Altering the level of illumination on a bycatch reduction device and its effect on the catch rates of Pacific hake and Chinook salmon

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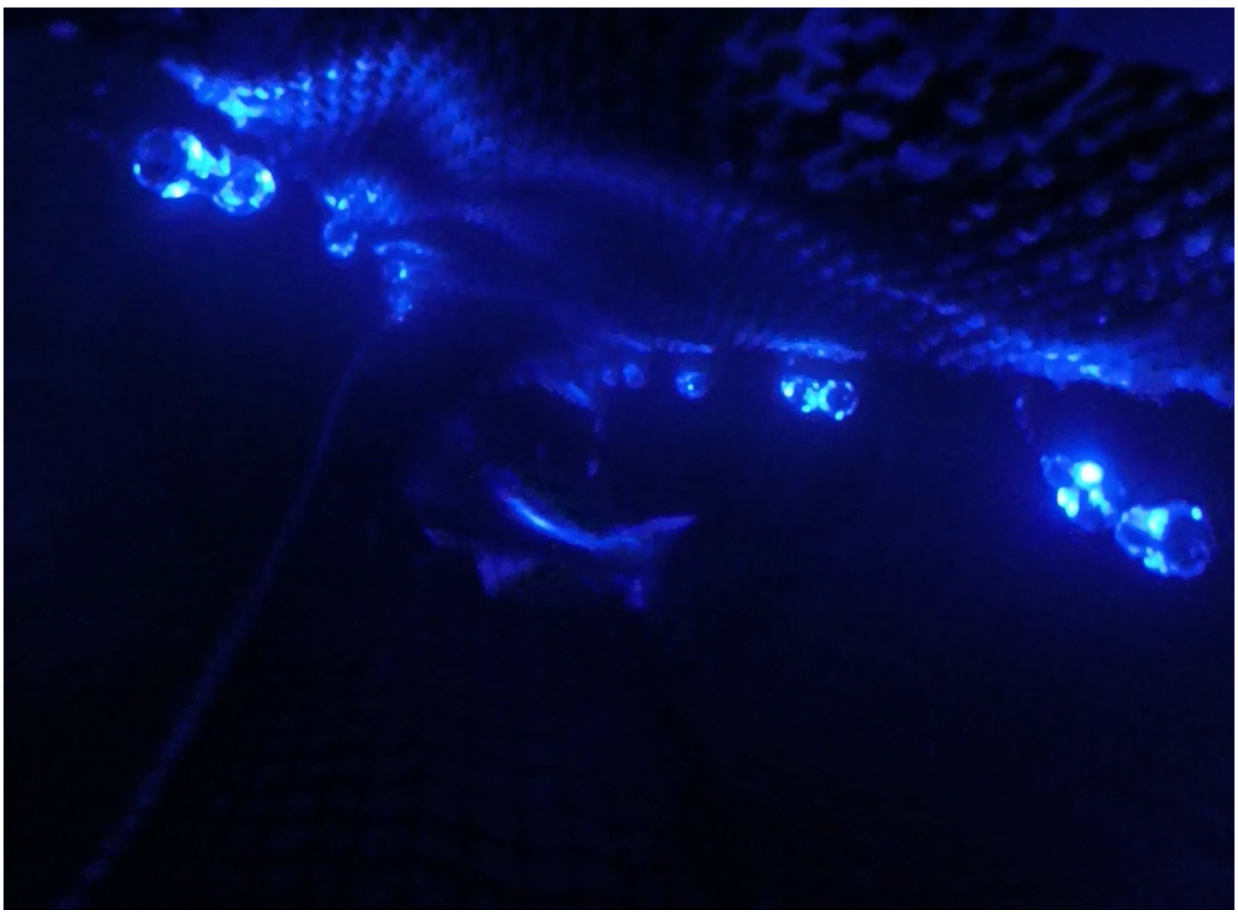

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Abstract

We compared the catch rates of Pacific hake (*Merluccius productus*) and Chinook salmon (*Oncorhynchus tshawytscha*) between a non-illuminated trawl (control trawl) and trawls configured with 16 and 32 LEDs along the escape area of a bycatch reduction device (BRD). This work was conducted over an extended period of commercial fishing, 3.5 months. Results showed the 16 and 32 LED-configured trawl on average caught 0.42 and 0.35 fewer Chinook salmon per hour towed, respectively, than the control trawl. However, this result was not significant as considerable within control and treatment catch variability contributed to large uncertainties around the mean catch rates. For Pacific hake, the 16 and 32 LED-configured trawl on average caught 9.8 and 17.5 MT less per hour towed than the control trawl. This mean reduction in catch rate in the LED-equipped trawls, only differed significant from the control trawl during a single month, August. Our observed trend of catching fewer Chinook salmon in the presence of illumination is similar to prior research that has shown a significant effect on the behavior and escapement of Chinook salmon. The trend of catching fewer Pacific hake with illuminated trawls, was not expected as studies have shown that Pacific hake are often too fatigued to exit out escape areas of BRDs in any meaningful numbers. Thus, continued research is needed to better understand how illumination effects the catch rate of Chinook salmon and Pacific hake across various BRD designs and conditions. Lastly, while our study has implications to the Pacific hake fishery, this research may have potential applications to the Alaska walleye pollock (*Gadus chalcogrammus*) fishery where bycatch of Chinook salmon and chum salmon (*O. keta*) can constrain the fishery.

Introduction

The Pacific hake (*Merluccius productus*) midwater trawl fishery is the largest trawl fishery by volume along the U.S. West Coast with annual landings often exceeding 250,000 MT (PacFIN, 2020). Pacific hake are harvested by catcher vessels delivering to shore-side processing plants, catcher vessels delivering to at-sea mothership processors, and catcher processor vessels. The Pacific hake fishery is a relatively clean fishery in terms of bycatch with landed catches comprising mostly Pacific hake, usually >95% by volume (PacFIN, 2020). However, Chinook salmon (*Oncorhynchus tshawytscha*) listed under the Endangered Species Act (ESA) are caught as bycatch in the fishery. Thus, fishery managers closely monitor the fishery's bycatch to ensure conservation thresholds are not exceeded. Currently, the annual bycatch limit for Chinook salmon in the Pacific hake fishery is limited to 11,000 individuals, plus a 3,500 individual buffer (NMFS WCR, 2017; NOAA, 2018). Management can minimize Chinook salmon bycatch in the Pacific hake fishery by closing the fishery in the area shoreward of the 200 fathom (365 m) depth contour off the West Coast. Management must also automatically close the fishery if catch exceeds 14,500 (11,000 individuals plus the 3,500 individual buffer). In November 2019, the Pacific Fishery Management Council (PFMC) recommended additional bycatch minimization tools to limit salmon bycatch in the Pacific hake fishery, including more refined depth based area closures, and an additional closure threshold at 11,000 individuals (PFMC, 2019). Management is currently evaluating the PFMC's recommendation, and expects to implement these additional measures in time for the 2021 Pacific hake fishing year.

