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Tests of artificial light for bycatch reduction in an ocean shrimp (*Pandalus jordani*) trawl: Strong but opposite effects at the footrope and near the bycatch reduction device

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ABSTRACT

We investigated how the addition of artificial light in the vicinity of the rigid-grate bycatch reduction device (BRD) and along the fishing line of an ocean shrimp (*Pandalus jordani*) trawl altered fish bycatch and ocean shrimp catch. In separate trials using double-rigged shrimp nets, with one net incorporating artificial lights and the other serving as a control, we 1) attached one to four Lindgren-Pitman Electralume® LED lights (colors green or blue) in locations around the rigid-grate BRD, and 2) attached 10 green lights along the trawl fishing line. Both experiments were conducted with rigid-grate BRDs with 19.1 mm bar spacing installed in each net. Contrary to expectations, in 12 paired hauls the addition of artificial light around the rigid-grate increased the bycatch of eulachon (*Thaleichthys pacificus*), a threatened anadromous smelt species, by 104% (all by weight, $P = 0.0005$) and slender sole (*Lyopsetta exilis*) by 77% ($P = 0.0082$), with no effect on ocean shrimp catch or bycatch of other fishes ($P > 0.05$). In 42 paired hauls, the addition of 10 LED lights along the fishing line dramatically reduced the bycatch of a wide variety of fishes with no effect on ocean shrimp catch ($P > 0.05$). Bycatch of eulachon was reduced by 91% ($P = 0.0001$). Bycatch of slender sole and other small flatfishes were each reduced by 69% ($P < 0.0005$). Bycatch of darkblotched rockfish (*Sebastes crameri*), a commercially important but depressed rockfish species, was reduced by 82% ($P = 0.0001$) while the bycatch of other juvenile rockfish (*Sebastes* spp.) was reduced by 56% ($P = 0.0001$). How the addition of artificial light is causing these changes in fish behavior and bycatch reduction is not known. However, in both experiments the addition of artificial light appears to have greatly increased the passage of fishes through restricted spaces (between BRD bars and the open space between trawl fishing line and groundline) that they typically would not pass through as readily under normal seafloor ambient light conditions.

1. Introduction

The limited species selectivity of trawls is a continuing concern for fisheries scientists and managers. Developing new technology to reduce non-target catch (bycatch) in trawl fisheries is especially important when a bycatch species is considered “threatened” or “endangered”. This is the case with eulachon (*Thaleichthys pacificus*), an anadromous smelt inhabiting the western coasts of the United States and Canada. The southern distinct population segment for this species has been listed as threatened under the U.S. Endangered Species Act (Gustafson et al., 2012; NWFSC, 2009) and is being considered for listing as “endangered” under the Canadian Species at Risk Act (http://www.dfo-mpo.gc.ca/species-especes/species-especes/eulachon-eulakane-eng.htm#information). Eulachon are regularly captured as bycatch in the small-mesh trawl fisheries targeting ocean shrimp (*Pandalus jordani*) operating on the west coasts of the United States and Canada. Fish bycatch, including the catch of eulachon, has been greatly reduced in these fisheries via the mandatory use of codend bycatch reduction devices (BRDs) similar to the Nordmøre grate system (Hannah and Jones, 2007, 2012; Isaksen et al., 1992) and through modifications to trawl footropes (Hannah and Jones, 2000). However, eulachon are a small fish that can easily fit between the 19.1 mm bar spacing of the rigid-grate BRDs required in this fishery. Their successful exclusion from shrimp trawls is behaviorally-based and is most efficient for larger (>150 mm TL) eulachon that are stronger swimmers (Hannah and Jones, 2012). So, when small eulachon are abundant, eulachon

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bycatch in ocean shrimp trawls can be large and has been increasing as eulachon have rebounded from very depressed population levels (Al-Humaidhi et al., 2012). Although eulachon population abundance has increased, the ocean shrimp fishery is still considered a moderate threat to eulachon recovery (Gustafson et al., 2012), thus, further reduction of eulachon bycatch in the ocean shrimp fishery is an important research priority.

Several studies have demonstrated that fish encountering trawls or simulated trawl components respond behaviorally to changes in visual stimuli (Glass et al., 1995; Glass and Wardle, 1995; Ryer and Olla, 2000; Ryer et al., 2010), suggesting the potential to use color or artificial light as a means to reduce bycatch. However, to our knowledge, no practical applications of such techniques for commercial trawl fisheries have been developed. We report on what we believe to be the first successful development of a practical bycatch reduction technology for a shrimp trawl fishery based on the use of artificial lighting.

Hannah and Jones (2012) analyzed the behavior of eulachon, as they escaped from shrimp trawls via BRDs, to evaluate their physical condition and showed that excluded eulachon were actively swimming and mostly avoiding contact with the rigid-grate BRD. That study utilized underwater video with bright artificial lighting, bringing into question how the presence of artificial light may have influenced eulachon escape behavior. Trawling for ocean shrimp is conducted at depths from about 90–300 m where ambient light levels are typically very low. The video observations showing that eulachon mostly avoided the rigid-grate BRD that was illuminated with artificial lights suggested the possibility that enhancing the visibility of the rigid-grate with artificial light under actual fishing conditions might improve eulachon exclusion efficiency (Hannah and Jones, 2012). In the first field experiment reported on here, we tested this hypothesis.

