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The effect of artificial illumination on Chinook salmon behavior and their escapement out of a midwater trawl bycatch reduction device

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ABSTRACT

The Pacific hake (*Merluccius productus*) midwater trawl fishery is the largest groundfish fishery off the U.S. West Coast by volume. Catches comprise mainly Pacific hake, however, bycatch of Chinook salmon (*Oncorhynchus tshawytscha*) can be an issue affecting the fishery as Endangered Species Act (ESA) listed Evolutionarily Significant Units represent a portion of the total Chinook salmon bycatch. We conducted two separate experiments evaluating the influence of artificial illumination on Chinook salmon behavior and their escapement out a bycatch reduction device (BRD) in a Pacific hake midwater trawl. In Experiment 1, we tested whether Chinook salmon could be attracted out specific escape windows of a BRD equipped with multiple escape windows using artificial illumination. In Experiment 2, we compared Chinook salmon escapement rates out of the BRD between tows conducted with and without artificial illumination to determine if illumination can enhance their escapement. Our results show that artificial illumination can influence where Chinook salmon exit out of the BRD, but also demonstrate that illumination can be used to enhance their escapement overall. As conservation of ESA-listed Chinook salmon is an ongoing management priority, our research contributes new information on how artificial illumination can minimize adverse interactions between the Pacific hake fishery and Chinook salmon.

1. Introduction

Along the U.S. West Coast there are 17 Evolutionarily Significant Units (ESUs) identified for Chinook salmon (*Oncorhynchus tshawytscha*). Of these ESUs, two are listed as “endangered” and seven as “threatened” under the U.S. Endangered Species Act (ESA) (National Marine Fisheries Service, West Coast Region (NMFS WCR, 2017a). As these ESA-listed Chinook salmon ESUs intermix with other fish populations, commercial fisheries targeting healthy fish stocks can be restricted at times to ensure catches of ESA-listed Chinook salmon do not exceed conservation thresholds. Aside from a directed Chinook salmon troll fishery and a limited river gillnet fishery, Chinook salmon catches are prohibited in West Coast commercial fisheries.

The Pacific hake (*Merluccius productus*), also known as Pacific whiting or whiting, midwater trawl fishery is the largest groundfish fishery off the U.S. West Coast by volume. Over the past five years, annual landings of Pacific hake have averaged 259,805 MT (Pacific Fisheries Information Network (PacFIN, 2019). Catches comprise mainly Pacific hake (typically > 95% by volume), however, bycatch of Chinook salmon can be an issue affecting the fishery as ESA-listed ESUs represent a portion of the total Chinook salmon bycatch. The current ESA biological opinion issued for the West Coast groundfish fishery addresses the potential effects of Chinook salmon bycatch in the Pacific hake fishery by restricting the annual bycatch of Chinook salmon to 11,000 individuals (National Marine Fisheries Service, West Coast Region (NMFS WCR, 2017a). If this bycatch threshold is exceeded, then conservation measures such as the Ocean Salmon Conservation Zone (OSCZ) may be implemented. The OSCZ is a zone shoreward of a boundary line that approximates the 183 m (100 fathom) depth contour where Pacific hake fishing vessels are prohibited from trawling. In 2014, the fishery exceeded the 11,000 Chinook salmon bycatch threshold resulting in the implementation of the OSCZ (National Marine Fisheries Service, West Coast Region (NMFS WCR, 2014), which affected the fleet's access to the Pacific hake stock. As ocean distributions of Chinook salmon and Pacific hake can overlap, interactions between Pacific hake trawl gear and Chinook salmon are likely to remain an issue for the fishery. Hence, developing techniques that minimize Chinook salmon bycatch are important to fishers, management, and the