In the Pacific hake fishery, most vessels now use bycatch reduction devices (BRDs) in efforts to minimize Chinook salmon bycatch. While several different BRD designs are used (e.g., over/under, flapper, side escape [Lomeli and Wakefield, 2012, 2019; Gauvin et al., 2015]), they all share a common design aspect in that they utilize a large escape opening on either the sides, top, or bottom of the net to allow actively swimming fish an opportunity to escape if they swim forward in the net. As fishers and gear researchers have used video camera systems (equipped with artificial illumination to obtain video imagery) over the years to test and develop various BRD designs, observations have indicated that the presence of artificial illumination might be enhancing the escapement of Chinook salmon out the BRDs (Lomeli and Wakefield, 2012; Gauvin et al., 2015; Gauvin, 2016). However, it was not until recently that research systematically tested the effect of artificial illumination on the behavior and escapement of Chinook salmon out a BRD integrated into a Pacific hake trawl (Lomeli and Wakefield, 2019). They performed to experiments: 1) testing if artificial illumination could attract Chinook salmon out specific escape openings of a BRD equipped with multiple escape openings, and 2) comparing Chinook salmon escapement rates out the BRD between tows conducted with and without artificial illumination to determine if their escapement can be enhanced using illumination. Results showed artificial illumination could influence where Chinook salmon exit out the BRD, but also that the presence of illumination enhanced their overall escapement.

While positive results were achieved in the Lomeli and Wakefield (2019) research, their study tested if artificial illumination in general could be used to reduce Chinook salmon bycatch. Research questions remain as to how much illumination (e.g., number of LEDs) is needed to enhance their escapement. If less, rather than more, illumination is needed to enhance Chinook salmon escapement, this result would have cost benefits to industry. For example, in the ocean shrimp (*Pandalus jordani*) trawl fishery Lomeli et al. (2018a) compared the catch efficiency for ocean shrimp, eulachon (*Thaleichthys pacificus*), and juvenile groundfishes between a non-illuminated trawl and trawls illuminated with 5, 10, and 20 LEDs along the trawl fishing line. Findings showed the presence of illumination significantly reduced the bycatch of eulachon and some groundfishes, without impacting ocean shrimp catches, but that the three LED quantities performed similar to each other at reducing bycatch. This demonstrated that beyond 5 LEDs there was no clear added bycatch reduction benefit of using more illumination. In the Pacific hake fishery, as fishers consider the potential use of artificial illumination as a technique to reduce Chinook salmon bycatch, better understanding of how light intensity can affect their bycatch and catches of Pacific hake is extremely important.

The objective of this study is to compare the catch rates of Pacific hake and Chinook salmon between a non-illuminated trawl and trawls configured with 16 and 32 LEDs around the escape area of a BRD.

Methods

We chartered the *F/V Raven* (28.3 m long, 1,200 hp) for this study. Commercial fishing operations occurred off the Oregon and Washington coast between 13 July and 29 October 2019 (Fig. 1). We used the *F/V Raven's* midwater trawl, which had a headrope and footrope both 274 m in length, and a mouth opening approximately 37 m high by 92 m wide. We used the vessel's "flapper" style salmon BRD (Gauvin et al., 2015; Gauvin, 2016) newly manufactured by Swan Net USA (Fig. 2). The BRD was constructed within a four-seam tube of netting that was 200 meshes, of 101.6 mm length meshes, in circumference (excluding meshes in each selvedge) and 100 meshes long. This design involves an inner section of diamond mesh netting that is weighted at the aft end to create a ramp designed to lead actively swimming fish towards a large escape opening on the top panel of the net. Further, the top panel is constructed with a hooded front section that tapers down over the length of the four-seam tube of netting to create the escape area. To create upward lift and maintain the escape opening, buoyant rope (4.8 m in length) was placed along the center section of the hood's leading edge (Fig. 2).

We compared catch rates of Pacific hake and Chinook salmon between a control trawl (e.g., non-illuminated trawl) and trawls configured with 16 and 32 LEDs placed along the leading edge of the BRD's hood. The 16 LED configuration consisted of 8 clusters of LEDs with each cluster containing two LEDs. The 32 LED configuration consisted of 8 clusters with each cluster containing four LEDs. The LED clusters were placed approximately 1.25 m apart along the length of the hood's leading edge. Attachment points along the hood were marked with twine to assure that the placement of the LED clusters was consistent on all tows. Blue Lindgren-Pitman Electralume® LED fishing lights, wavelength centered on 464 nm (Nguyen et al., 2017), were used as the artificial light source. This color was selected as it is the same color used in the Lomeli and Wakefield (2019) study, this wavelength transmits well through open ocean water, and the predominant spectral component of coastal and continental shelf waters along the Pacific Northeast is blue-green light (Jerlov, 1976; Bowmaker, 1990; Schweikert et al., 2018). The trawl was fished with and without LEDs in an alternating trip order throughout the study in the following pattern: control, 16, 32, control, 32, 16 (Table 1). The batteries in the LEDs were replaced after six trips of use. A Wildlife Computers TDR-MK9 archival tag was used to measure light level and temperature. The tag was attached facing upwards in the center of the inner diamond mesh section of netting where the orange and black mesh are sewn together (Fig. 2). Refer to Lomeli et al. (2018b) for the equation used to convert the MK9 tag relative light units to irradiance units.

Catch data was collected using the fish ticket data associated with the vessel's landed catches. Their logbook was used to gather data on average depth of catch, tow durations, and area fished. Least squares regression was used to examine if Chinook salmon bycatch rates changed linearly by month (and overall) with trawl configuration, light level, depth of catch, and area fished as combined model parameters. Further, area fished was separated into three regions (north [>47°0'N lat.], central [47°0' to 45°0'N lat.], and south [<45°0'N lat.] to examine if area fished had an effect on catch rates. To account for trips when the bycatch rate of Chinook salmon was zero, the model was weighted by tow duration. A Students *t*-test was used to examine Chinook salmon length data between the control and two treatments. The above analyses were performed using the statistical software JMP (version 15.0.0).

Results

Sampling conditions and fishing effort

The *F/V Raven* completed 48 chartered fishing trips with 16 trips made per each trawl configuration (Table 1). Fishing trips ranged from one to two days. Total fishing effort for the control, and 16, and 32 LED-configured trawl was 60.03 hours, 80.36 hours, and 106.82 hours, respectively. By area, fishing effort was 55.26 hours (15 trips), 96.85 hours (17 trips), and 95.1 hours (16 trips) in the north, central, and south, respectively. By month, most fishing effort was concentrated in the central area (45°0'-47°0' N Lat.) during July, in the north area (>47°0' N Lat.) during August, and in the south area (<45°0' N Lat.) during September and October. Towing occurred between sunrise and sunset at speeds ranging from 3.2-3.4 knots. The mean light level measured in the control BRD was $7.47e^{-03}$ (SE $\pm 2.4e^{-03}$) µmol photons m^{-2} s^{-1}. For the 16 and 32 LED-configured trawl, the mean light level measured increased 3.7% to $2.85e^{-02}$ ($\pm 3.2e^{-03}$) and 55.0 % to $4.26e^{-02}$ ($\pm 2.3e^{-03}$) µmol photons m^{-2} s^{-1}, respectively. Mean light levels per fishing trip are shown in Figure 3. The mean temperature at trawl depths was 7.3 (±0.01) for the control trawl, and 7.4°C (± 0.01) in the 16 and 32 LED-configured trawls.

