" under the US Endangered Species Act. Using a double-rigged trawl vessel, with one trawl illuminated and the other unilluminated, we compared the catch efficiencies for ocean shrimp, eulachon, and juvenile groundfish between an unilluminated trawl and trawls illuminated with 5, 10, and 20 LED fishing lights along their fishing line. The addition of artificial illumination along the trawl fishing line significantly affected the average catch efficiency for eulachon, rockfish (*Sebastes* spp.), and flatfish, with the three LED configurations each catching significantly fewer individuals than the unilluminated trawl without impacting ocean shrimp catches. For Pacific hake (*Merluccius productus*), the ten LED-configured trawl caught significantly more fish than the unilluminated trawl. For the five and 20 LED configurations, mean Pacific hake catches did not differ from the unilluminated trawl. This study contributes new data on how artificial illumination can affect eulachon catches (and other fish) and contribute to their conservation.

Keywords: artificial illumination, bycatch reduction, eulachon, fish behaviour, groundfish, LEDs, ocean shrimp.

Introduction

The ocean shrimp (*Pandalus jordani*) trawl fishery is an economically important fishery along the US west coast. From 2010 to 2017, annual landings of ocean shrimp averaged 28 635 tonnes resulting in an average annual ex-vessel value of $35.5 million (PacFIN, 2018). This fishery is managed by the states of Washington, Oregon, and California, with each state having jurisdiction of fishing operations for catches delivered to their ports. The mandatory use of rigid sorting grid bycatch reduction devices (BRDs), similar to the Nordmøre grate, with 19.1-mm maximum bar spacings are required off Washington and Oregon to minimize fish bycatch (WDFW, 2017; ODFW, 2018). Off California, fishers are required to use either a rigid sorting grid BRD with 50.8-mm maximum bar spacings, a soft-panel BRD made of netting no >15.2 cm, or a fisheye excluder (CDFW, 2017).

Fish bycatch in the ocean shrimp trawl fishery has been significantly reduced by using sorting grid BRDs (Hannah and Jones, 2007; Hannah *et al.*, 2011). However, bycatch of juvenile groundfish, such as Pacific hake (*Merluccius productus*), rockfish (*Sebastes* spp.), and flatfish, and eulachon (*Thaleichthys pacificus*) and whitebait smelt (*Allosmerus elongatus*) can still occur at considerable levels as these fish can pass through the bar spacings of the BRDs. For eulachon, an anadromous smelt species endemic to the eastern North Pacific, bycatch is of special concern, as the species' southern Distinct Population Segment (DPS) is listed as "threatened" under the US Endangered Species Act (ESA; DOC, 2011; Gustafson *et al.*, 2012). An ESA recovery plan has been implemented to protect and recover the southern DPS of eulachon; however, there are many uncertainties in forecasting their recovery (NMFS, 2017). As ocean distributions of eulachon and ocean shrimp often overlap, interactions between ocean shrimp trawl gear and eulachon are likely to continue to be an issue facing the fishery and the conservation of eulachon.

A typical ocean shrimp trawl consists of a bottom-tending groundline (steel cable covered with rubber discs) connected by drop chains to a fishing line (the leading edge of the trawl) that operates 30–70 cm off bottom (Hannah *et al.*, 2013). Hannah *et al.* (2015) tested if placing ten green LED fishing lights along an ocean shrimp trawl fishing line could enhance the ability of eulachon and other fish to perceive the space between the groundline and the fishing line (that they may not see as readily under normal seabed light levels) and allow them an opportunity to pass through the gap and avoid trawl entrainment. Findings showed that catches (by weight) of eulachon, juvenile rockfish, such as darkblotched rockfish (*Sebasres crameri*), and flatfish, such as slender sole (*Lyopsetta exillis*) were substantially reduced, while not affecting ocean shrimp catches. When testing whether adding illumination around the sorting grid could achieve the same effect, the opposite result was observed, as bycatch of eulachon and slender sole significantly increased. The authors speculated that the presence of illumination influenced fish to dive in a threatened response and pass through the spaces between the sorting grid bars and the groundline and fishing line at rates higher than would occur in the absence of artificial illumination. Following the Hannah *et al.* (2015) study, fisheries managers for the state of Oregon considered implementing the required use of LED fishing lights along ocean shrimp trawl fishing lines to minimize the fisheries impact on eulachon, groundfish, and other fish. However, further research examining the number of LEDs necessary to achieve optimal bycatch reduction was recognized as data needed before implementing the required use of footrope lighting (ODFW, Marine Resources Shellfish Program, pers. comm.).

Our study objectives were to (i) compare how catches of ocean shrimp, eulachon, and juvenile groundfish are affected by testing various configurations (quantity and spacing) of LED fishing lights along an ocean shrimp trawl fishing line compared to a simultaneous, identically configured, but unilluminated trawl, (ii) examine if the catch efficiencies between the three LED configurations differ from each other, (iii) provide fisheries managers quantitative information for making decisions when developing and implementing the required use of footrope lighting, and (iv) enhance our knowledge about the use of LED fishing lights as a technique to improve trawl selectivity in the ocean shrimp trawl fishery and contribute to the conservation of ESA-listed eulachon.

Material and methods

Sea trials and sampling

Sea trials occurred aboard the double-rigged ocean shrimp trawler FV "Miss Yvonne," an 18.6-m, 350-HP vessel. Tows were conducted off Oregon between 43°18′N and 45°29′N and between 124°13′W and 124°34′W during July and September 2017 (Figure 1). Towing occurred over the continental shelf during daylight hours at bottom fishing depths averaging 124 m. Towing speed ranged from 3.3 to 3.9 km h^{-1} (1.8–2.1 knots). Tow durations averaged 66 min and ranged from 60 to 105 min.