The footropes (defined as the combination of groundline, fishing line and connecting hardware) used on ocean shrimp trawls are designed to keep the fishing line of the trawl (where the netting is attached) elevated about 35–70 cm above the groundline which drags along the seafloor (Hannah et al., 2011). Recent studies have shown that modifying the trawl footrope to eliminate portions of the groundline can significantly reduce the bycatch of eulachon, however the modifications tested also caused significant shrimp loss (Hannah and Jones, 2013; Hannah et al., 2011). If footrope modifications can be found that reduce eulachon bycatch with minimal shrimp loss, they would have the added benefit of completely avoiding trawl entrainment of these fish, thus minimizing exhaustion or associated behavioral impairment (Hannah and Jones, 2012; Ryer et al., 2004). Footrope modifications also have a greater potential than codend BRDs to reduce the bycatch of many small fishes, which may have enough swimming ability to escape the approaching trawl at the footrope, but be too fatigued to respond effectively when they reach a codend BRD (Hannah and Jones, 2013).

Bycatch reduction technology in shrimp trawls relies, in part, on a fundamental behavioral difference between fish and shrimp. Fish respond to the approaching components of the trawl with a patterned avoidance, or optomotor (station-keeping), response, while shrimp exhibit either no response or a more random, reflexive and unpatterned response (Hannah et al., 2003; Wardle, 1993; Watson et al., 1992). However, the patterned response of fish that can be used to separate them from shrimp depends on the fish's ability to see the approaching trawl components and respond to them (Kim and Wardle, 2003). In our second experiment, we tested whether using artificial lights to make the fishing line of an ocean shrimp trawl more visible to eulachon and other fish species would enhance their ability to avoid the net and escape under it, generating bycatch reduction with little or no shrimp loss.

2. Methods

2.1. Field methods

We evaluated the effect of artificial light on fish bycatch in ocean shrimp trawl nets by comparing catches from the port and starboard nets of a double-rigged shrimp vessel, with one net incorporating artificial lighting and the other acting as a control. To generate artificial light underwater we used a number of green (centered on 540 nm, ≥0.5–2.0 lx) or blue (centered on 460 nm, ≥0.5–2.0 lx) Lindgren-Pitman LED Electralume® fishing lights attached to selected portions of the trawl (detailed below). These lights were chosen for several reasons. They are small, inexpensive and use low amounts of battery power. They are also pressure-rated to water depths greater than the fishery operates at and are rugged enough to withstand the net handling procedures used by vessel operators. Green and blue lights were chosen simply because these colors transmit well through seawater.

Both experiments were conducted utilizing the 21 m double-rigged shrimp trawler F/V *Miss Yvonne*, out of Newport, Oregon, in July 2014. The trawl nets used were high-rise box trawls, typical for the ocean shrimp fishery. Each net had footrope and headrope lengths of 23 m and codend mesh size of 35 mm (BK, stretched). Each net was spread with 1.8 × 2.1 m wood and steel doors. All experimental hauls were conducted during daylight hours which is also typical for the fishery, as ocean shrimp are known to migrate vertically into the water column at night, becoming unavailable to bottom trawl gear (Pearcy, 1970). The study area chosen was the shrimp grounds between Cascade Head and Cape Lookout, Oregon (45.0–45.34°N. latitude), an area in which both eulachon and ocean shrimp were expected to be found in moderate abundance. For both experiments, each net incorporated a rigid-grate BRD with 19.1-mm bar spacing. Neither BRD incorporated a guiding panel to concentrate catch at the bottom of the grate (for a diagram of typical rigid-grate BRDs in this fishery, see Hannah and Jones, 2007). To avoid catches that were too large to sort and weigh with the staff available, areas where moderate levels of shrimp catch were expected were targeted and haul duration was also limited to about 45–75 min. Commercial fishery hauls are frequently of this duration but are sometimes as long as 2–4 h, depending on anticipated catch and bycatch levels. Towing speed over ground was typical for ocean shrimp trawling, ranging from 3.0 to 3.3 km h^{-1} (1.6–1.8 kt).

We used three techniques to control for potential differences in catch efficiency between the two nets. First, both nets were inspected to ensure they were similarly constructed. Second, the treatment effect was interchanged periodically between the two nets at regular intervals. Lastly, we used recording inclinometers attached to the fishing line of each net to measure and equalize fishing line height (FLH) between the two nets. FLH has been shown to strongly influence both shrimp catch and fish bycatch in ocean shrimp trawls (Hannah and Jones, 2003). The inclinometers were also used continuously on both nets throughout our study so that hauls in which the equality of FLH between the nets was compromised by large debris getting tangled on the footrope of one net could be excluded prior to data analysis. The inclinometer data showed that both nets were fishing at comparable FLH throughout the 8 days of experiments, with some normal haul-to-haul variability (Fig. 1). No hauls were excluded due to abnormal variation in the FLH of a particular net.