Catch rates

Pacific hake – The mean catch rate of Pacific hake varied largely by month between the control and two treatments, with the exception of September where catch rates were similar (Table 2). In July, the 16 LED-configured trawl had the highest mean catch rate of Pacific hake (39.4 MT per hour towed) and was significantly different from the 32 LED-configured trawl, but not the control trawl. During August, the mean catch rate of Pacific hake was highest in the control trawl (80.7 MT per hour towed) and was significantly different from the 16 and 32 LED-configured trawls. For October, the control trawl showed the highest mean catch rate, however, the mean value was not significantly different from the 16 and 32 LED-configured trawls due to high catch variability. Overall, July through October, the mean catch rate of Pacific hake did not differ significantly between the control trawl and 16 LED-configured trawl (34.2 MT vs 24.3 MT per hour towed, respectively) (Table 3, Fig. 4). Between the control trawl and 32 LED-configured trawl, however, a significant difference was found with the control trawl exhibiting a higher mean catch rate of Pacific hake (34.2 MT vs 16.7 MT per hour towed, respectively). However, this overall result was driven by catches made by the control trawl during August. For the months of July, September, and October, the mean catch rate of Pacific hake between the control and 32 LED-configured trawl did not differ significantly from each other. By area, the south had the highest mean catch rate of Pacific hake and differed significantly from the central area (Table 3). The mean catch rate between the north and central, and south and north did not differ significantly from each other. In terms of depth of catch, the mean catch rate of Pacific hake decreased significantly as mean depth of catch increased from 98 to 313 m (Table 3). Mean light level did not have an effect on the catch rate of Pacific hake. Appendix 1-4 show the fit statistics for the least squares regression model examining whether Pacific hake mean catch rates by month changed linearly with trawl configuration, light level, depth of catch, and/or area fished.

Chinook salmon – The control trawl had the highest overall mean bycatch rate of Chinook salmon with 48 individuals caught over 60.03 hours of fishing effort, a bycatch rate of 0.79 individuals per hour towed (Fig. 5). This bycatch rate was largely influenced by trips made during October where a total of 38 Chinook salmon were landed over 13.96 hours of fishing effort (Table 1). For the 16 LED-configured trawl, 30 Chinook salmon were caught over 80.36 hours of fishing effort, a bycatch rate of 0.37 individuals per hour towed (Fig. 5). The 32 LED-configured trawl had a bycatch rate of 0.44 individuals per hour towed with 47 Chinook salmon caught over 106.82 hours of fishing effort (Table 4, Fig. 5). As occurred in the control trawl, the bycatch rate for the 32 LED-configured trawl was impacted by trips made during October where a total of 37 Chinook salmon were landed over 36.5 hours of fishing effort (Table 1). While the 16 and 32 LED-configured trawls had mean lower Chinook salmon bycatch rates than the control trawl, the catch differences were not significantly different from each other due to considerable catch variability that occurred within the control and treatments (Table 4, Fig. 5). By month, October had the largest Chinook salmon bycatch rate with 66% of all Chinook salmon caught during this month. By area, Chinook salmon bycatch rates were significantly higher in the central and southern area than the north area in August and significantly higher in the south area than the north area in September. For October, while the majority of Chinook salmon where caught in south area, their mean bycatch rate did not differ significantly from the central area. No fishing effort occurred in the north area in October. Mean light level and depth of catch had no effect on the bycatch rate of Chinook salmon. Appendix 5-8 show the fit statistics for the least squares regression model examining whether Chinook salmon mean bycatch rates by month changed linearly with trawl configuration, light level, depth of catch, and/or area fished.

The mean length of Chinook salmon caught in the control, 16, and 32 LED-configured trawl was 51.2 (SE ±1.3), 54.4 (±1.5), and 53.4 cm (±1.2), respectively. These mean lengths did not differ significantly from each other (p >0.05).

Other bycatch – Additional species caught, but not included in the analysis due to considerable catch variability included American shad (*Alosa sapidissima*), Jack mackerel (*Trachurus symmetricus*), rockfishes (*Sebastes* spp.), and sablefish (*Anoplopoma fimbria*).

Discussion

Under normal commercial fishing conditions, over a 3.5 month period, we examined the catch rates of Pacific hake and Chinook salmon between a control trawl and trawls configured with 16 and 32 LEDs around the escape area of a "flapper" style BRD. We found the trawls equipped with 16 and 32 LEDs had lower Chinook salmon mean bycatch rates than the control trawl, but not significant. For Pacific hake, the LED equipped trawls had a lower mean catch rate than the control trawl. However, this mean catch rate reduction in the LED equipped trawls was only significant during the month of August. For all other months, the mean catch rate of Pacific hake in the control trawl did not differ significantly from the 16 and 32 LED-configured trawl.

Catch variability associated with alternate-tow sampling can lead to large uncertainty surrounding the mean value, making it difficult to detect significant differences (Wileman et al., 1996). In our study, an alternate tow method was not feasible as multiple tows are often made during a fishing trip and the vessel's fish holds configurations in this fishery do not allow tow-by-tow separation of catch. Therefore, we used an alternate trip sampling method. However, this technique may have contributed to the large catch variability that we observed within the control and two treatments. Thus, to identify if a significant effect exits, further fishing trips is needed to increase sample sizes and the precision around the mean catch values when using an alternate trip sampling method. A recapture net method (Wileman et al., 1996; Lomeli and Wakefield, 2019), which can achieve high precision estimates with less fishing effort, was not a viable option either for the current study as it is difficult to apply without impacting normal commercial fishing operations.

While our analyses did not detect a significant bycatch rate reduction for Chinook salmon between the control and two treatments, the general trend of catching fewer Chinook salmon in the presence of illumination is consistent with results presented in Lomeli and Wakefield (2019). Further, as the mean bycatch rate for Chinook salmon was relatively similar between the 16 and 32 LED-configured trawl indicates that 16 LEDs may be sufficient to reduce Chinook salmon bycatch. For Pacific hake, the 16 LED-configured trawl had a higher mean catch rate than the 32 LED-configured trawl. This result was significant for the month of July, but not during the remaining months. Nonetheless, these trends in mean catch rates suggest that perhaps the 16 LED-configured trawl might be the most effective at reducing the bycatch rate of Chinook salmon while minimizing the loss of Pacific hake. Continued research investigating how fewer quantities of LEDs (i.e., 4, 8, etc.) may affect Chinook salmon and Pacific hake catch rates would provide valuable data to fishers and managers.