We used the trawl gear components of the FV "Miss Yvonne" for this study. The port and starboard gear components were identical in material and design. Wood and steel combination doors, 1.8 × 2.1 m (length × height), were used to spread each trawl. The trawl sweeps and bridles were 19-mm steel cable and 4.5 m in length. The headropes and fishing lines were 22 m in length. Drop chains measuring 39 cm in length attached the fishing line to the groundline at 1.2-m separations. The groundlines were 22 m in length, with the centre 7.3-m section covered with 7.6-cm diameter rubber disks. Rigid sorting-grid BRDs with 19.1-mm bar spacing were used in each trawl. Both trawls had a codend mesh size of 35 mm.

Lindgren-Pitman Electralume® green LED fishing lights, centred on 519 nm (Nguyen *et al.*, 2017), were used to illuminate the trawl groundgear components (e.g. fishing line, drop chains, groundline). 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, the predominant spectral component of coastal waters (Bowmaker, 1990; Britt, 2009). Therefore, we selected green LEDs for two reasons: (i) to allow for a comparison of results with the Hannah *et al.* (2015) study, and (ii) this colour somewhat matches the ambient light environment encountered in our study area and transmits well through coastal and continental shelf waters. For this study, when we refer to an LED, we are referring to a single Lindgren-Pitman fishing light. For the illuminated trawl, quantities of 5, 10, and 20 LEDs were fished in an alternate tow randomized design, with each LED configuration fished for two or three tows per day. Under the 5- and 10-LED configurations, the LEDs were placed 1.2 m apart from the centre section of the fishing line and moving outward (Figure 2). In the 20-LED configuration, the LEDs were placed 0.6 m apart. The LEDs were attached to the trawl fishing line using zip ties, with the light-emitting end pointing progressively forward moving towards the wing tips. The LED configurations were switched between the port and starboard sides throughout the study, with one trawl serving as the illuminated and the other as the unilluminated.

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 selected species were measured. Eulachon, whitebait smelt, and rockfish were measured to fork length (FL), whereas Pacific hake and flatfish were measured to total length (TL). For ocean shrimp, catches were collected in baskets as they came off the conveyor

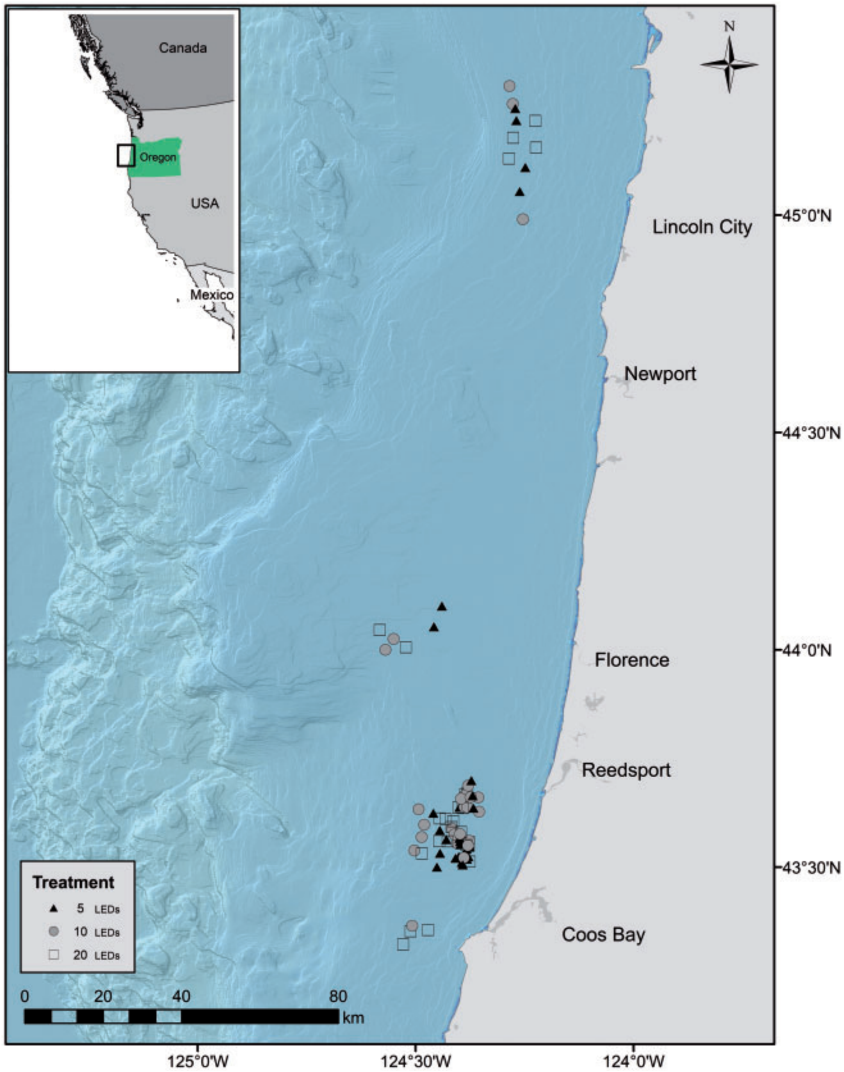

Figure 1. Map of the area off the Oregon coast where sea trials were conducted. Symbols represent trawl locations by LED configuration.

belt and set aside until sorting was completed. Following, a basket(s) of ocean shrimp 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 measurement (carapace length, CL). Given the small length class structure of ocean shrimp encountered (mainly 14–20 mm CL) and our random collection of ocean shrimp samples, measuring 100 individuals per net per tow was considered an adequate representation of the trawl catch. Further, this sampling rate has been found to accurately characterize mean sizes by age, used in distinguishing growth patterns by month and area, which is used in the ocean shrimp virtual population estimate (ODFW, Marine Resources Shellfish Program, pers. comm.).

Fishing line height was measured using Star-Oddi *DST tilt* sensors (0.05° tilt resolution, ±3° tilt accuracy) attached to the centre of the fishing line of each trawl to ensure uniformity between the trawls. Each tag was placed in a customized aluminium bracket outfitted with a rod that extended from the fishing line to the seabed (Supplementary Figure S1). The mean tilt angle for the *x*-axis was converted to height using the following formula:

$$\text{Fishing line height} = y \times \text{SIN}[\text{Radians}(x^\circ)] \quad (1)$$

where y is the length of the aluminium bracket (86.4 cm, Supplementary Figure S1) and x° is the tilt *x*-axis degree angle. 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.