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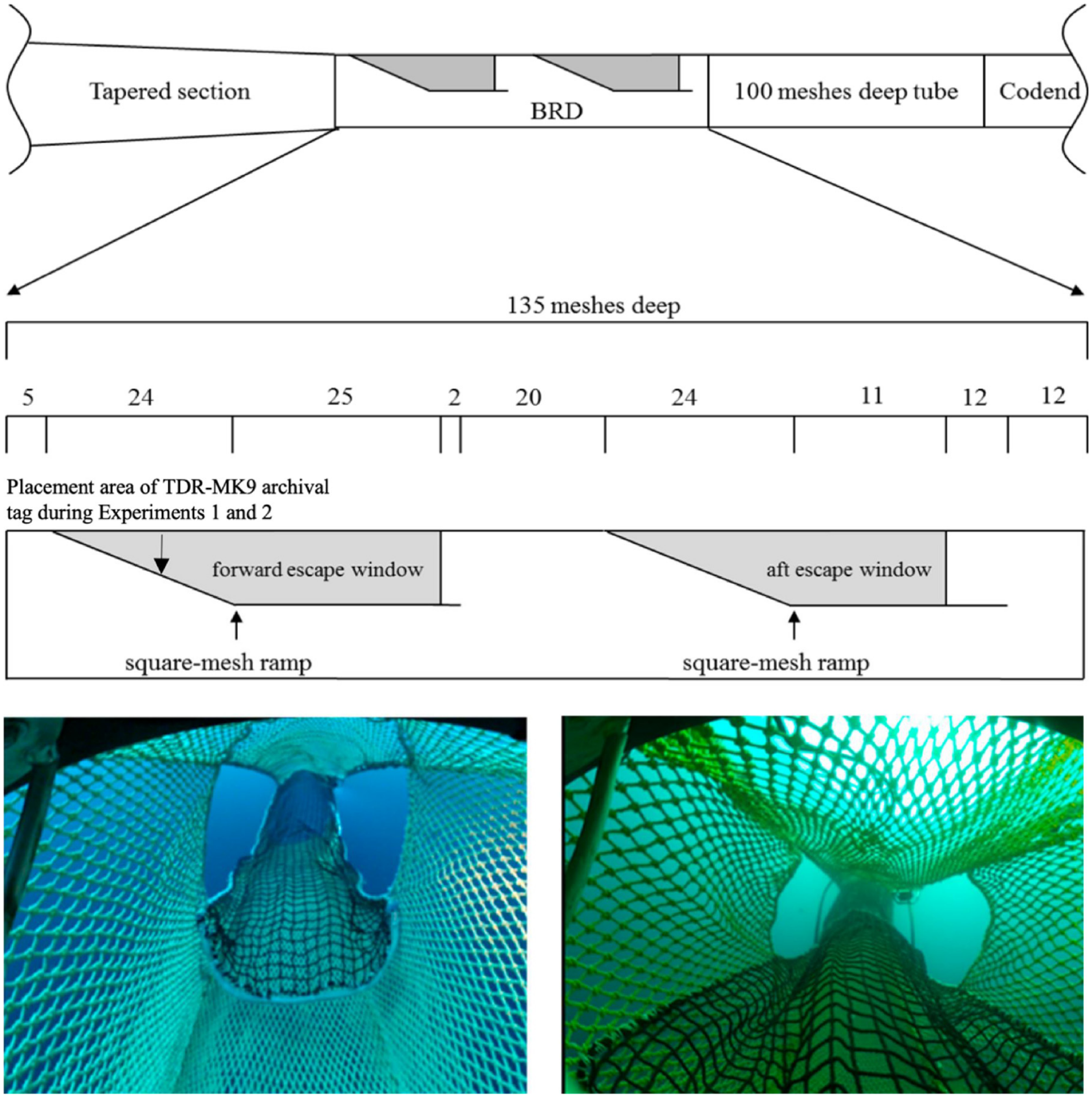

Fig. 1. Schematic diagram of the open escape window BRD tested in Experiment 1 and 2 (top); forward view of the forward set of escape windows under ambient light (left image); forward view of the aft set of escape windows under ambient light (right image). Note: diagram not to scale.

conservation of ESA-listed Chinook salmon.

Use of artificial illumination to reduce fish bycatch in trawl fisheries has recently received considerable attention (Hannah et al., 2015; Larsen et al., 2017, 2018; Grimaldo et al., 2018; Lomeli et al., 2018a,b; Melli et al., 2018). These studies have mostly used illumination as a technique to enhance fishes' visual perception of trawl gear components and escape areas. In the ocean shrimp (*Pandalus jordani*) trawl fishery, researchers have placed LEDs along trawl fishing lines to illuminate open spaces between the fishing line and groundline, and observed significant catch reductions for eulachon (*Thaleichthys pacificus*), juvenile rockfishes (*Sebastes* spp.), and flatfishes without impacting ocean shrimp catches (Hannah et al., 2015; Lomeli et al., 2018a). Comparing an unilluminated trawl to a trawl with an illuminated headrope in the U.S. West Coast groundfish bottom trawl fishery, Lomeli et al. (2018b) found that the illuminated trawl caught significantly fewer sablefish (*Anoplopoma fimbria*) and Dover sole (*Microstomus pacificus*). Catches of other groundfishes did not differ between the two trawls. Research has also used illumination in efforts to startle fish towards mesh sorting panels. For example, in the Barents Sea demersal trawl fishery, Grimaldo et al. (2018) positioned LEDs on lines with floats in the center of a square mesh section (creating a moving effect of the stimuli and a physical barrier) in efforts to improve the release efficiency for smaller-sized cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) by startling them towards the square mesh netting. Findings showed haddock displayed an erratic behavioral response to the illumination and reacted by swimming quickly either towards the square mesh netting or the codend. When interacting with the square mesh netting, however, they were not optimally oriented for escapement. Cod, on the other hand, did not display a noticeable behavioral response to the illumination and continued to move aft towards the codend.

In the Pacific hake fishery, Lomeli and Wakefield (2012) conducted research on a bycatch reduction device (BRD) that is similar to the design that is subject of the current study. Video camera systems outfitted with LED lights were used to measure fish escapement out the BRD. While the study was not focused on the effect of artificial illumination on fish behavior and escapement rates, they found that a significant proportion of Chinook salmon exited out of an escape window where artificial illumination was directed towards. These observations suggested that artificial illumination could potentially be used to reduce Chinook salmon bycatch.

The objectives of this study were to: 1) test whether artificial illumination can influence which escape window Chinook salmon utilize when exiting a BRD, and 2) determine if artificial illumination can enhance Chinook salmon escapement overall.