The “flapper” style BRD we examined is one of a few designs used by fishers to minimize salmon bycatch in the Pacific hake fishery and Alaska walleye pollock (*Gadus chalcogrammus*) fishery (Lomeli and Wakefield, 2012, 2019; Gauvin et al., 2015; Gauvin, 2016). In the current study, there was a decreasing trend in the mean catch rate of Pacific hake in the illuminated trawls compared to the control trawl. While these differences in mean catch rates only differed significantly during the month of August, this observation is interesting as previous research has found that Pacific hake are often too fatigued to exit out escape areas, located in the trawl intermediate, in any meaningful numbers (Lomeli and Wakefield, 2012, 2019). In the Alaska walleye pollock fishery, research has shown that walleye pollock escapement from “flapper” style excluders is quite low, $<1.5\%$ by volume. While acknowledging that it is a different fishery and species, we would expect similar escapement rates for Pacific hake as video observations show Pacific hake and walleye pollock exhibiting similar swimming abilities (Lomeli and Wakefield, 2012; Gauvin, 2016). Although it is plausible that the high catch variability due to the alternate-trip design we used in this study, coupled with changes that can occur in Pacific hake density over space and time, could be the cause of this result. However, it should be mentioned that the BRD we used differs from the BRD previously tested in the fishery (which uses multiple lateral escape openings along the upper side panels of the net [Lomeli and Wakefield, 2012, 2019]), and that our study was conducted under normal commercial fishing operations over an extended time period. It is also important to note that the effectiveness of the “flapper” design can be affected by the amount and distribution of weight on the flapper panel (Gauvin et al., 2015). In this study, we did not directly observe the shape of the flapper panel, but assumed it was weighted appropriately given the net manufacture that built the excluder has extensive experience and knowledge of salmon BRDs used along the West Coast and Alaska. Thus, further research is needed to better understand how artificial illuminating may affect the catch rate of Pacific hake across various BRD designs (Lomeli and Wakefield, 2012, 2019; Gauvin et al., 2015).

In conclusion, this research investigated how altering the level of illumination on a "flapper" style BRD could affect the catch rates of Pacific hake and Chinook salmon. Results showed the 16 and 32 LED-configured trawl each had a considerably lower, but not significant, mean bycatch rate for Chinook salmon than the control trawl, 0.42 to 0.35 fewer Chinook salmon per hour towed, respectively. The illuminated trawls also showed a reduced catch rate for Pacific hake. However, this result was only significant during the month of August. While prior research has shown the ability to significantly affect the behavior and escapement of Chinook salmon using illumination, our study was only able to show a general trend of reducing Chinook salmon in the presence of illumination. Therefore, continued research is needed to better understand the level of illumination needed to reduce Chinook salmon bycatch while minimizing the catch loss of Pacific hake. In the event management discussions on the use of LEDs as a mitigation measure to conserve ESA-listed Chinook salmon occurred, results from this study and Lomeli and Wakefield (2012, 2019) provide fishers and managers valuable data for making sound management decisions. Lastly, while our study has implications to the Pacific hake fishery, it may also have potential applications to the Alaska walleye pollock fishery where bycatch of Chinook salmon and chum salmon (*O. keta*) can constrain the fishery.

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References

Bowmaker, J. K. 1990. Visual pigments of fishes. *In* The Visual System of Fish. *Edited by* R. H. Douglas and M. B. A. Djamgoz. Chapman & Hall, London. Pp. 81–107.

Gauvin, J., Gruver, J., McGauley, K. 2015. Central Gulf of Alaska salmon excluder EFP 13-01 final report.

Gauvin, J. 2016. Bering Sea salmon excluder EFP 15-01 final report.

Jerlov, N.G. 1976. Marine Optics. Elsevier Oceanography Series, 14. Amsterdam: Elsevier, Pp. 231.

Lomeli, M.J.M., Wakefield, W.W. 2012. Efforts to reduce Chinook salmon (*Oncorhynchus tshawytscha*) and Rockfish (*Sebastes* spp.) bycatch in the U.S. West Coast Pacific hake (*Merluccius productus*) fishery. Fish. Res. 119–120: 128–132.

Lomeli, M. J. M., Groth, S. D., Blume, M. T. O., Herrmann, B., and Wakefield, W.W. 2018a. Effects on the bycatch of eulachon and juvenile groundfish by altering the level of artificial illumination along an ocean shrimp trawl fishing line. ICES J. Mar. Sci. 75: 2224-2234.

Lomeli, M.J.M., Wakefield, W.W., Herrmann, B. 2018b. Illuminating the headrope of a selective flatfish trawl: Effect on catches of groundfishes, including Pacific halibut. Mar. Coast. Fish. 10: 118-131.

Lomeli, M.J.M., Wakefield, W.W. 2019. The effect of artificial illumination on Chinook salmon behavior and their escapement out of a midwater trawl bycatch reduction device. Fish. Res. 218: 112-119.

National Marine Fisheries Service (NMFS) West Coast Region (WCR). 2017. Endangered Species Act (ESA) section 7(a)(2) biological opinion. Reinitiation of Section 7 Consultation Regarding the Pacific Fisheries Management Council's Groundfish Fishery Management Plan. NMFS Consultation Number: F/WCR-2017-7552

NOAA. 2018. Magnuson-Stevens Act Provisions; Fisheries Off West Coast States; Pacific Coast Groundfish Fishery; 2019–2020 Biennial Specifications and Management Measures. Federal Register. Vol. 83, No. 238, December 12, 2018.

Nguyen, K.Q., Winger, P.D., Morris, C., Grant, S.M. 2017. Artificial lights improve the catchability of snow crab (*Chionoecetes opilio*) traps. Aquac. Fish. 2: 124–133.

Pacific Fisheries Information Network (PacFIN). 2020. Species Report: Commercial Landed Catch: Metric-Tons (mt), Revenue, and Price-Per-Pound (price/lbs).

Pacific Fishery Management Council (PFMC). 2019. Decision summary document. September 13-18, 2019.

Schweikert, L.E., Fitak, R.R., Caves, E.M., Sutton, T.T., Johnsen, S. 2018. Spectral sensitivity in ray-finned fishes: diversity, ecology and shared descent. J. Exp. Biol. 221.

Wileman, D.A., Ferro, R.S.T., Fonteyne, R., Millar, R.B. (Ed.). 1996. Manual of Methods of Measuring the Selectivity of Towed Fishing Gears. ICES Coop. Res. Rep. No. 215, ICES, Copenhagen, Denmark.