In each net, a Wildlife Computers TDR-MK9 archival tag was used (attached to the belly of the net directly behind the centre of the fishing line and facing upward) to measure the amount of light available. 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

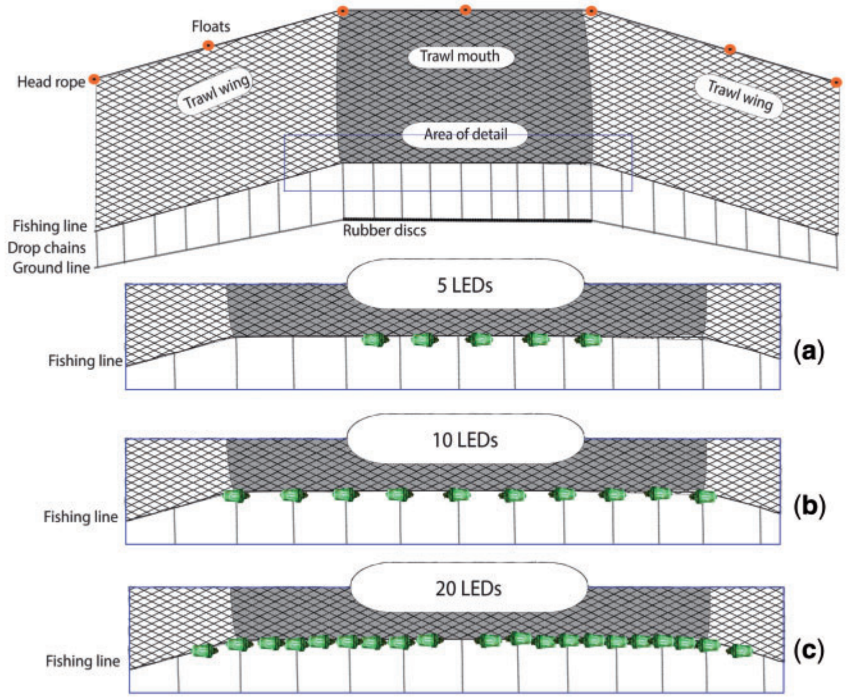

Figure 2. Schematic of an ocean shrimp trawl viewed from the front (top image) and diagrams depicting the placement and orientation of the LEDs along the trawl fishing line for the 5- (a), 10- (b), and 20-LED (c) configurations. Note: diagram not to scale.

Table 1. Length data used for the catch comparison and catch ratio analyses.

	5-LED configuration		10-LED configuration		20-LED configuration	
	No. measured		No. measured		No. measured	
Species	Illuminated trawl	Unilluminated trawl	Illuminated trawl	Unilluminated trawl	Illuminated trawl	Unilluminated trawl
Ocean shrimp	1 500 (0.01)	1 500 (0.01)	1 300 (0.004)	1 300 (0.005)	1 300 (0.005)	1 300 (0.004)
Eulachon	27 (1.0)	147 (1.0)	55 (1.0)	138 (1.0)	82 (1.0)	155 (1.0)
Whitebait smelt	134 (1.0)	460 (0.70)	27 (1.0)	253 (1.0)	33 (1.0)	47 (1.0)
Pacific hake	2 920 (0.26)	3 041 (0.24)	3 066 (0.21)	2 950 (0.16)	2 605 (0.28)	3 086 (0.26)
Rockfishes	109 (1.0)	318 (1.0)	62 (1.0)	189 (1.0)	119 (1.0)	414 (1.0)
Pacific sanddab	164 (1.0)	464 (1.0)	65 (1.0)	258 (1.0)	50 (1.0)	217 (1.0)
Rex sole	68 (1.0)	222 (1.0)	71 (1.0)	222 (1.0)	58 (1.0)	209 (1.0)
Slender sole	657 (0.83)	1 109 (0.65)	283 (1.0)	821 (0.82)	253 (1.0)	760 (0.78)

Values in parentheses are the length measurement subsample ratio from the total catch.

generated. The calibration function used to convert the MK9 relative light units to irradiance units was:

$$y = 1 \times 10^{-9} e^{0.1476x} \quad (2)$$

where x is the relative light unit from the MK9 and y is the corresponding irradiance unit in μmol photons $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$. The r^2 value from our calibration curve was 0.9867.

Method for estimating relative catch efficiency between illuminated and unilluminated trawls

We used the statistical analysis software SELNET (SELection in trawl NETting) to analyse the catch data (Sistiaga *et al.*, 2010; Herrmann *et al.*, 2012, 2016) and conducted length-dependent catch comparison and catch ratio analyses. Table 1 summarizes the data used in each analysis. The analysis was conducted separately for each species following the procedure described below. For ocean shrimp, only tows with ≥10 kg of total catch (combined catch between the port and starboard trawls) were used in the catch analyses.

Using the catch information (numbers and length of ocean shrimp or a given species of fish for each of the tows), we wanted to determine whether there was a significant difference in catch efficiency between the unilluminated and illuminated trawls. We also wanted to determine if a potential difference between the trawls could be related to the size of the 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:

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

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, respectively, in tows l and j, 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 for the specific LED configuration. The functional form of the catch comparison rate $CC(l, \boldsymbol{v})$ [the experimental being expressed by Equation (3)] was obtained using maximum likelihood estimation by minimizing the following equation:

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

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 trawls 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 modelled by the function $CC(l, \boldsymbol{v})$, on the following form:

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

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 four 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 $CC(l, \boldsymbol{v})$. 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).