Handling of data in the field was similar for both experiments. The catch from each net was emptied into one side of a divided hopper, and then sorted to species and counted and weighed at sea. In a few cases, hauls were subsampled (approximately 30 kg) by weight before sorting and total weight by species was estimated from the species composition of the subsample and the total catch weight. Eulachon and juvenile rockfish (*Sebastes* spp.) were placed

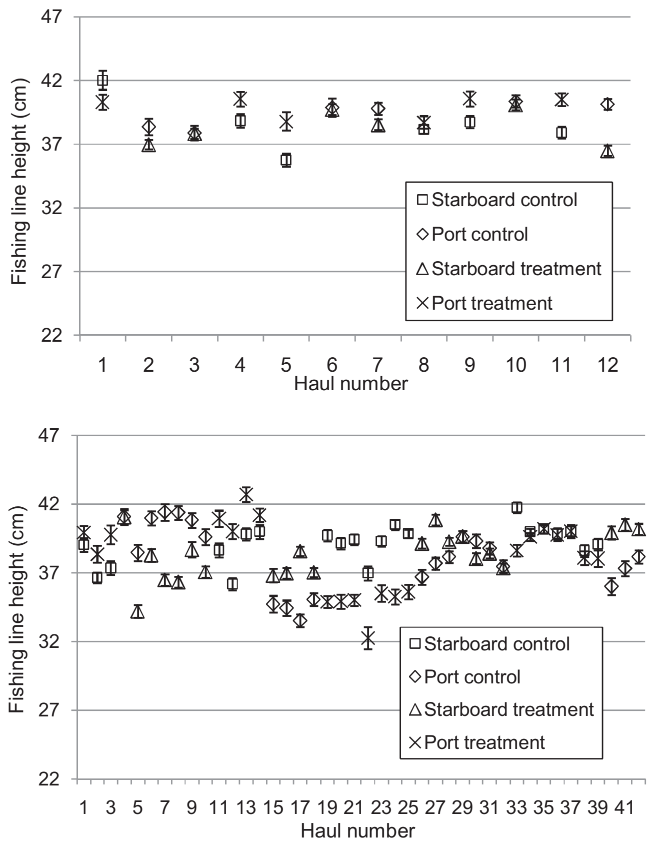


Fig. 1. Mean fishing line height (cm, measured at the center of the fishing line) in port and starboard nets, by treatment, in fishing experiments comparing catches in ocean shrimp trawl nets with 1–4 LED lights attached in the vicinity of the bycatch reduction device (upper panel) and with 10 LED lights attached to the trawl fishing line (lower panel), by haul number.

into labeled sample bags and frozen for later lab analysis. Lengths (TL, mm) were measured only for eulachon and were generated during lab analysis. In some cases, the complete eulachon catch for one or both nets was too large to retain. For those catches, a subsample (approximately 1–2 kg) was bagged and frozen and the rest were weighed and discarded at sea.

Light levels inside the nets were measured using Wildlife Computers TDR-MK9 archival tags. 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:

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

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

2.2. Artificial light near the rigid-grate BRD

The initial light configuration tested was four green Lindgren-Pitman Electralume® LED lights attached with zip-ties directly to the forward side of the rigid-grate BRD, spaced evenly around the edges of the circular grate. Several different locations in the vicinity of the BRD were also tried, with either green or blue lights. Due to the difficulty of interpreting effects of the different light configurations with such small sample sizes, we present all of the data combined from 12 hauls over two days of field trials with lights on, or near, the BRD, including behind the BRD and arranged around the escape hole in front of the BRD, as all results were similar. For this experiment, we attached the Wildlife Computers TDR-MK9 archival tags on the floor of each net facing upward, directly in front of the BRD, to measure light levels in-situ both with and without the LED lights.

2.3. Artificial light along the fishing line

To evaluate the effect of artificial light in the vicinity of the trawl footrope, we attached 10 green Lindgren-Pitman Electralume® LED lights with zip-ties directly to the central 40% of the fishing line of the trawl (Fig. 2). Lights were equally spaced at about 1.2 m apart. We conducted 42 hauls evaluating this configuration, switching the lights from the port to the starboard net periodically over 6 days of field trials. For this experiment the MK9 archival tags were attached to the floor of the net directly behind the center of the fishing line, facing upward, to measure light levels near the seafloor in each net.

2.4. Data analysis

Catch weight (kg) data were analyzed as a 3-factor ANOVA, with haul, side of gear (port or starboard) and the treatment as main effects without interaction, following Hannah et al. (2011). For some species or species groups, transformations were utilized to achieve normality of model residuals. Length data for eulachon were expected to be multi-modal and therefore length samples were compared between treatment and control nets using the non-parametric Wilcoxon two-sample test (Sokal and Rohlf, 1981) and also evaluated graphically. For graphical comparison, length frequency sample data, by treatment, were combined across hauls using a catch-weighted average and expressed as a percentage of the total frequency.