2. Materials and methods

We carried out two experiments aboard the *F/V Miss Sue*, a 24.7 m long, 640 horsepower trawler out of Newport, Oregon. Experiment 1 occurred off Oregon between 43°30′ and 45°09′N and between 124°17′ and 124°55′W in September 2015, whereas Experiment 2 occurred off Oregon between 43°37′ and 45°33′N and between 124°01′ and 124°57′W in May and November 2017. We used the commercial trawler's midwater trawl which had a headrope, footrope, and mouth opening measurement of 125, 164, and 36 m, respectively. Both experiments were conducted between sunrise and sunset hours at an average seafloor depth of 195 m and average headrope fishing depth of ca. 135 m (measured using a Wesmar TCS series trawl sonar). Towing speed ranged from 2.7 to 3.2 knots.

2.1. BRD design

The BRD was built around a four-seam tube of Euroline premium diamond netting 102 mm knot-to-knot nominal mesh size (6.0 mm single twine) that was 135 meshes long and 136 meshes in circumference, excluding meshes in each selvedge. This BRD design consisted of two Ultra Cross knotless square mesh netting ramps of 108 mm center-to-center nominal mesh size (800 ply) that were inserted inside the BRD tube of netting. The square mesh ramps are designed to guide actively swimming fish toward two large sets of escape windows cut out of each side of the net on the upper portions of the port and starboard side panels (Fig. 1).

In Experiments 1 and 2, we attempted to make several tows each day to increase the probability of encountering Chinook salmon and obtaining the data needed to answer our research questions. However, this created logistical difficulties for sampling catches of Pacific hake aboard a catcher vessel. Specifically, 1) single tow catches of Pacific hake often occur in volumes too large (e.g., > 30 MT) to weigh at sea using fish baskets (48 × 48 × 43 cm, L × W × H) and require delivering to a shore-side processing plant (a transit upwards to 8 h depending on fishing location) where the catch data can be quantified, and 2) the vessel's fish holds are typically not configured to separate catches beyond one or two tows. Considering these factors and vessel time, we elected not to retain and deliver Pacific hake to a shore-side processing plant for data processing. Further, not focusing on quantifying Pacific hake escapement in this study was based on prior gear trials (conducted by the current authors) that have shown Pacific hake lack the ability to escape out of this BRD design in meaningful numbers. When testing this BRD design in the absence of artificial illumination, the mean escapement of Pacific hake was found to be < 2% by weight (Table 1). Under conditions where this BRD design was tested in the presence of illumination, video observations showed Pacific hake rarely escaped (Lomeli and Wakefield, 2012; PSMFC unpubl. data 2014). Supplementary Video 1 shows footage of Pacific hake and their behavior as they encounter this BRD design in the presence of illumination (PSMFC, unpubl. data 2014).

2.2. Artificial illumination

Lindgren-Pitman Electralume® blue LED fishing lights, wavelength centered on 464 nm (Nguyen et al., 2017), were used as the artificial light source. Blue colored LEDs were selected as this wavelength transmits the furthest in water and the predominant spectral component of coastal and continental shelf waters in this region is blue-green light (Jerlov, 1976; Bowmaker, 1990; Schweikert et al., 2018). In both experiments, the lights were grouped into clusters of two andattached

Table 1
Pacific hake catch by weight (MT) from 2011 gear trials using a recapture net to evaluate the catch performance of the BRD presented in Fig. 1 under fishing conditions without LEDs on the BRD.

Trip	No. of tows	Pacific hake catch totals		
		Recapture net	Trawl codend	Codend retention (%)
1	2	1.35	111.35	98.8
2	1	1.86	99.49	98.2
3	2	0.95	100.32	99.1
4	1	1.51	87.83	98.3
5	1	0.86	96.05	99.1
6	2	0.86	104.39	99.2
7	1	0.21	36.61	99.4
8	1	0.86	44.49	98.1
9	2	1.01	113.36	99.1
Total	13	9.47	793.89	98.8