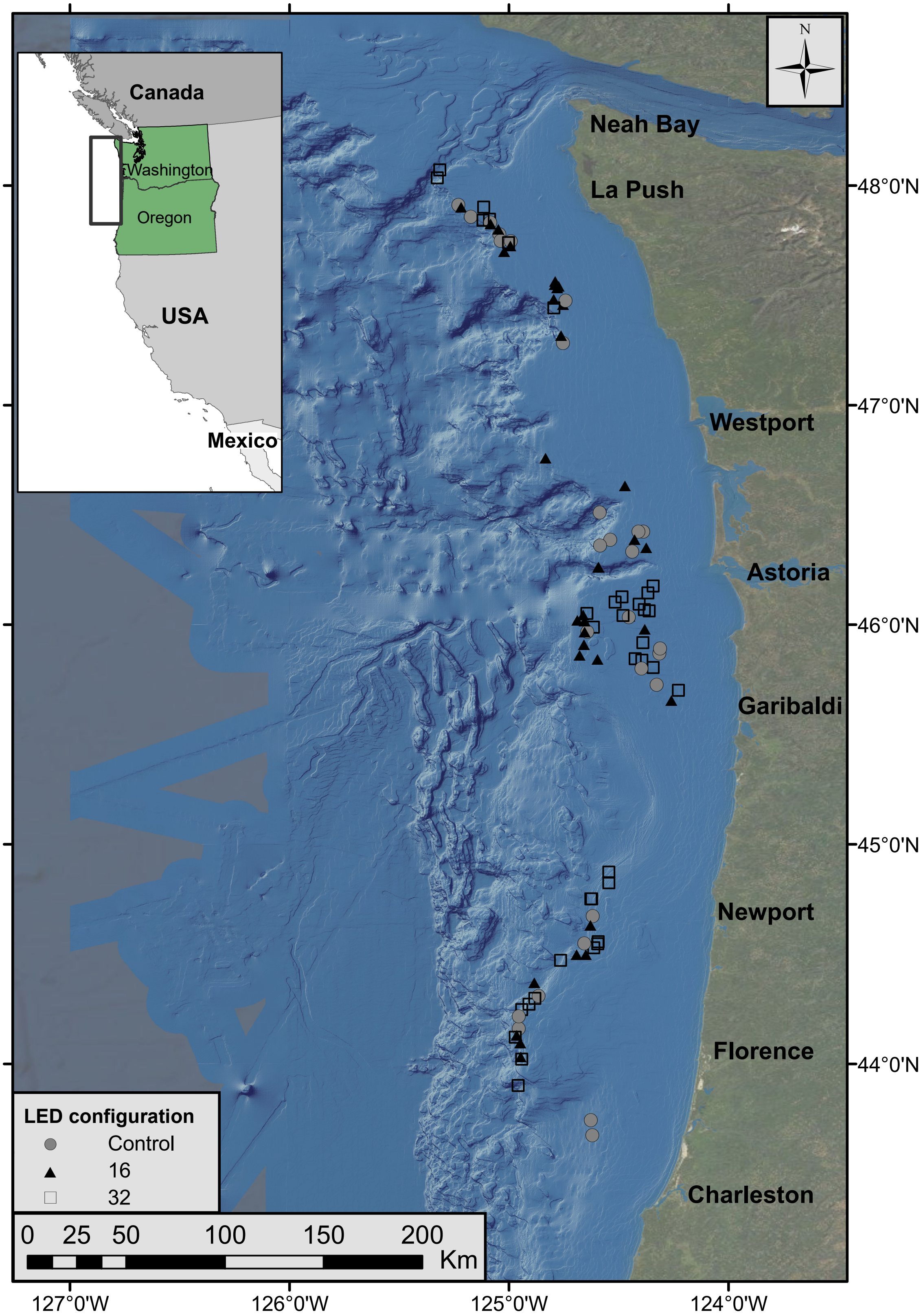

Figure 1. Map showing starting tow locations for the control, 16, and 32 LED-configured trawl.

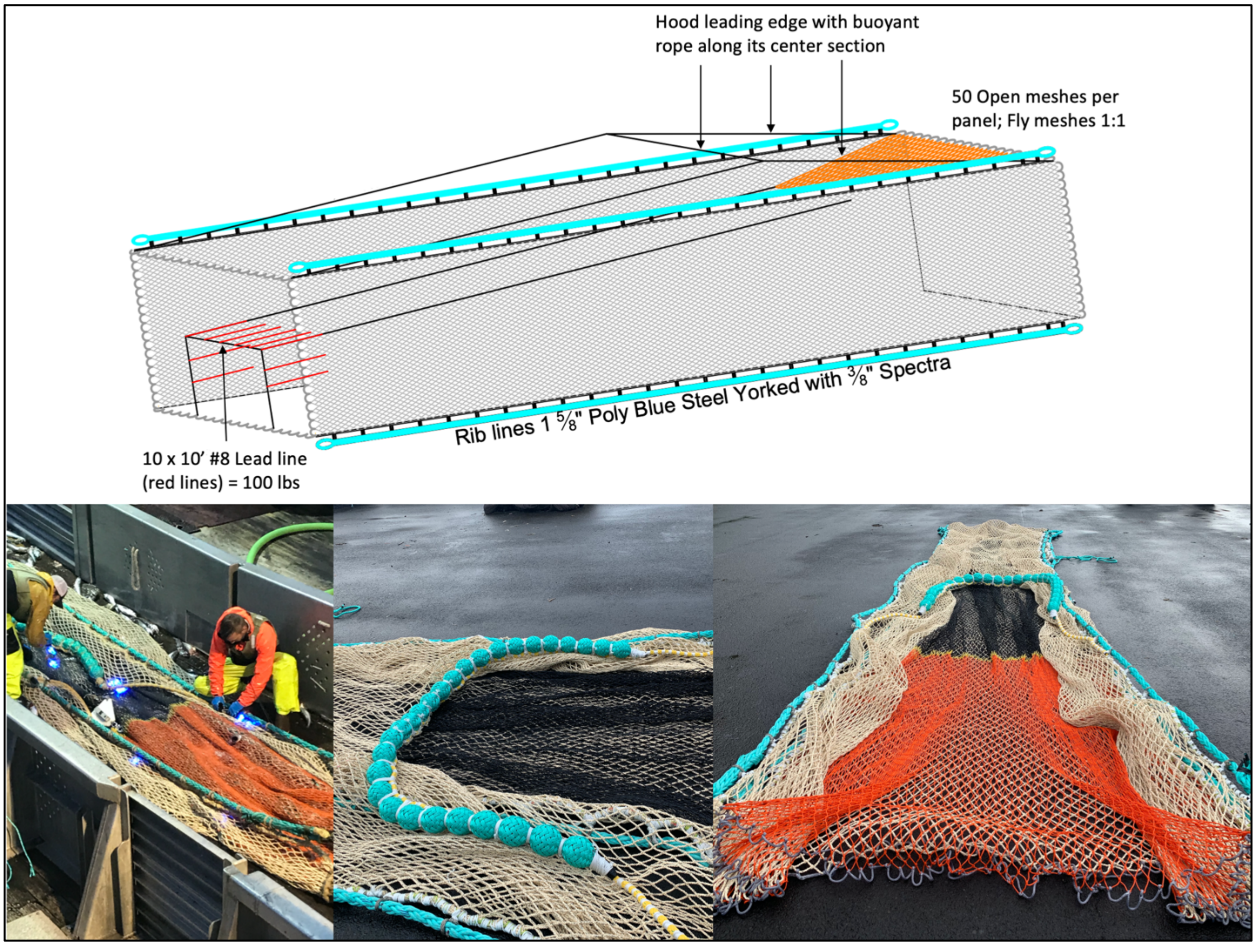

Figure 2. Schematic of the "flapper" style BRD used (top [schematic credit: Swan Net USA]); aft view of the BRD showing the escape area out the top of the net (bottom right); view of the buoyant rope placed along the center section of the BRDs hood leading edge (bottom middle); fishers attaching LED clusters to the leading edge of the BRD hood and the MK9 tag to the inner diamond mesh section of netting (bottom left [photo credit: F/V *Raven*]).