On the basis of the estimated catch comparison function $CC(l, \boldsymbol{v})$, we obtained the relative catch ratio $CR(l, \boldsymbol{v})$ between fishing with the two trawls by the general relationship:

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{[1 - CC(l,\boldsymbol{v})]} \tag{6}$$

The catch ratio provides a direct relative value of the catch efficiency between fishing with and without LEDs. Thus, if the catch efficiency of both trawls is equal, $CR(l, \boldsymbol{v})$ should always be 1.0. Thus, $CR(l, \boldsymbol{v}) = 1.5$ would mean that the illuminated trawl is catching on average 50% more ocean shrimp or a given species of fish with length l than the unilluminated trawl. In contrast, $CR(l, \boldsymbol{v}) = 0.8$ would mean that the illuminated trawl is only catching 80% of the ocean shrimp or a given species of fish with length l that the unilluminated trawl is catching.

The confidence interval (CI) limits for the catch comparison and catch ratio curves were estimated using a double bootstrapping method (Herrmann *et al.*, 2017). This bootstrapping method accounts for the uncertainty in the estimation resulting from variation in catch efficiency among tows and availability of ocean shrimp or a given species of fish as well as uncertainty about the size structure of the catch for the individual tows. However, contrary to the method by Herrmann *et al.* (2017), the outer bootstrapping loop accounting for between-haul variation was performed paired for the illuminated and unilluminated trawl in the current study. By multimodel inference in each bootstrap iteration, the method also accounts for the uncertainty due to uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) CI limits. To identify sizes of ocean shrimp or a given species of fish with significant differences in catch efficiency, we checked for length classes in which the CI 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:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m}\{nt_{lj}/qt_j\}}{\sum_l \sum_{j=1}^{m}\{nc_{lj}/qc_{ij}\}} \tag{7}$$

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

On the basis of Equation (6), the percentage change in average catch efficiency between fishing with the unilluminated trawl to the illuminated trawl was estimated by:

$$\Delta CR_{average} = 100 \times \left(CR_{average} - 1.0\right) \tag{8}$$

By incorporating $\Delta CR_{average}$ into each of the bootstrap iterations described above, we could assess the 95% CI limits for $\Delta CR_{average}$. 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. In contrast to the length-dependent evaluation of the catch ratio, $\Delta CR_{average}$ is specific to the size classes encountered during the experimental sea trials.

Small sample sizes of rockfish necessitated pooling data from 10 rockfish species. For whitebait smelt, too few length classes were caught to perform catch comparison and catch ratio analyses. Therefore, only the $\Delta CR_{average}$ analysis was conducted on whitebait smelt.

Method for estimating relative catch efficiency between the three LED configurations

With the approach described above, we can quantify by Equation (6) the length-dependent ratio in catch efficiency between the illuminated and unilluminated trawls. Considering that each of the illuminated trawl configurations (5, 10, or 20 LEDs) are compared to the same unilluminated trawl configuration, we can obtain an estimate for relative catch efficiency between the three LED trawl configurations by:

$$CR(l)_{10_5} = \frac{CR(l)_{10}}{CR(l)_5}$$
$$CR(l)_{20_5} = \frac{CR(l)_{20}}{CR(l)_5} \quad (9)$$
$$CR(l)_{20_{10}} = \frac{CR(l)_{20}}{CR(l)_{10}}$$

where $CR(l)_5$, $CR(l)_{10}$, and $CR(l)_{20}$ are the length-dependent catch ratios [obtained by Equation (6)] for the illuminated and unilluminated trawls for the illuminated configuration with 5, 10, and 20 LEDs, respectively. For simplicity, we have omitted the parameter $\boldsymbol{v}$ in the notation. We obtained 95% *CI* limits for $CR(l)_{10_5}$, $CR(l)_{20_5}$, and $CR(l)_{20_{10}}$ based on the three bootstrap population of results (1000 bootstrap repetitions in each) for, respectively, $CR(l)_5$, $CR(l)_{10}$, and $CR(l)_{20}$ as they are obtained independently. Using these bootstrap results, we created new bootstrap populations of results by:

$$CR(l)_{10_5 i} = \frac{CR(l)_{10_i}}{CR(l)_{5_i}}$$
$$CR(l)_{20_5 i} = \frac{CR(l)_{20_i}}{CR(l)_{5_i}} \quad i \in \ [1 \ldots 1000] \quad (10)$$
$$CR(l)_{20_{10} i} = \frac{CR(l)_{20_i}}{CR(l)_{10_i}}$$

where *i* denotes the bootstrap repetition index. Because sampling was random and independent for the three groups of results, it is valid to generate the bootstrap populations of results for the ratios based on Equation (10) using the three independent generated bootstrap files (Moore *et al*., 2003). On the basis of the bootstrap populations, we can obtain Efron percentile 95% *CI* limits for $CR(l)_{10_5}$, $CR(l)_{20_5}$, and $CR(l)_{20_{10}}$.

Results

We completed 29, 25, and 24 paired tows with the 5-, 10-, and 20-LED configuration, respectively. The most abundant species caught were ocean shrimp, Pacific hake, slender sole, Pacific sanddab (*Citharichthys sordidus*), rockfish, whitebait smelt, rex sole (*Glyptocephalus zachirus*), and eulachon (Table 1).

The average fishing line height (FLH) for the port trawl during the 5-, 10-, and 20-LED treatment was 30.1 (s.e. ±0.03), 30.2 (±0.04), and 30.0 (±0.04) cm, respectively. The average FLH for the starboard trawl during the 5-, 10-, and 20-LED treatment was 31.5 (±0.03), 31.2 (±0.04), and 31.1 (±0.05) cm, respectively. Figure 3 depicts the mean FLH per tow and LED configuration for the port and starboard trawl.

The mean ambient light level measured in the unilluminated trawl during the 5-, 10-, and 20-LED treatment was $3.4e^{-04}$ (s.e. $\pm 2.5e^{-05}$), $5.5e^{-04}$ ($\pm 4.0e^{-05}$), and $8.0e^{-04}$ ($\pm 4.9e^{-05}$) μmol photons $m^{-2}\,s^{-1}$, respectively. In the 5-, 10-, and 20-LED configured trawl, the mean light level measured increased to $4.0e^{-04}$ ($\pm 2.4e^{-05}$), $6.4e^{-04}$ ($\pm 4.1e^{-05}$), and $1.1e^{-03}$ ($\pm 5.1e^{-05}$) μmol photons $m^{-2}\,s^{-1}$, respectively. Mean light levels per tow for the unilluminated and illuminated trawls are shown in Figure 4.