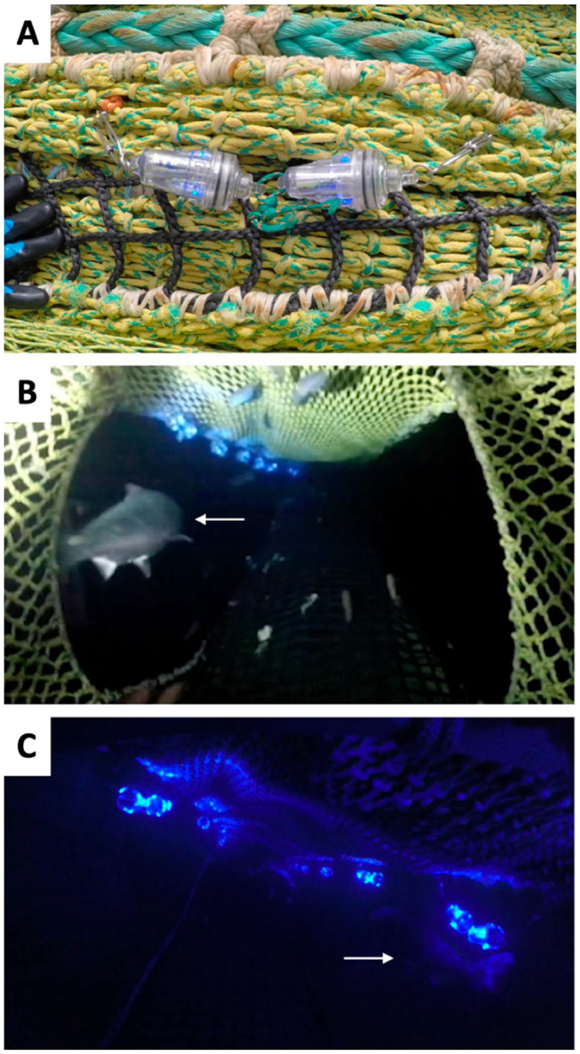

Fig. 2. Image of an LED cluster attached to the trawl netting in a horizontal position with the light-emitting end pointing forward (image A); forward view with LEDs attached along the port-side of the BRD of the forward escape window and a Chinook salmon exiting the BRD in Experiment 1 (image B); forward view with LEDs along port and starboard side forward escape windows and a Chinook salmon exiting the BRD in Experiment 2 (image C). Arrows depict Chinook salmon en route of exiting out of the BRD.

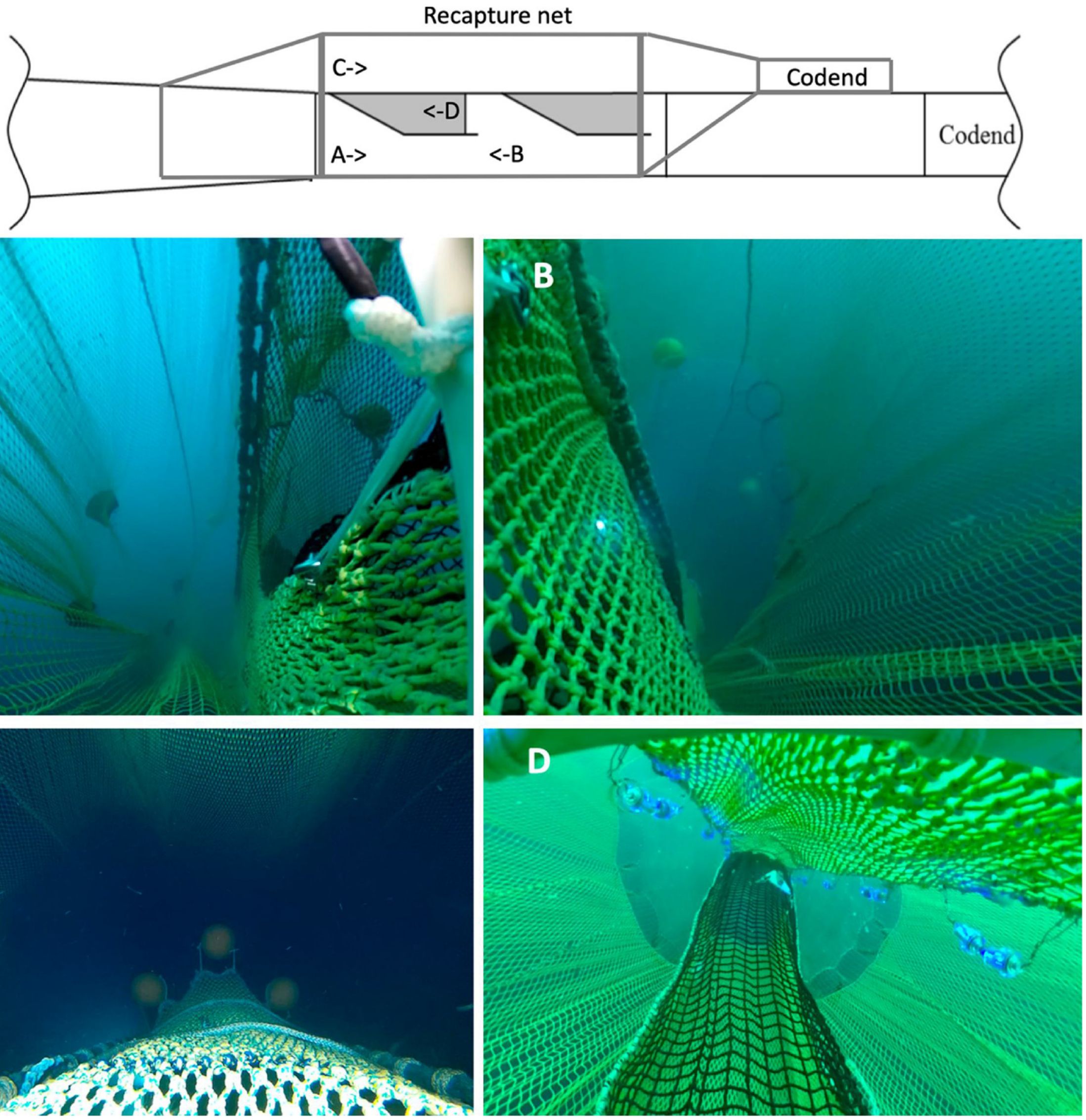

Fig. 3. Schematic diagram and images under ambient light examining the recapture net over the BRD in Experiment 2. Port-side aft view from outside of the BRD (image A); starboard-side forward view from outside of the BRD (image B); top panel aft view from outside the BRD (image C); forward view of the forward set of escape windows from within the BRD (image D). Note: diagram not to scale.

to the trawl netting in a horizontal position with the light-emitting end pointing forward (Fig. 2, image A) upon deployment and then removed upon retrieval to avoid damage when winding the trawl onto the net reel. Attachment points were marked with twine to assure that the placement of the LEDs was consistent on all tows.