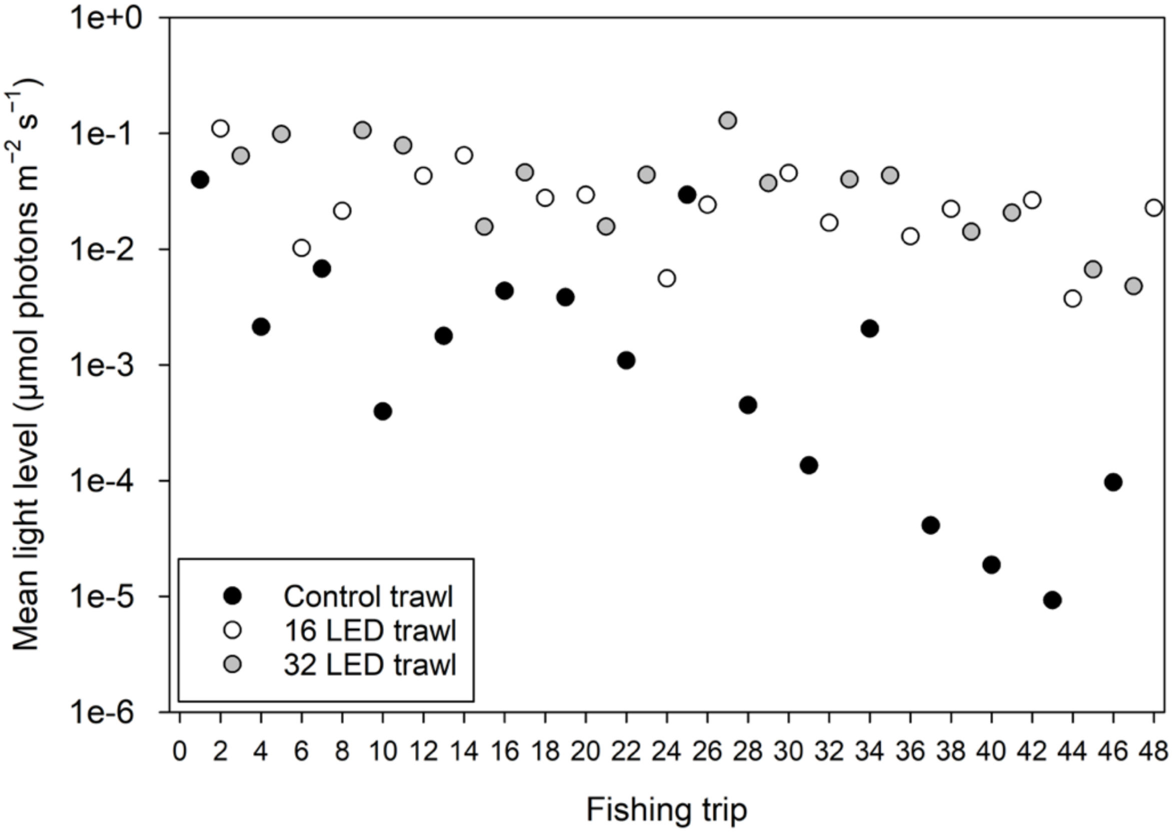

Figure 3. Mean light level per fishing trip for the control, 16, and 32 LED-configured trawl as measured in situ at the mesh section of netting near the escape opening of the BRD.

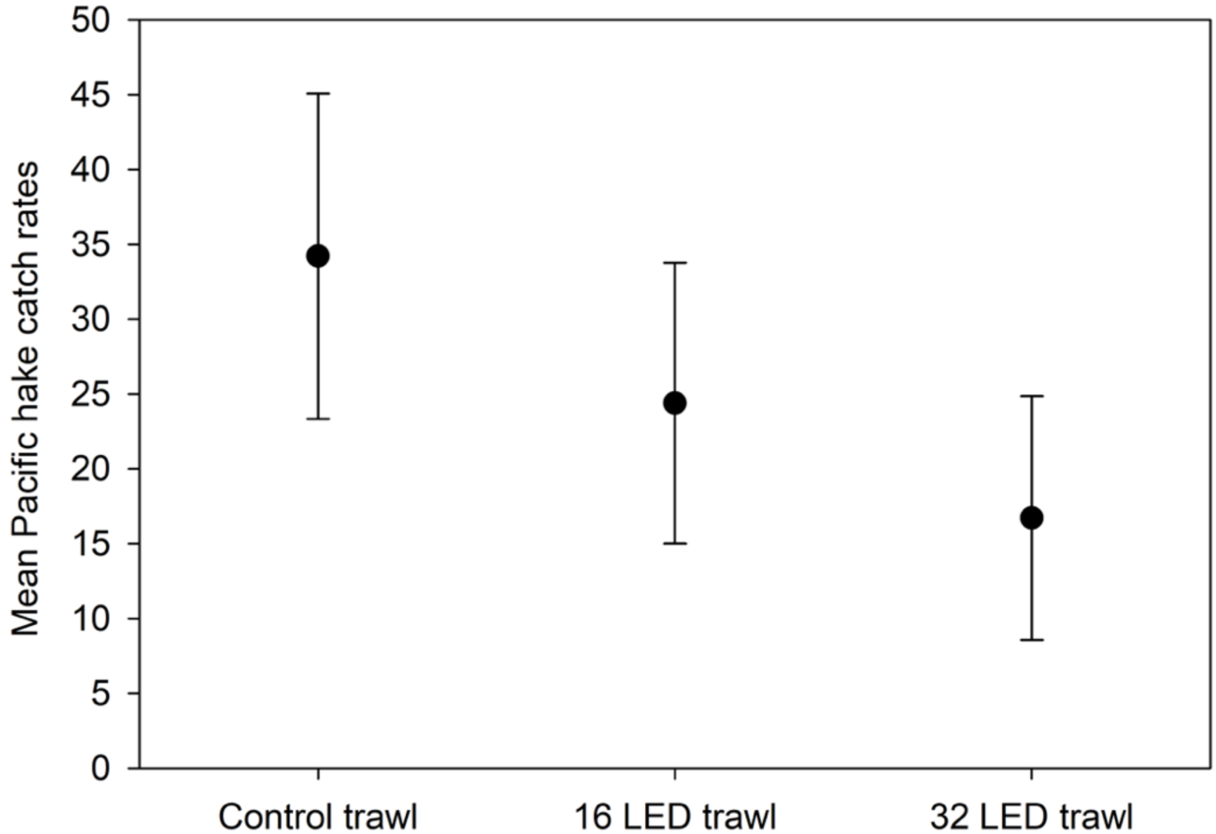

Figure 4. Mean Pacific hake catch rate (MT per hour towed) for the control, 16, and 32 LED-configured trawl. Bars represent 95% CIs.