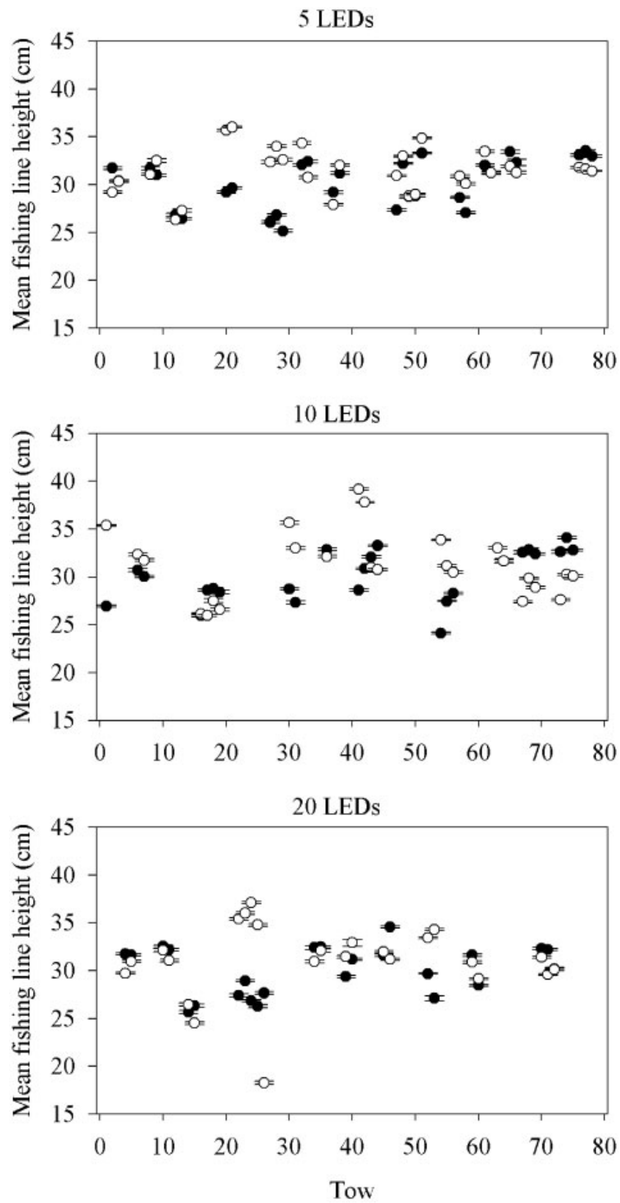

Figure 3. Mean fishing line height measured at the centre of the fishing line using Star-Oddi DST tilt sensors for the port (closed circles) and starboard (open circles) trawl per tow and LED configuration. ± bars are standard errors ($n = 300$ measurements per net per tow).

Relative catch efficiency

Ocean shrimp – The change in average catch efficiency of ocean shrimp for the three LED configurations did not differ significantly from the unilluminated trawl (Figure 5).

For each LED configuration, the catch comparison and ratio of ocean shrimp was not significantly different from the unilluminated trawl as depicted by the mean $CC(l, \boldsymbol{v})$ and $CR(l, \boldsymbol{v})$ 95% *CIs* extended above and below the $CC(l, \boldsymbol{v})$ rate of 0.5 and $CR(l, \boldsymbol{v})$ ratio of 1.0 (Supplementary Figure S2). Between the three LED configurations, the catch ratios did not differ significantly from each other for ocean shrimp of marketable-size, that is ocean shrimp >14.5 mm (Supplementary Figure S3).

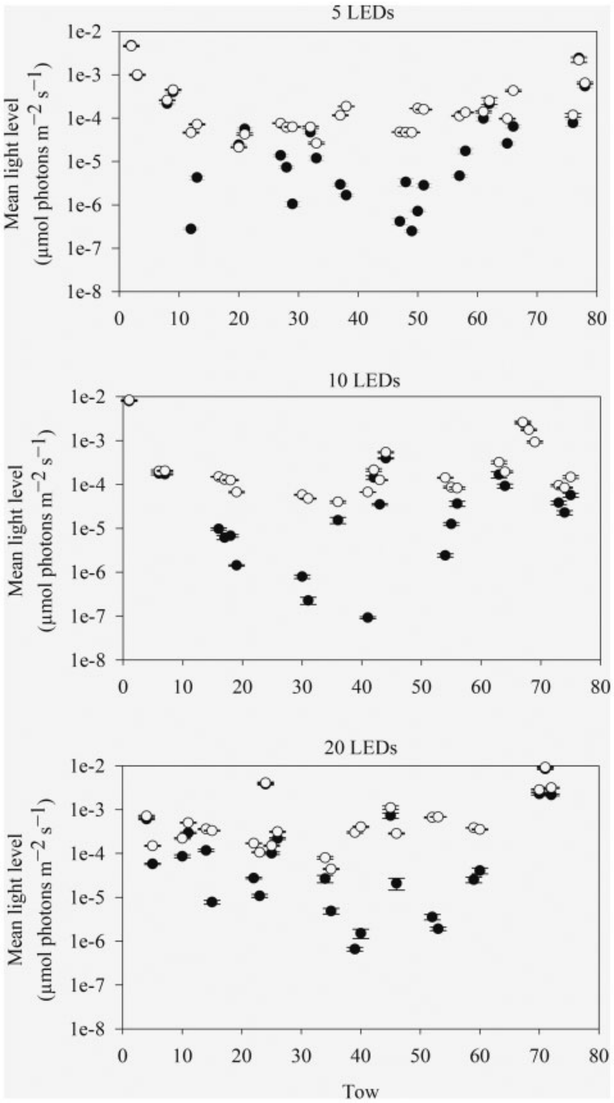

Figure 4. Mean light level measured at the centre of the fishing line for the unilluminated trawl (closed circles) and illuminated trawl (open circles) per tow and LED configuration. ± bars are standard errors ($n = 50$ measurements per net per tow).