In each experiment, a Wildlife Computers TDR-MK9 archival tag was used (attached to the front center section of the forward square mesh ramp and facing upward) to measure the amount of light available (Fig. 1). The calibration function used to convert the MK9 relative light units to irradiance units was:

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

where x is the relative light unit from the MK9 and y is the corresponding irradiance unit in μmol photons $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$ (Lomeli et al., 2018a).

2.3. Experiment 1: illuminating specific escape windows

To test whether artificial illumination could attract Chinook salmon out specific escape windows of the BRD, we attached clusters of LEDs inside the net along the outer edge of the top panel of either the port or starboard side escape windows (Fig. 2, image B). For example, if the port side was selected for illumination then the LEDs would only be attached along the forward and aft escape windows of the port side. The sequence in which the port and starboard side escape windows were illuminated was randomly selected. The LEDs were attached ca. 61 cm apart over the distance of the escape windows (Fig. 2, image B). Because the forward and aft sets of escape windows differ in length, this attachment distance resulted in 8 LED clusters along a forward escape window and 6 LED clusters along an aft escape window.

We used a video camera system at each escape window to observe fish behavior and escapement. Because the LEDs alone could not provide enough illumination for the cameras to produce an image of useable quality for identifying fish, we integrated a DeepSea Power and Light nano Sealite® white LED (color temperature = 6500–8000 K; lumens = 700; beam pattern 70° flood) with each camera system to obtain video of suitable quality. Each camera system was mounted on an ultra-high-molecular-weight board (60.9 × 30.4 × 2.5 cm, L × W × H) and placed in the same location on all tows inside the trawl against the center of the trawl top panel just aft of the escape openings. To avoid illuminating one side of the trawl more than the other with the nano

Table 2
Chinook salmon catch data for Experiment 1 tows where specific escape windows were illuminated. S = starboard; P = port; values in parentheses represent 95% confidence intervals surrounding the mean value; *p*-values in bold represent significant values.

Tow	LED side	No. observed	No. to exit the BRD	% to exit the BRD	No. of escapes that occurred out an LED window	% of escapes to occurred out an LED window	*p*-value
1	S	117	84	71.8	73	86.9	**< 0.0001**
2	P	6	0	0	0	0	n/a
3	P	0	–	–	–	–	–
4	S	11	6	54.5	5	83.3	0.1003
5	P	51	34	66.7	27	79.4	**< 0.0001**
6	S	25	19	76.0	16	84.2	**0.0002**
7	P	3	3	100.0	3	100.0	0.2482
8	S	12	5	41.7	5	100.0	0.0736
9	P	34	24	70.6	21	87.5	**< 0.0001**
10	S	27	17	63.0	14	82.4	**0.0015**
11	S	11	9	81.8	6	66.7	0.4795
12	P	38	24	63.2	17	70.8	**0.0433**
13	P	11	8	72.7	6	75.0	0.2207
14	S	53	45	84.9	38	84.4	**< 0.0001**
15	P	15	7	46.7	6	85.7	**0.0308**
16	S	24	14	58.3	6	42.9	0.7871
Total		438	299	68.3 (63.8–72.4)	243	81.3 (76.5–85.3)	**< 0.0001**

Sealite®, the light was positioned along the midline of the BRD. Thus, the only modification in the placement of artificial illumination between tows were the blue LEDs mounted along the BRD escape windows (Supplementary Video 2).

Tow durations were set to 3.5 h. to maximize video recording time. After each tow, codend catches were dumped on deck and sorted for Chinook salmon. Escapement rates were subsequently measured from combining the video and trawl codend catch data.

A one proportion Z test was used to examine whether the proportion of Chinook salmon to exit out an illuminated escape window was significantly greater than the proportion of Chinook salmon to exit out a non-illuminated escape window:

$$Z = \frac{\hat{p} - p_o}{\sqrt{\frac{p_o(1-p_o)}{n}}} \tag{2}$$

where $\hat{p}$ is the observed proportion, p_o is the null hypothesized proportion (0.5), and n is the sample size.

2.4. Experiment 2: comparing tows with and without artificial illumination

To determine the effect that illumination had on the overall escapement of Chinook salmon, we conducted tows with and without artificial illumination on the BRD. The only source of artificial illumination used in this experiment were the blue LED fishing lights. The sequence in which the trawl was fished with and without artificial illumination was randomly selected. When fishing with LEDs, all escape windows were illuminated (Fig. 2, image C). Seven LED clusters were used on each forward escape window, whereas 5 LED clusters were used on each aft escape window.

We used a recapture net with its main body constructed of Euroline premium diamond netting of 102 mm knot-to-knot nominal mesh size (3.5 mm single twine) to enumerate fish escapement out the BRD. The recapture net codend and trawl codend were also made of Euroline premium diamond netting of 102 mm knot-to-knot nominal mesh size, but with 6.0 mm single twine. A combination of trapezoidal-shaped kites (0.95 cm thick conveyor belt material; dimensions = 61 × 31 × 31 cm) and 28 cm diameter floats were used to spread and lift the recapture net open. Before data was collected, video camera systems with LED lights were used to confirm that the recapture net was performing as expected and not masking the BRD escape windows (Fig. 3; Supplementary Video 3). Once data collection began, the blue LEDs were the only source of artificial illumination present.