3. Results

3.1. Artificial light near the rigid-grate BRD

The first four hauls with green LED lights attached directly to the rigid-grate BRD (hauls 1–4) showed a strong and unexpected result of greatly increased eulachon bycatch in the net incorporating the lights (Fig. 3). Subsequent hauls with 1 green light attached to the BRD escape opening (hauls 5–8), 4 green lights behind the rigid-grate (hauls 9–10) and 3 blue lights attached to the edges of the escape opening (hauls 11–12) provided similar results (Fig. 3). Blue lights were used on the last two hauls to see if difference in color would strongly alter the results being observed. For these 12 hauls, fishing line height (cm) was well equalized between the port and starboard nets, averaging (±SE) 39.6 (±0.3) and 38.4 (±0.5) cm for the port and starboard nets, respectively, (Fig. 1). After 12 hauls, further experimentation with lights near the BRD was abandoned in favor of using the remaining vessel time to investigate the effects of artificial light at the footrope, a change that was also necessitated by the need to limit, to the extent practicable, total eulachon catch mortality in these two experiments.

The mean ambient light level (±SE) measured in front of the rigid-grate BRD in the control net during this experiment was 3.11×10^{-5} ($\pm 1.05 \times 10^{-5}$) μmol photons m^{-2} s^{-1} and ranged from 5.70×10^{-7} to 1.30×10^{-4} μmol photons m^{-2} s^{-1} (Fig. 4). The LED lights in the vicinity of the BRD increased the average light level measured at this location to 3.86×10^{-3} μmol photons m^{-2} s^{-1} ($\pm 1.00 \times 10^{-3}$), or about 1–2 orders of magnitude (Fig. 4).

Considered together, these 12 hauls showed that artificial light in the vicinity of the rigid-grate BRD increased eulachon bycatch by 104% (all by weight unless noted, $P = 0.0005$, Table 1), but had

Fig. 2. Image of a green Lindgren-Pitman Electralume® LED light zip-tied to the fishing line of an ocean shrimp trawl (lower left); image of the placement of a green LED in relation to the drop-chains and groundline of an ocean shrimp trawl (upper left); image depicting green LED lights attached to the fishing line of an ocean shrimp trawl prior to trawl deployment (right).

no effect on shrimp catch or the bycatch of darkblotched rockfish (*S. crameri*) or other juvenile rockfish ($P > 0.05$). Interestingly, the bycatch of slender sole (*Lyopsetta exilis*) was also increased by 77% when artificial light was present in the vicinity of the BRD ($P = 0.0082$, Table 1) while bycatch of other small flatfishes was not influenced ($P > 0.05$). Eulachon captured in the treatment net were slightly larger than in the control net, with the treatment and control catch samples averaging (±SE) 123.1 (±0.5) and 121.1 (±0.5) mm, respectively ($P = 0.0158$). The graphical comparison of length frequency (Fig. 5, upper panel) suggests that some of the larger eulachon, which typically would have escaped the net via the BRD in the absence of artificial light, passed through the rigid-grate BRD more frequently when artificial light was present. Given the large increase in eulachon bycatch with artificial lights near the rigid-grate (Table 1) and the very modest shift in eulachon length (Fig. 5, upper panel), the influence of artificial light on eulachon behavior near the rigid-grate was not considered to be strongly size-based.

3.2. Artificial light along the fishing line

Along the fishing line, the effect of introducing green artificial light in 42 comparison hauls was nearly opposite of what we observed at the rigid-grate BRD. The LED lights reduced eulachon bycatch by 91% (Fig. 6, Table 2, $P = 0.0001$). The lights also reduced

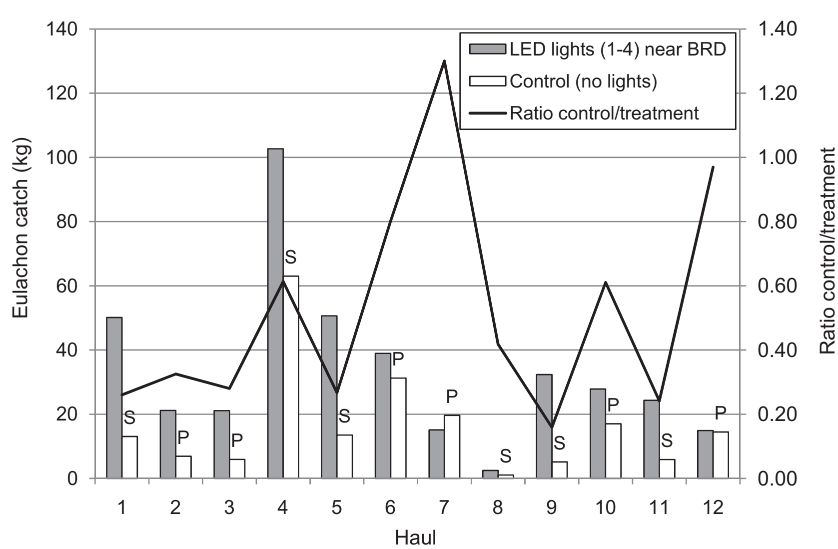


Fig. 3. Haul-by-haul comparison of the catch of eulachon (kg) in the two nets of a double-rigged shrimp trawl vessel with one side incorporating 1–4 LED lights near the bycatch reduction device (see text for light configuration by haul number) and the other acting as a control (no lights). The ratio of control/treatment catch is also shown (solid line). Label “P” or “S” denotes the side of trawl gear (port or starboard) used as the control net.