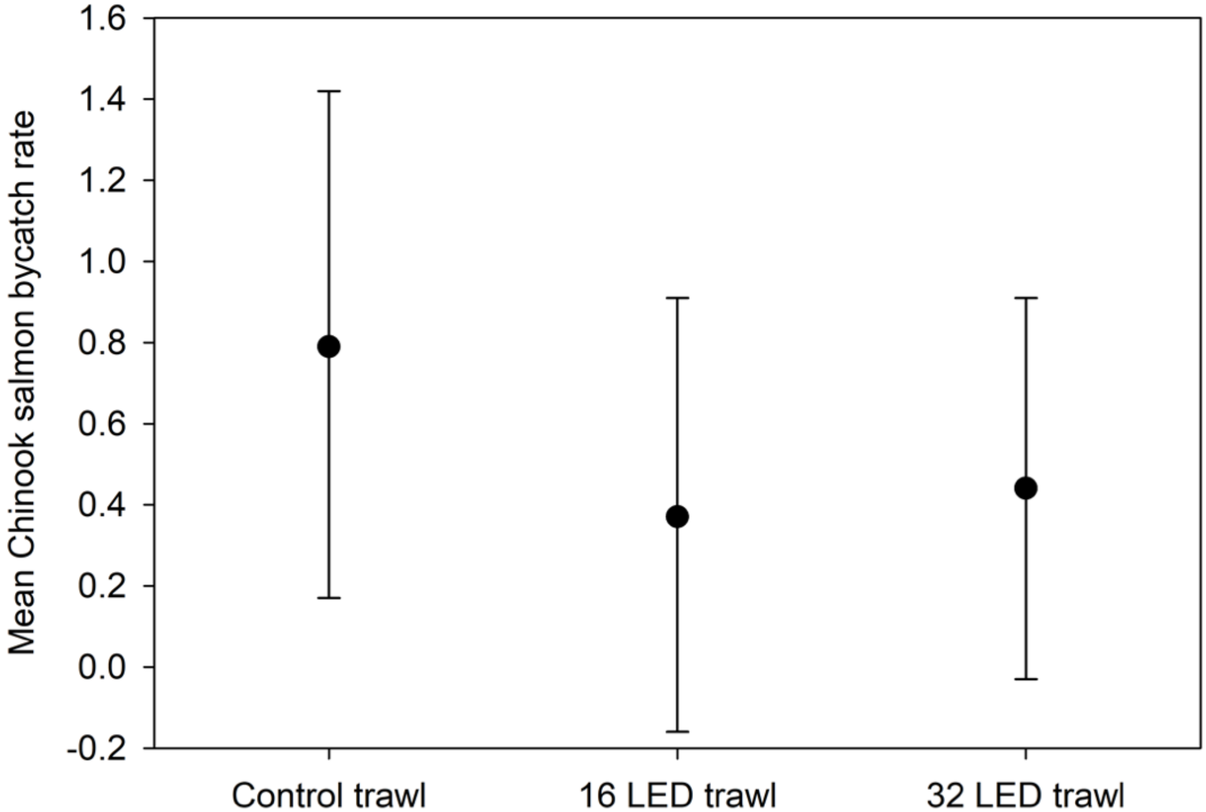

Figure 5. Mean Chinook salmon bycatch rate (# of fish per hour towed) for the control, 16, and 32 LED-configured trawl. Bars represent 95% CIs.

Table 1. Data from the 48 fishing trips conducted comparing the catch rates of Pacific hake (MT) and Chinook salmon (# of fish) between a non-illuminated trawl (Control) and trawls configured with 16 and 32 LEDs around the escape area of a bycatch reduction device.

Fishing trip	Month	Trawl configuration	Pacific hake (MT)	Chinook salmon (# of fish)	Fishing effort (hour:min.)	# of tows	Depth of catch (m)	Light level (μmol photons $m^{-2} s^{-1}$)	Area
1	July	Control	114.1	2	4:39	2	99	3.97E-02	Central
2	July	16 LED	127.2	0	3:54	1	108	1.10E-01	Central
3	July	32 LED	71.7	0	11:20	2	111	6.40E-02	Central
4	July	Control	115.2	0	3:46	2	153	2.13E-03	North
5	July	32 LED	118.6	4	6:36	2	154	9.85E-02	North
6	July	16 LED	128.1	0	3:34	2	137	1.02E-02	Central
7	July	Control	121.8	0	2:28	3	142	6.76E-03	Central
8	July	16 LED	125.7	1	2:11	1	135	2.14E-02	Central
9	July	32 LED	128.9	0	7:33	4	143	1.06E-01	Central
10	July	Control	128.2	0	6:34	2	158	3.95E-04	Central
11	July	32 LED	125.4	0	3:48	2	177	7.84E-02	Central
12	Aug.	16 LED	122.2	0	3:19	3	107	4.29E-02	North
13	Aug.	Control	139.5	0	1:55	2	186	1.78E-03	North
14	Aug.	16 LED	112.8	2	2:46	3	140	6.44E-02	North
15	Aug.	32 LED	112.4	1	7:11	3	123	1.56E-02	Central
16	Aug.	Control	129.3	0	0:47	1	101	4.35E-03	North
17	Aug.	32 LED	110.0	0	6:41	3	139	4.59E-02	Central
18	Aug.	16 LED	127.2	8	4:00	2	104	2.76E-02	Central
19	Aug.	Control	137.6	1	1:13	2	142	3.84E-03	South
20	Aug.	16 LED	134.7	3	1:50	2	199	2.94E-02	South
21	Aug.	32 LED	107.9	1	7:01	2	166	1.56E-02	South

Table 1. Continued.