Tow durations were set to 1.5 h. to maximize the number of tows conducted. After each tow, the entire recapture net catch was dumped on deck and sorted for bycatch of Chinook salmon and rockfishes. All other fish from the recapture net were then discarded. Subsequently the trawl codend was progressively hauled onboard where the catch was gradually dumped on deck and sorted for Chinook salmon and rockfishes, and then discarded. Catches of Chinook salmon and rockfishes between the two codends were then sampled with fork length (cm) data collected on Chinook salmon and total weight (kg) data collected on rockfishes.

A Student's *t*-test was used to: 1) examine whether the proportion of Chinook salmon to exit the BRD when artificial illumination was present was significantly greater than the proportion of Chinook salmon to exit the BRD when artificial illumination was absent, and 2) analyze the Chinook salmon length data and rockfish weight data.

3. Results

3.1. Experiment 1: illuminating specific escape windows

Chinook salmon were encountered in 15 of the 16 tows conducted. In this experiment, interactions with Chinook salmon were exceptionally high, which was likely a result from increased Chinook salmon ocean abundances occurring in 2015 compared to previous years (Pacific Fishery Management Council (PFMC, 2018).

We observed 438 Chinook salmon, of which 299 individuals escaped (68.3%, 95% confidence interval [CI] = 63.8–72.4%). Of the 299 Chinook salmon to escape, 243 individuals exited out a window that was illuminated (81.3%, 95% CI = 76.5–85.3%) (Table 2). The proportion of Chinook salmon exiting out of an illuminated escape window was significantly greater ($p < 0.0001$) than the proportion to exit out a non-illuminated escape window. These data demonstrate the ability of blue LED lights, placed along specific escape windows, to influence Chinook salmon escapement.

Chinook salmon exhibited various behaviors while encountering the BRD. For example, some individuals would enter the BRD and immediately burst towards and out an illuminated window and continue to swim away from the trawl, whereas others would gradually move towards and out an illumination window then swim alongside the trawl (one individual was noted to swim alongside the trawl for ca. 10 min.) before swimming away. On a few occasions, individuals would be swimming towards and out a non-illuminated window before changing direction and swimming across the BRD tube to exit out an illuminated window. On one occurrence, a Chinook salmon was noted to feed on a shortbelly rockfish (*S. jordani*).

Additional fish species observed, but encountered in numbers too large to enumerate escapement, included Pacific hake, Pacific herring (*Clupea pallasii*), and widow (*S. entomelas*), yellowtail (*S. flavidus*), shortbelly, canary (*S. pinniger*), and redstripe (*S. proriger*) rockfishes. When in the BRD area, Pacific herring and shortbelly rockfish would usually swim upwards and school near the top panel of the net until haulback, at which time they would exit out the BRD in large numbers. Widow, yellowtail, and canary rockfishes moved throughout the BRD area before either exiting out the BRD or drifting back to the codend. Observations of Pacific hake (fish ca. 20–30 cm in length) were of fish either actively swimming, but unable to swim forward enough to exit out the BRD, or tumbling or passively drifting back towards the codend.

The mean light level during this experiment was 3.3e^{-02} (SE ± 2.6e^{-03}) μmol photons m^{-2} s^{-1} and ranged from 4.1e^{-05} to 9.4e^{-01} μmol photons m^{-2} s^{-1}.

Various video footage of Chinook salmon, Pacific hake, Pacific herring, yellowtail, shortbelly, and redstripe rockfishes, and jack mackerel (*Trachurus symmetricus*) observed during Experiment 1 can be viewed in Supplementary Video 2.

3.2. Experiment 2: comparing tows with and without artificial illumination

A total of 39 tows were completed. In contrast to Experiment 1, estimated Chinook salmon ocean abundances in 2017 were exceptionally low (Pacific Fishery Management Council (PFMC, 2018), which likely contributed to the small sample size for Chinook salmon during the second experiment.

For tows conducted with artificial illumination, 24 Chinook salmon encountered the BRD with escapement occurring in 18 of those individuals, a mean escapement rate of 75.0% (95% CI = 56.3–93.6%) (Table 3). During tows made without artificial illumination, 38 Chinook salmon encountered the BRD with escapement occurring in 20 of those individuals, a mean escapement rate of 52.6% (95% CI = 35.9–69.2%) (Table 3). Overall, the proportion of Chinook salmon to exit the BRD when artificial illumination was present was significantly greater ($p = 0.0362$) than the proportion to exit the BRD when artificial illumination was absent.

Table 3

Chinook salmon catch data for Experiment 2 for tows with and without artificial illumination. Values in parentheses represent 95% confidence intervals surrounding the mean value.