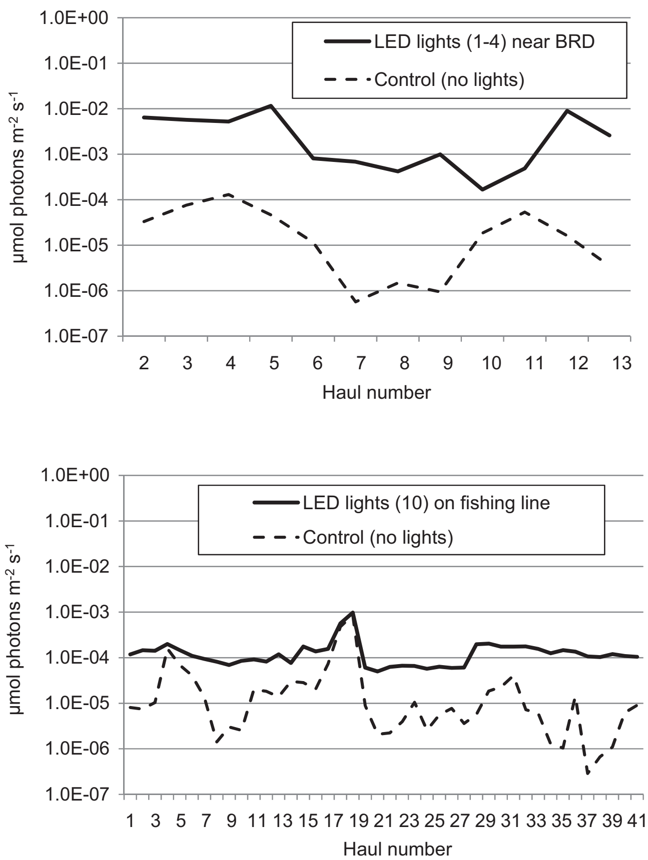


Fig. 4. Light levels (μmol photons m^{-2} s^{-1}), by treatment and haul number, measured in the fishing experiments testing the effect of 1–4 LED lights in the vicinity of the bycatch reduction device (upper panel, see text) and 10 LED lights attached to the trawl fishing line (lower panel, see text).

juvenile darkblotched rockfish bycatch by 82% (Table 2, P = 0.0001) and bycatch of other juvenile rockfishes by 56% (Table 2, P = 0.0004). Bycatch of slender sole and other small flatfishes were both also reduced 69% (Table 2, P = 0.0001). The presence of the LED lights at the footrope had no measurable effect on shrimp catches, with shrimp catches in the net with lights reduced on average by just 0.7%, a difference that was non-significant (Table 2, P > 0.05).

The mean ambient light level measured at the control net during the footrope experiment was 4.84×10^{-5} ($\pm 2.30 \times 10^{-5}$) μmol photons m^{-2} s^{-1} and ranged from 2.88×10^{-7} to 8.56×10^{-4} μmol photons m^{-2} s^{-1}, indicating similar levels of ambient light on the seafloor in the two experiments (Fig. 4). The LED lights on the fishing line increased the average light level measured to 1.47×10^{-4} ($\pm 2.40 \times 10^{-5}$) μmol photons m^{-2} s^{-1}. This difference probably understates the increase in light available directly under the net because the MK9 archival tags were oriented upwards such that any added light from the artificial lights secured to the fishing line would have reached the sensor only indirectly. The addition of lights to the fishing line did not alter the mean size of eulachon captured (P > 0.05), but did alter the shape of the distribution. The graphical comparison of length frequency in the treatment and control nets (Fig. 5, lower panel) shows a pattern that is consistent with a weak density-dependent escapement response. The largest relative proportional decrease in eulachon capture was between 116 and 134 mm, the length range in which eulachon were also most abundant, with relatively reduced effects for both smaller and larger-sized eulachon. The mean fork length of eulachon captured in the control net in this experiment was 127.7 (±0.4) mm, slightly larger than in the first experiment.