Eulachon – The change in average catch efficiency results for eulachon showed the unilluminated trawl caught 81, 60, and 47% more eulachon than the 5-, 10-, and 20-LED configuration, respectively (Figure 5). These differences in average catch efficiency were significant.

Catch comparisons and ratios of eulachon between the three LED configurations and the unilluminated trawl varied across length classes (Supplementary Figure S4). For the 5-LED configuration, the illuminated trawl caught significantly fewer eulachon across all length classes. On average, the 5-LED configuration caught only 17% of the number of eulachon compared to the unilluminated trawl. For the 10- and 20-LED configurations, the illuminated trawls caught significantly fewer fish of 13.5–17.5 cm in length and 15.5–20.5 cm in length, respectively, than the unilluminated trawl. Over these size classes, the 10-LED configuration caught only 39% of the number of eulachon compared to the unilluminated trawl, while the 20-LED configuration caught only 51% of the number of eulachon compared to the unilluminated trawl (Supplementary Figure S4). Between the three LED configurations, the catch ratios of eulachon did not differ significantly from each other for fish >14.5 cm (Supplementary Figure S5).

Whitebait smelt – For the 5- and 10-LED configurations, there was a significant difference in average catch efficiency with the unilluminated trawls catching 79 and 89%, respectively, more whitebait smelt than the illuminated trawls (Figure 5). Under the 20-LED configuration, while the general trend shows higher average catches of whitebait smelt in the unilluminated trawl, the large 95% *CI*s generated from the limited sample size (Table 1) show that there is no significant difference in the average catch efficiency between the illuminated and unilluminated trawl.

Pacific hake – The change in average catch efficiency of Pacific hake between the 10-LED configured trawl and unilluminated trawl differed significantly, with the illuminated trawl catching 66% more Pacific hake than the unilluminated trawl (Figure 5). Under the 5- and 20-LED configurations, the change in average catch efficiency did not differ significantly from the unilluminated trawl.

The Pacific hake catch comparison and ratio results for the three LED configurations were similar to each other in that each configuration caught significantly fewer larger-sized fish (>20.5 cm in length) than the unilluminated trawl (Supplementary Figure S6). For smaller-sized fish (9.5–16.5 cm in length), the 10-LED configured trawl caught on average twofold more Pacific hake than the unilluminated trawl. The 20-LED configuration showed a similar trend; however, a significant difference was not detected. For the 5-LED configuration, the illuminated trawl caught fewer smaller-size Pacific hake. However, this result was not significant. The catch ratio of Pacific hake between the 5-, 10-, and 20-LED configurations differed significantly from each other for some length classes. The most pronounced difference was noted between the 5- and 10-LED configurations, with the 5-LED configuration catching significantly fewer Pacific hake of 10.5–19.5 cm in length than the 10-LED configuration (Supplementary Figure S5).

Rockfish – Stripetail (*S. saxicola*) and darkblotched rockfish were the most frequently caught rockfish. Stripetail and darkblotched rockfish comprised 66 and 22% of the total catch of rockfish by numbers, respectively. Greenstriped (*Sebastes elongatus*), shortbelly (*Sebastes jordani*), quillback (*Sebastes maliger*), redstripe (*Sebastes proriger*), halfbanded (*Sebastes semicinctus*), and sharpchin (*Sebastes zacentrus*) rockfish, and Pacific ocean perch (*Sebastes alutus*), and chilipepper (*Sebastes goodei*) comprised the remaining 12% of the total catch of rockfish by numbers.

For the three LED configurations, the change in average catch efficiency for rockfish differed significantly from the unilluminated trawl. Compared to the 5-, 10-, and 20-LED illuminated trawls, the unilluminated trawl caught 65, 67, and 71% more rockfish, respectively (Figure 5).

Results from the catch comparison and ratio analyses showed the 5-, 10-, and 20-LED configured trawls caught significantly fewer rockfish of 8.5–13.5, 9.5–14.5, and 7.5–14.5 cm, respectively, than the unilluminated trawl (Supplementary Figure S7). Over these size classes, the 5-, 10-, and 20-LED configured trawls caught on average only 30, 26, and 30%, respectively, of the number of rockfish compared to the unilluminated trawl. Between the three LED configurations, the catch ratios of rockfish did not differ significantly from each other (Supplementary Figure S5).