Tow	With artificial illumination			Without artificial illumination		
	No. in trawl	No. in recapture net	% escapement	No. in trawl	No. caught in recapture net	% escapement
1	4	4	50.0	–	–	–
4	–	–	–	0	2	100.0
9	–	–	–	2	7	77.8
11	–	–	–	4	5	55.6
14	–	–	–	2	2	50.0
15	0	1	100.0	–	–	–
16	0	1	100.0	–	–	–
17	1	0	0.0	–	–	–
19	–	–	–	2	0	0.0
21	0	1	100.0	–	–	–
22	–	–	–	1	0	0.0
23	0	4	100.0	–	–	–
27	0	1	100.0	–	–	–
28	–	–	–	0	2	100.0
32	0	1	100.0	–	–	–
35	0	4	100.0	–	–	–
36	–	–	–	2	0	0.0
37	0	1	100.0	–	–	–
38	–	–	–	5	2	28.6
39	1	0	0.0	–	–	–
Total	6	18	75.0 (56.3–93.6)	18	20	52.6 (35.9–69.2)

The mean length of Chinook salmon caught between the recapture net and codend when artificial illumination was present was 59.7 cm (SE ± 3.2) and 67.1 cm (± 4.4), respectively. This difference in mean length was not significant ($p = 0.2017$). When artificial illumination was absent, the mean length of Chinook salmon caught between the recapture net and the codend was 70.4 cm (± 3.4) and 55.7 cm (± 2.9), respectively. This difference in mean length was significant ($p = 0.0026$).

Five rockfish species were caught, however, only two of these species (widow and yellowtail rockfishes) occurred in trawls made with and without artificial illumination. Due to the limited sample size, no statistical analysis of escapement between tows made with and without artificial illumination could be performed for these two species. For all rockfish catches combined, the overall mean percent escapement (by weight) between tows with and without artificial illumination was 45.8% (95% CI = 43.3–48.2%) and 47.9% (95% CI = 41.8–54.3%), respectively (Table 4). The presence of artificial illumination did not have a significant effect on rockfishes' escapement out of the BRD ($p > 0.05$).

The mean light level for tows made with artificial illumination was 1.0e^{-01} (SE ± 2.9e^{-02}) μmol photons m^{-2} s^{-1} and ranged from 1.4e^{-02} to 2.9e^{-01} μmol photons m^{-2} s^{-1}. For tows made without artificial illumination, the mean ambient light level decreased to 4.6e^{-03} (± 2.7e^{-03}) μmol photons m^{-2} s^{-1} and ranged from 6.1e^{-06} to 2.4e^{-02} μmol photons m^{-2} s^{-1}.

Various video footage of the recapture net surrounding the BRD, and Chinook salmon and Pacific herring interacting with the gear can be viewed in Supplementary Video 3.

4. Discussion

In our experiments, we influenced the behavior and escapement of Chinook salmon out a BRD using artificial illumination. In Experiment 1, we demonstrated the ability of artificial illumination to influence their escapement out specific windows of the BRD. Specifically, the proportion of Chinook salmon to exit out of an illuminated escape window was significantly greater than the proportion to exit out a non-illuminated escape window. One explanation for this observed behavior is having illumination along one side of the BRD hinders their ability to perceive the environment outside the BRD on the other side. Thus, deterring them away from non-illuminated escape windows and towards illuminated escape windows where they can better perceive the environment outside the trawl. Findings from this experiment supports previous research by Lomeli and Wakefield (2012) suggesting that illumination can influence where Chinook salmon exit out of a BRD. In Experiment 2, our results showed the proportion of Chinook salmon to exit the BRD when artificial illumination was present was significantly greater than the proportion to exit the BRD when artificial illumination was absent. Although this result was moderate in effect, a significant difference was still noted while having a small sample size of Chinook salmon.

Prior to our research, studies using artificial illumination inside trawls have been unsuccessful at reducing bycatch (Hannah et al., 2015; Larsen et al., 2017, 2018; Grimaldo et al., 2018; Melli et al., 2018). The studies that have demonstrated the ability to reduce fish catches using artificial illumination have occurred in the front part of the trawl (Hannah et al., 2015; Lomeli et al., 2018a,b). While our study found that use of artificial illumination inside the trawl can reduce Chinook salmon bycatch, the endurance and strong swimming ability of Chinook salmon coupled with the BRD used in our experiments likely contributed to our successful results. As prior video observations (Lomeli and Wakefield, 2012) and catch data have noted that Pacific hake lack the ability to escape out of the BRD in meaningful numbers, the device is able to utilize escape windows with exceedingly large openings that span several meters in length. Further, the square mesh ramps used in the design create a large area above them where fish

Table 4
Total catch by weight (kg) for rockfishes between the recapture net and trawl codend for tows with and without artificial illumination along the BRD escape windows during Experiment 2. Values in parentheses represent 95% confidence intervals surrounding the mean value.

	With artificial illumination			Without artificial illumination		
Species	Trawl	Recapture net	% escapement	Trawl	Recapture net	% escapement
Darkblotched rockfish	17.7	14.5	45.0	–	–	–
Widow rockfish	33.2	91.7	73.4	9.3	7.0	42.9
Yellowtail rockfish	223.7	110.8	33.1	11.8	28.3	70.6
Chilipepper	–	–	–	113.4	88.6	43.9
Canary rockfish	602.5	522.8	46.5	–	–	–
Total	877.1	739.8	45.8 (43.3–48.2)	134.5	123.9	47.9 (41.8–54.3)

swimming forward can interact with the escape areas while avoiding contact with fish passing aft under the ramps. As Chinook salmon are attracted towards the illuminated area, these aspects of the BRD provide an easy opportunity for Chinook salmon to escape. An example where fish responded to artificial illumination stimuli, but were unable to escape as a result of the size of the escape opening occurred in the Grimaldo et al. (2018) study. In their research, they were able to direct haddock towards panels of square mesh netting using artificial illumination. However, haddock responded to the stimuli in an erratic behavior and upon contacting the netting they were positioned in an orientation that prevented escapement through the meshes.