4. Discussion

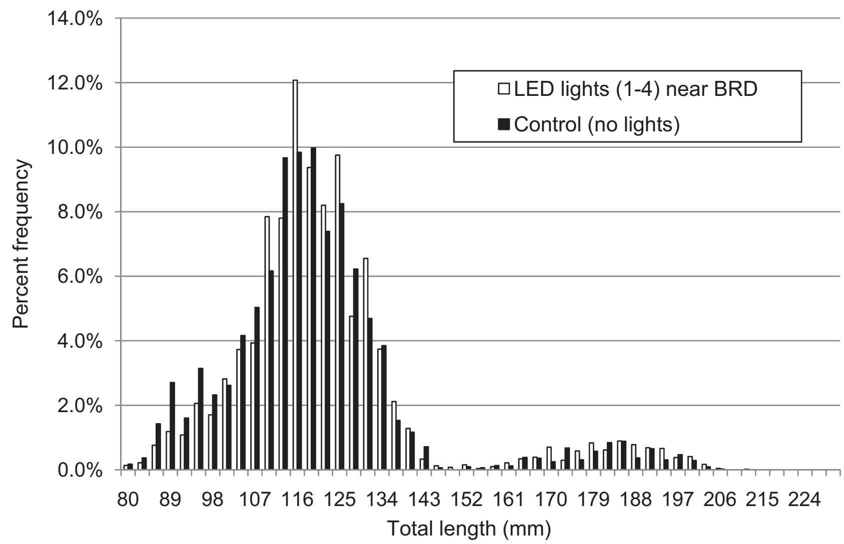
The addition of LED lights along the fishing line of an ocean shrimp trawl was highly effective at reducing bycatch of all sizes of eulachon, an important result for a species of current high conservation concern (Gustafson et al., 2012), with negligible loss of ocean shrimp. The lights also caused a large percentage reduction in the bycatch of juvenile darkblotched rockfish, a depressed species, as well as large reductions in bycatch of other small fishes. These results illustrate the increased effectiveness of bycatch reduction technologies for small fishes when implemented near the front of the trawl, where these fish retain more swimming ability. Facilitating escapement at the front of the trawl may also minimize adverse effects on escaping fish from their interactions with the trawl. These fish are spared the exhaustion, crowding and physical contact with trawl components that can occur prior to exclusion via rigid-grate BRDs (Hannah and Jones, 2012; Soldal and Engås, 1997) or escapement through trawl meshes (Ryer et al., 2004; Suuronen et al., 1996, 2005). We would expect such a brief encounter with the trawl to have minimal impact on subsequent survival. It is worth noting also, that our results are based on measuring the residual bycatch in nets with fully functioning rigid-grate BRDs with 19.1 mm bar spacing. Thus, we could not have sampled large fish that would typically be excluded by the BRD and are uncertain how many of these fish may have also completely avoided trawl entrainment.

Our two experiments obtained strong but opposite effects on eulachon bycatch from adding artificial lights in the vicinity of the rigid-grate BRD and along the fishing line. Although the effect on

Table 1
Comparison of mean catch by species or group (weight, kg $haul^{-1}$ except for darkblotched rockfish, other juvenile rockfishes and other small flatfish, which are expressed as g $haul^{-1}$) between ocean shrimp trawl nets equipped with artificial LED lights in the vicinity of a rigid-grate bycatch reduction device (BRD) with 19.1 mm bar spacing. Species were captured off the Oregon coast in 12 hauls employing double-rigged nets, one incorporating artificial lights near the BRD, during July 2014. SE = standard error.

	Artificial lights	Control net (no lights)	Percent reduction with lights (%)	
Species or group	Mean catch (SE)	Mean catch (SE)		P-value[1]
Ocean shrimp *Pandalus jordani*	117.05 (26.13)	117.08 (27.56)	0.0	ns
Pacific eulachon *Thaleichthys pacificus*	33.48 (2.42)	16.40 (2.42)	−104.2	0.0005
Slender sole *Lyopsetta exilis*	1.49 (0.25)	0.84 (0.16)	−77.4	0.0082
Other small flatfish	291.06 (54.70)	287.28 (89.70)	−1.3	ns
Darkblotched rockfish *Sebastes crameri*	389.88 (109.80)	428.42 (135.07)	9.0	ns
Other juvenile rockfish *Sebastes* spp.	71.50 (17.25)	109.34 (34.83)	34.6	ns

[1] 3 factor ANOVA (see text).