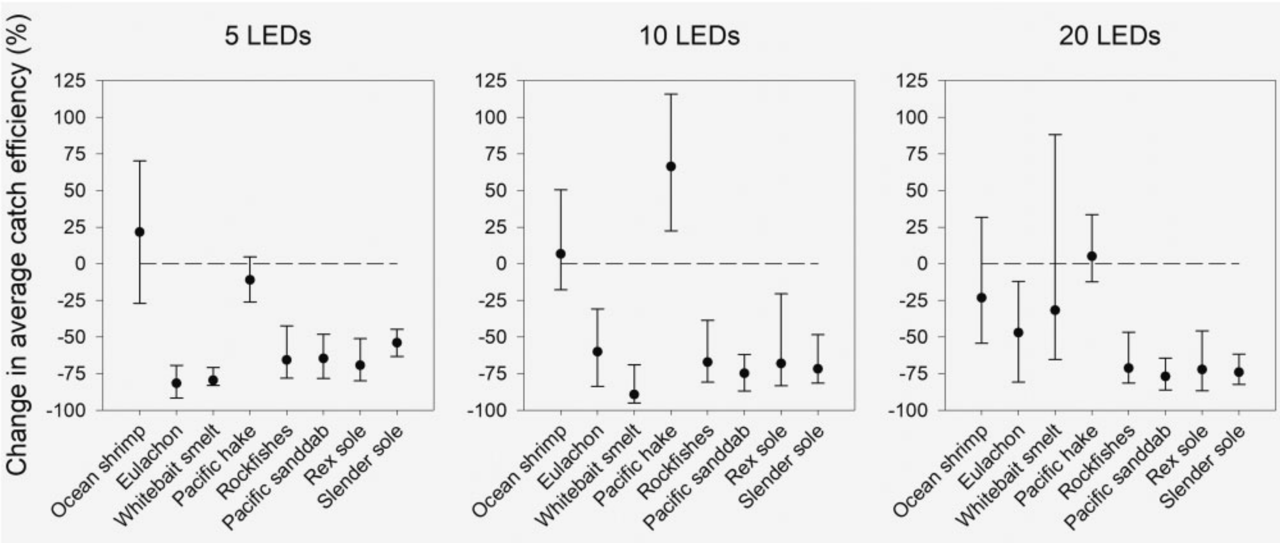

Figure 5. Change in average catch efficiency (%) between the three LED illuminated trawls and the unilluminated trawl. Values below zero indicate more ocean shrimp or a given species of fish were caught in the unilluminated trawl, and vice versa for values above zero.

Pacific sanddab – The change in average catch efficiency results show the unilluminated trawl caught 64, 74, and 76% more Pacific sanddab than the 5-, 10-, and 20-LED configurations, respectively (Figure 5). These differences in average catch efficiency were significant.

The Pacific sanddab catch comparison and ratio results showed the 5-LED configuration caught significantly fewer fish across all length classes compared to the unilluminated trawl (Supplementary Figure S8). On average, the 5-LED illuminated trawl caught only 33% of the number of Pacific sanddab compared to the unilluminated trawl. For the 10- and 20-LED configurations, the illuminated trawls caught significantly fewer fish <24.5 cm than the unilluminated trawl (Supplementary Figure S8). Of Pacific sanddab <24.5 cm, the 10- and 20-LED configurations caught on average only 24 and 23%, respectively, of the number of fish compared to the unilluminated trawl. The catch ratios of Pacific sanddab between the three LED configurations did not differ significantly from each other (Supplementary Figure S9).

Rex sole – The average catch efficiency of the unilluminated trawl was significantly higher for rex sole than the three LED configured trawls. Overall, the unilluminated trawl caught 69, 68, and 72% more rex sole than the 5-, 10-, and 20-LED configurations, respectively (Figure 5).

The catch comparisons and ratios of rex sole between the three LED configured trawls and the unilluminated trawl varied across length classes (Supplementary Figure S10). For the 5-LED configuration, the illuminated trawl caught significantly fewer 8.5–29.5 cm rex sole. Over these length classes, the 5-LED configuration caught only 29% of the number of rex sole compared to the unilluminated trawl. For the 10-LED configuration, the illuminated trawl caught significantly fewer 21.5–25.5 cm fish than the unilluminated trawl. Under the 20-LED configuration, the illuminated trawl caught significantly fewer fish of 10.5–21.5 cm and 25.5–31.5 cm than the unilluminated trawl. Between the three LED configurations, the catch ratios of rex sole did not differ significantly from each other (Supplementary Figure S9).

Slender sole – A significant difference in the change in average catch efficiency between the illuminated trawls and the unilluminated trawl was noted for slender sole, with the unilluminated trawl catching 54, 71, and 74% more fish than the 5-, 10-, and 20-LED configured trawls, respectively (Figure 5).

The slender sole catch comparison and ratio analyses showed that the 5-, 10-, and 20-LED configured trawls caught significantly fewer 11.5–23.5, 9.5–26.5, and 9.5–27.5 cm fish, respectively, than the unilluminated trawl (Supplementary Figure S11). Over these length classes, the 5-, 10-, and 20-LED illuminated trawls caught only 39, 28, and 22%, respectively, of the number of slender sole compared to the unilluminated trawl. Between the three LED configurations, the catch ratios of slender sole did not differ significantly from each other for fish >12.5 cm (Supplementary Figure S9).

Discussion

We demonstrated that the addition of illumination along the fishing line of an ocean shrimp trawl can significantly affect the catch efficiency for eulachon, whitebait smelt, and juvenile groundfish without affecting ocean shrimp catches. Overall, the average catch efficiency for eulachon, rockfish, and flatfish were significantly lower in the illuminated trawls than in the unilluminated trawl. The opposite was noted for Pacific hake under the 10-LED illuminated trawl. For the 5- and 20-LED illuminated trawls, the average catch efficiency for Pacific hake did not differ significantly from the unilluminated trawl.

Studies have shown that vision is the primary sense affecting fish behaviour when encountering trawl gear (Glass and Wardle, 1989; Olla *et al.*, 1997; Kim and Wardle, 1998; Olla *et al.*, 2000; Kim and Wardle, 2003; Ryer *et al.*, 2010) and that light can influence their behaviour (Ryer and Olla, 2000; Ryer and Barnett, 2006; Lomeli and Wakefield, 2012; Hannah *et al.*, 2015; Lomeli *et al.*, 2018). Prior to our study, we speculated that the 10- and 20-LED configurations would perform better at reducing bycatch than the 5-LED configuration because more illumination along the fishing line length would enhance fishes' visual perception of the approaching trawl gear and provide them increased opportunities to avoid trawl entrainment. However, our findings suggest that the light emitted by the 5-LED configuration provided sufficient illumination for most fishes to perceive the contrast between the trawl fishing line and the seabed and thus avoid capture, and that use of more illumination provides no clear added bycatch reduction benefit. The groundgear components herding and concentrating fish towards the centre of the trawl, where fish encounter the five LEDs and behaviourally respond by diving under the fishing line, is likely a contributing factor to the noted results as well.