In Experiment 2, 18 of the 24 Chinook salmon encountered when artificial illumination was present exited out of the BRD. From these data, the analysis showed larger-sized Chinook salmon occurred in the codend than the recapture net. However, this result was not significant and the small number of Chinook salmon retained in the codend (6 fish) was not a large enough sample size to make any conclusions on fish length and its effect on escapement in response to illumination. In contrast, a larger number of Chinook salmon were encountered when artificial illumination was absent (18 fish in the trawl codend vs. 20 fish in the recapture net). From catches when artificial illumination was absent, the length analysis showed Chinook salmon caught in the recapture net were on average significantly larger than Chinook salmon caught in the codend. This result suggests that fish length could potentially be a contributing factor to Chinook salmon escapement. Had the sample size of Chinook salmon encountered in Experiment 1 been encountered in Experiment 2, a length-dependent catch comparison analysis (Larsen et al., 2018; Lomeli et al., 2018a,b) could have been performed to determine if a difference in catch efficiency between non-illuminated to illuminated trawls is related to specific length classes. Further research investigating how length may affect fish escapement is needed.

In recent years, several overfished and rebuilding rockfish stocks have been rebuilt (e.g., darkblotched [*S. crameri*], widow, and canary rockfishes, Pacific Ocean Perch [*S. alutus*], and bocaccio [*S. paucispinis*]) along the U.S. West Coast (He et al., 2011; Thorson and Wetzel, 2016; He and Field, 2017; Wallace and Gertseva, 2017; Wetzel et al., 2017). These stock recoveries have resulted in an emerging midwater trawl rockfish fishery. However, there are management concerns on the potential impact that the fishery could have on Chinook salmon bycatch as many of the rockfish stocks targeted occur at depths were Chinook salmon bycatch rates are relatively high (National Marine Fisheries Service, West Coast Region (NMFS WCR, 2017b). Because the BRD we evaluated performed well at reducing Chinook salmon catches, its use as a salmon excluder in the midwater trawl rockfish fishery would likely create economic trade-offs between catch yields and bycatch reduction as considerable catch reductions (> 40% by weight) of rockfishes occurred both with and without artificial illumination on the BRD. As other designs of salmon excluders have been developed by the industry for use in the Pacific hake fishery, the designs are the same in concept as the BRD we tested (e.g., use of large open escape windows). Thus, developing new approaches (such as gear designs, use of other light colors, wavelengths, and/or patterns) and understanding their effects on rockfishes and Chinook salmon would provide critical information if Chinook salmon bycatch became an issue impacting the midwater trawl rockfish fishery.

While the mechanism(s) triggering Chinook salmon to exhibit the behaviors we observed in our experiments is unclear, the presence of artificial illumination appears to enhance their visual perception and their ability to perceive the contrast between the trawl gear and the surrounding environment that otherwise they would not be able to perceive as well under dark conditions. How Chinook salmon perceive and interact with this BRD under conditions when artificial illumination is absent is unclear. Further research using imaging sonar equipment such as ARIS (Adaptive Resolution Imaging Sonar) or DIDSON (Dual-Frequency Identification Sonar) to observe how Chinook salmon interact with this BRD under dark conditions could provide insights that could help improve our knowledge of what makes artificial illumination affective at reducing their bycatch.

The escapement of Pacific hake was not quantified in Experiment 2 due to logistical difficulties of sampling catches of Pacific hake aboard a catcher vessel. However, past gear trials (Lomeli and Wakefield, 2012; Table 1; PSMFC unpubl. data 2014) conducted under conditions with and without artificial illumination on this BRD design all indicate that Pacific hake lack the ability to escape out this BRD design in meaningful numbers. Nonetheless, we acknowledge that the BRD configuration used in Experiment 2 is different from the configurations tested in past sea trials and that the BRD configuration used in Experiment 2 may produce different results. Thus, research quantifying the effect of artificial illumination on Pacific hake escapement out the BRD tested in Experiment 2 is needed to determine if this gear configuration performs similarly to the other configurations tested.

In summary, our research demonstrated that artificial illumination can influence where Chinook salmon exit out of the BRD we tested, and that illumination can be used to enhance their escapement overall. These results contribute new information on how artificial illumination can minimize adverse interactions between the Pacific hake fishery and Chinook salmon. Improving gear selectivity and reducing the level of Chinook salmon bycatch would also contribute to the conservation and management of ESA-listed Chinook salmon. Lastly, while our research has regional impacts, our findings may have potential applications in the Bering Sea walleye pollock (*Gadus chalcogrammus*) midwater trawl fishery, and in the Icelandic pelagic mackerel (*Scomber scombrus*) trawl fishery where salmon bycatch also occurs (Stram and Ianelli, 2015; Olafsson et al., 2016).

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2019.04.013.

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