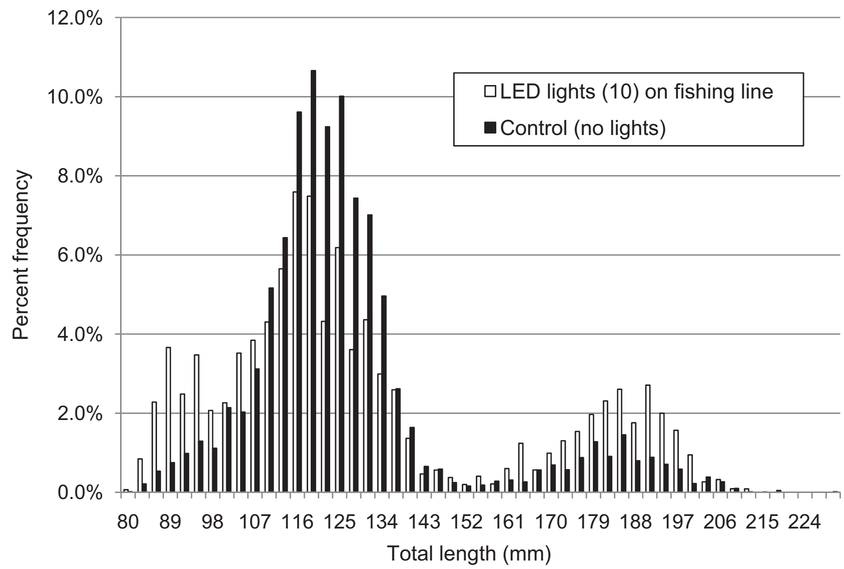


Fig. 5. Percent length frequency of eulachon (total length, mm) captured in ocean shrimp trawl nets with and without 1–4 LED lights attached in the vicinity of the bycatch reduction device (upper panel) and with and without 10 LED lights attached to the trawl fishing line (lower panel).

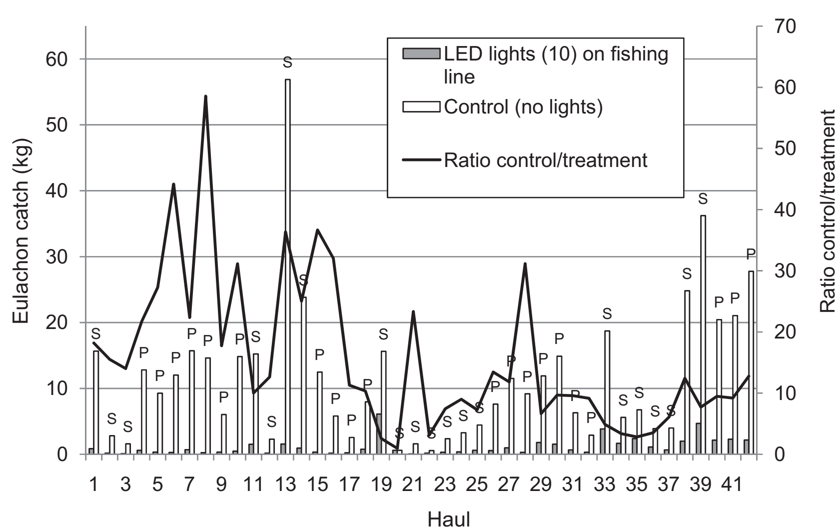


Fig. 6. Haul-by-haul comparison of the catch of eulachon (kg) in the two nets of a double-rigged shrimp trawl vessel with one side incorporating 10 LED lights on the fishing line and the other acting as a control. The ratio of control/treatment catch is also shown (solid line). Label “P” or “S” denotes the side of trawl gear (port or starboard) used as the control net.

Table 2
Comparison of mean catch by species or group (weight, kg $haul^{-1}$ except for darkblotched rockfish, other juvenile rockfishes and other small flatfish, which are expressed as g $haul^{-1}$) between ocean shrimp trawl nets equipped with artificial LED lights attached to the fishing line (at the footrope, see text) and a control net with no lights. Species were captured off the Oregon coast in 42 hauls employing double-rigged nets, one incorporating the artificial lights, during July 2014. SE = standard error.

Species or group	Artificial lights	Control net (no lights)	Percent reduction with lights (%)	*P*-value[1]
	Mean catch (SE)	Mean catch (SE)		
Ocean shrimp *Pandalus jordani*	203.68 (24.19)	205.15 (23.69)	0.7	ns
Pacific eulachon *Thaleichthys pacificus*	1.12 (0.20)	11.77 (1.68)	90.5	0.0001
Slender sole *Lyopsetta exilis*	0.72 (0.17)	2.29 (0.35)	68.6	0.0001
Other small flatfish	171.18 (28.24)	559.97 (60.25)	69.4	0.0001
Darkblotched rockfish *Sebastes crameri*	95.44 (21.63)	537.23 (91.01)	82.2	0.0001
Other juvenile rockfish *Sebastes* spp.	55.09 (22.40)	126.13 (29.73)	56.3	0.0004

[1] 3 factor ANOVA (see text).

bycatch was opposite, the mechanism behind the changes in behavior may be similar. For eulachon, our initial hypothesis of "increased avoidance" of the rigid grate or fishing line with artificial lighting cannot account for these results; it is inconsistent with increased bycatch with an illuminated rigid-grate BRD. In each experiment, the addition of artificial light appears to have encouraged eulachon to pass through a restricted open space with much greater consistency, either between the bars of the rigid-grate BRD or between the fishing line and groundline of the trawl, with, of course, opposite effects on escapement. This reasoning suggests that the successful exclusion of most eulachon by rigid-grate BRDs depends, to some degree, on the BRD being only poorly illuminated under typical seafloor ambient light conditions in this fishery. If this is correct, it follows that for some small fishes that can pass through the bars of a rigid-grate BRD but retain some swimming ability as they encounter the BRD, modifications to the grate to make it less visible to fishes, such as changing the color of the grate or even the shape of the vertical bars, may improve exclusion efficiency. Such modifications would be expected to be most effective in situations where typical seafloor ambient light levels are similar to or higher than in the ocean shrimp fishery.