While the catch efficiency analyses showed catch variability occurring across some length classes between the three LED configurations, the 95% *CI*s for the mean delta catch ratio curves extending above and below the ratio of 1.0 show that the three LED configurations do not differ significantly from each other at reducing catches of rockfish, Pacific sanddab, and rex sole across all length classes. The 95% *CI*s extended outside the ratio of 1.0 for ocean shrimp (5- vs. 20-LED), slender sole (5- vs. 10-, 20-LED), and eulachon (5- vs. 20-LED); however, the ratio difference was very minimal and only occurred over one or two length classes and was not considered to hold any meaningful significant difference. In contrast to the species above, the presence of illumination did not have a bycatch reduction effect on Pacific hake. Under the 10-LED configuration, catches of Pacific hake were found to significantly increase in the illuminated trawl. Compared to the 5- and 20-LED configurations, the mean delta catch ratio for the 10-LED illuminated trawl differed significantly from the 5-LED configuration across several length classes, but not from the 20-LED configuration to a degree that was considered significantly meaningful. While it is unclear why this catch variability occurred between the three LED configurations for Pacific hake, factors other than the presence of artificial illumination likely had an effect. As Pacific hake can often form large schools near the seabed, and juveniles and subadults have been described as weak swimmers when encountering a BRD in the extension section of a midwater trawl (Lomeli and Wakefield, 2012), it is possible that a schooling behavioural response to the approaching trawl, variability in school density and/or the rate that the school encountered the trawl throughout the tow, their swimming ability, and/or their ability to visually perceive the trawl gear had an effect. Unfortunately, we were unable to compare our results to Hannah *et al.* (2015) as they did not encounter this species.

The light levels measured in the illuminated trawls likely underestimate the amount of light occurring under the trawl fishing line (and across its length) as we positioned a single MK9 tag in the net directly behind the centre of the fishing line and facing upward to measure the amount light available inside the net. A more suitable method to capture the amount of light occurring near the seabed would have been to place multiple MK9 tags across the fishing line length and have them positioned on the underside of the net. While it is possible that light from an illuminated trawl could spread towards the unilluminated trawl, our catch results show no effect of this occurring between the three LED configurations to a degree that is detectable.

As a result of this study and the work by Hannah *et al.* (2015), the Oregon Fish and Wildlife Commission (the regulatory authority for the state of Oregon) has implemented the required use of lighting along ocean shrimp trawl fishing lines to reduce bycatch of eulachon and groundfishes (ODFW, 2018). The regulation requires fishers landing ocean shrimp off Oregon to use a minimum of five green LEDs (spaced 1.2 m apart starting from the centre section of the fishing line) within 15.2 cm of the forward leading edge of the bottom panel of the trawl netting. The state of Washington is in the process of applying similar regulatory requirements. At this current time, it is unknown if the state of California will pursue actions requiring ocean shrimp trawl fishers to use lighting devices along their trawl fishing lines.

To the best of our knowledge, the Hannah *et al.* (2015) research was the first peer-reviewed study presented where artificial illumination was successfully used to reduce bycatch in a trawl fishery. Because of their research, other studies have occurred in trawl fisheries where artificial illumination was used in efforts to affect fish behaviour and catchability. In the US west coast groundfish bottom trawl fishery, Lomeli *et al.* (2018) compared an unilluminated trawl to a trawl with an illuminated headrope and found that the illuminated trawl caught significantly fewer sablefish (*Anoplopoma fimbria*) and Dover sole (*Microstomus pacificus*). Catches of other groundfish did not differ between the two trawls. In the Barents Sea demersal trawl fishery, Grimaldo *et al.* (2018) placed LEDs in the centre of a square-mesh section (forward of the codend) in efforts to improve the release efficiency for smaller-sized cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) by startling them towards the trawl meshes. Findings suggested that haddock escapement could be improved using illumination, but not for cod. Further, Larsen *et al.* (2017, 2018) tested how placing LEDs along the escape exit above a Nordmøre grate and along the base of the grate in a northern prawn (*Pandalus borealis*) trawl could affect bycatch of fishes such as cod, haddock, and redfish (*Sebastes* spp.). They found the addition of illumination near and on the Nordmøre grate had no significant result on fish bycatch. In the Pacific hake fishery, Lomeli and Wakefield (2012) examined a Chinook salmon (*Oncorhynchus tshawytscha*) BRD (equipped with multiple escape windows) and observed that Chinook salmon tended to escape out windows that artificial illumination was directed towards. Based off these observations, a study was conducted to specifically test if illumination could be used to attract them towards and out specific escape windows. Findings showed that artificial illumination can influence where Chinook salmon exit out the BRD, but also that illumination can be used to enhance their escapement overall (PSMFC, unpubl. data). In our study, where we examined the effects on fish bycatch of altering the number of LEDs along an ocean shrimp trawl fishing line, our results contribute new data to the growing field of research exploring catch effects of artificial illumination on trawl gear (as described above) and has helped fisheries managers develop and implement the required use of LEDs in the ocean shrimp trawl fishery. While our results have regional impacts, our research findings could have potential applications in other trawl fisheries internationally; for example, the ocean shrimp trawl fishery off British Columbia, Canada where eulachon occur as bycatch (Hay and McCarter, 2000; NMFS, 2017), and northern prawn trawl fisheries in the North Atlantic (He and Balzano, 2013; Larsen *et al.*, 2017, 2018) where bycatch of marine fishes occur.

In conclusion, this study examined how catches of ocean shrimp, eulachon, and juvenile groundfish are affected by using 5, 10, and 20 LED fishing lights along an ocean shrimp trawl fishing line. In general, the three LED configurations performed similarly to each other at reducing catches of eulachon and juvenile rockfish and flatfish without impacting ocean shrimp catches. As the southern DPS of eulachon faces many uncertainties in their

ESA recovery, our study contributes new data on how artificial illumination along an ocean shrimp trawl fishing line can affect eulachon catches (and other fishes) and contribute to their conservation. Lastly, this study provided fisheries management with quantitative information used to implement the required use of an inexpensive and practical technique to improve trawl selectivity and reduce bycatch of an ESA-listed species.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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