The exact mechanism behind these divergent effects from artificial lighting is unknown. We speculate that the increased movement of fishes through restricted spaces in both experiments may have to do with illuminating the area behind the "threatening" object, either the rigid-grate BRD or the trawl groundline. In both instances, the effect likely encouraged some species to also move downwards, perhaps exploiting a natural tendency to move towards the seafloor when threatened. It is also possible that artificial illumination simply increases the contrast between the trawl components and the background, facilitating fish navigating between the trawl components, or possibly giving fish more time to react to the approaching threat. Glass and Wardle (1995) and Glass et al. (1995) showed that for some species trawl mesh escapement behavior could be modified by changing the relative contrast of light and dark trawl components. In our first experiment, there were statistically non-significant reductions in bycatch of juvenile rockfishes with artificial lights near the rigid-grate BRD (Table 1), suggesting the effects of altering the contrast or visibility of the BRD may also be variable between species. The effect of adding artificial lights is also likely to vary with changes in ambient light on the seafloor, and thus with depth and time of day, as well as fish density and other factors (Godø et al., 1999; Walsh and Godø, 2003). The comparison of length frequency data from the nets with and without LED lights on the fishing line (Fig. 5, lower panel) suggests that, for eulachon, escapement between the groundline and fishing line of an ocean shrimp trawl involves a weak density-dependent component. This is also supported by the apparent association of large percentage reductions in eulachon catch with LED lights on the fishing line with larger eulachon catches in the control net (Fig. 6).

Although we were surprised by these results, they are consistent with partial results from some studies of fish behavior under different light intensities. Weinberg and Munro (1999) noted increased escapement of flathead sole (*Hippoglossoides elassodon*) under a survey trawl footrope in the presence of artificial light, but no effect on other species. In a Pacific hake (*Merluccius productus*) midwater trawl, Lomeli and Wakefield (2012) noted Chinook salmon (*Oncorhyncus tshawytscha*) had a stronger tendency to exit an open escape window that artificial light was directed towards. However, this behavior was not exhibited by widow rockfish (*Sebastes entomelas*). In contrast, in our study, adding artificial light along the fishing line of an ocean shrimp trawl greatly increased escapement for a wide variety of fishes (Table 2).

Our results from adding artificial lights in the vicinity of the BRD conflict somewhat with the prior behavioral analysis of eulachon escaping via a rigid-grate BRD as detailed by Hannah and Jones (2012). In that study, most large eulachon were observed avoiding contact with the grate and swimming upwards and out of the exit hole, just in front of the grate, while a small percentage were observed swimming directly aft through the grate. In our current study, artificial light near the BRD greatly reduced the exclusion efficiency of the rigid-grate BRD for eulachon, causing large numbers to swim aft through the grate. Since artificial lighting was present in both studies, the two findings are difficult to reconcile. However, there were three notable differences in the lighting used in these two studies, the color of the lighting, the intensity and its orientation. Hannah and Jones (2012) used a single white Deep Sea Power and Light LED Mini-Sealite® (50 W, 3000 °K, 950 lm) aimed across the rigid-grate, while in this study we used 1–4 weaker, more diffuse, green or blue LED Lindgren-Pitman lights in several locations on or near the rigid grate. It's possible that the diffuse LED lights used in this study were more effective at illuminating the area behind the rigid-grate than the Mini-Sealite® that was pointed directly across the surface of the grate.

To our knowledge, our results with artificial light along the fishing line represent the first successful application of artificial light to modify fish escapement behavior in a trawl to greatly reduce bycatch. Importantly, the type of lights we tested that generated high levels of bycatch reduction have an excellent potential for implementation at a fishery scale and may help to greatly reduce total fish bycatch in this fishery. As word of the results from our study spread through the California, Oregon and Washington shrimp fleets, numerous vessel operators began buying and attaching green LED lights to the fishing lines of their trawls, reporting results very similar to our research findings.

It will be interesting to see if the results from our study find application in other trawl fisheries to reduce bycatch. Most other trawl fisheries utilize nets that lack the large open space between the groundline and the fishing line that is typical for ocean shrimp trawls. Thus, simply illuminating the fishing line or groundline in most other trawl fisheries seems unlikely to be similarly effective. However, there may be some ways to use the behavioral changes that underlie our results to reduce bycatch elsewhere. For example, placing a large mesh panel behind the fishing line of a shrimp, prawn or finfish trawl, along with LED lights to illuminate the panel and the seafloor below, might increase small fish escapement through the panel and reduce bycatch, with minimal effect on the catch of the target species. Of course, such modifications would only be likely to be useful in trawl fisheries operating at low seafloor ambient light levels similar to the ocean shrimp trawl fishery, such as fisheries operating at similar depths, or trawl fisheries that operate primarily at night.

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