Fishing trip	Month	Trawl configuration	Pacific hake (MT)	Chinook salmon (# of fish)	Fishing effort (hour:min.)	# of tows	Depth of catch (m)	Light level (μmol photons $m^{-2} s^{-1}$)	Area
22	Aug.	Control	147.9	0	2:13	1	146	1.09E-03	North
23	Aug.	32 LED	120.9	0	1:15	1	123	4.38E-02	North
24	Aug.	16 LED	110.1	0	4:11	2	127	5.59E-03	North
25	Aug.	Control	128.3	0	2:19	1	130	2.93E-02	North
26	Aug.	16 LED	94.7	0	7:05	3	185	2.41E-02	North
27	Aug.	32 LED	117.2	0	1:16	1	104	1.29E-01	North
28	Sept.	Control	145.5	0	3:40	1	146	4.49E-04	North
29	Sept.	32 LED	126.6	0	7:11	3	181	3.71E-02	North
30	Sept.	16 LED	115.3	0	6:57	1	149	4.53E-02	North
31	Sept.	Control	131.7	0	3:35	1	201	1.35E-04	South
32	Sept.	16 LED	142.0	1	1:55	1	201	1.68E-02	South
33	Sept.	32 LED	132.6	1	2:13	2	177	4.00E-02	Central
34	Sept.	Control	135.5	3	8:24	3	155	2.05E-03	Central
35	Sept.	32 LED	119.7	3	8:14	3	237	4.32E-02	South
36	Sept.	16 LED	110.9	6	4:23	2	194	1.29E-02	Central
37	Sept.	Control	116.0	4	4:31	3	250	4.10E-05	South
38	Sept.	16 LED	133.8	1	8:38	2	267	2.22E-02	South
39	Oct.	32 LED	63.5	23	10:26	3	220	1.41E-02	South
40	Oct.	Control	126.4	0	2:20	1	201	1.87E-05	South
41	Oct.	32 LED	133.1	0	5:22	1	220	2.06E-02	South
42	Oct.	16 LED	126.4	0	7:41	1	284	2.64E-02	South
43	Oct.	Control	123.7	4	6:20	1	284	9.26E-06	South

Table 1. Continued.

Fishing trip	Month	Trawl configuration	Pacific hake (MT)	Chinook salmon (# of fish)	Fishing effort (hour:min.)	# of tows	Depth of catch (m)	Light level (µmol photons $m^{-2} s^{-1}$)	Area
44	Oct.	16 LED	137.7	7	9:39	3	199	3.72E-03	Central
45	Oct.	32 LED	111.8	10	14:15	2	269	6.67E-03	South
46	Oct.	Control	113.7	34	5:18	1	293	9.63E-05	South
47	Oct.	32 LED	85.6	4	7:21	2	312	4.79E-03	South
48	Oct.	16 LED	111.9	1	8:19	5	212	2.27E-02	Central

Table 2. Least squares means of Pacific hake catch rate (MT) per hour towed by month and overall per trawl configuration. Values in parentheses are 95% CIs.

	Control trawl			16 LED trawl			32 LED trawl		
Month	Catch rate	Effort (hrs.)	Trips	Catch rate	Effort (hrs.)	Trips	Catch rate	Effort (hrs.)	Trips
July	27.4 (13.9-40.9)	17.45	4	39.4 (21.3-57.6)	9.65	3	15.1 (4.7-25.6)	29.28	4
Aug.	80.7 (45.7-115.7)	8.46	5	30.2 (9.1-51.3)	23.18	6	24.2 (3.2-45.3)	23.41	5
Sept.	26.2 (6.7-45.6)	20.16	4	22.9 (4.2-41.6)	21.88	4	21.4 (0.6-42.2)	17.63	3
Oct.	26.0 (11.6-40.4)	13.96	3	14.6 (4.0-25.2)	25.65	3	10.7 (1.9-19.6)	36.50	4
Overall	34.2 (23.3-45.0)	60.03	16	24.3 (15.0-33.7)	80.36	16	16.7 (8.5-24.8)	106.82	16

Table 3. Fit statistics for the least squares regression model examining whether Pacific hake mean catch rates changed linearly with trawl configuration, light level, depth of catch, and/or area fished between 13 July to 29 October 2020.

Term	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Trawl [Control]	11.32	-2.45	25.09	0.1045
Trawl [16 LED]	-0.65	-9.57	8.26	0.8827
Trawl [32 LED]	-10.66	-20.30	-1.02	**0.0310**
Light level	2.61	-7.60	12.84	0.6076
Depth of catch	-0.30	-0.58	-0.01	**0.0370**
Area [North]	1.23	-8.31	10.78	0.7953
Area [Central]	-9.72	-18.25	-1.19	**0.0265**
Area [South]	8.49	-3.65	20.64	0.1656

Table 4. Least squares means of Chinook salmon bycatch rate (# of fish) per hour towed by month and overall per trawl configuration. Values in parentheses are 95% CIs.

	Control trawl			16 LED trawl			32 LED trawl		
Month	Bycatch rate	Effort (hrs.)	Trips	Bycatch rate	Effort (hrs.)	Trips	Bycatch rate	Effort (hrs.)	Trips
July	0.11 (-0.21-0.44)	17.45	4	0.10 (-0.34-0.54)	9.65	3	0.13 (-0.11-0.39)	29.28	4
Aug.	0.11 (-0.70-0.93)	8.46	5	0.56 (0.06-1.05)	23.18	6	0.08 (-0.40-0.57)	23.41	5
Sept.	0.34 (-0.18-0.88)	20.16	4	0.36 (-0.14-0.88)	21.88	4	0.22 (-0.34-0.80)	17.63	3
Oct.	2.72 (-0.18-5.62)	13.96	3	0.31 (-1.82-2.45)	25.65	3	1.01 (-0.78-2.80)	36.50	4
Overall	0.79 (0.17-1.42)	60.03	16	0.37 (-0.16-0.91)	80.36	16	0.44 (-0.03-0.91)	106.82	16

Table 5. Fit statistics for the least squares regression model examining whether Chinook salmon mean bycatch rates changed linearly with trawl configuration, light level, depth of catch, and/or area fished between 13 July to 29 October 2020.

Term	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Trawl [Control]	0.092	-0.731	0.917	0.8212
Trawl [16 LED]	-0.043	-0.577	0.490	0.8696
Trawl [32 LED]	-0.049	-0.626	0.528	0.8642
Light level	-0.158	-0.770	0.453	0.6033
Depth of catch	0.005	-0.011	0.022	0.4941
Area [North]	-0.208	-0.780	0.363	0.4656
Area [Central]	<0.001	-0.510	0.511	0.9980
Area [South]	0.207	-0.519	0.935	0.5670

Appendix 1. Fit statistics for the least squares regression model examining whether Pacific hake mean catch rates changed linearly with trawl configuration, light level, depth of catch, and/or area fished during July. n/a = zero fishing effort.

Term	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Trawl [Control]	9.65	-5.99	25.30	0.1736
Trawl [16 LED]	12.25	0.46	24.04	**0.0443**
Trawl [32 LED]	-21.90	-35.40	-8.41	**0.0087**
Light level	13.96	-2.07	29.47	0.0760
Depth of catch	0.75	0.08	1.42	**0.0341**
Area [North]	-2.29	-11.41	6.82	0.5460
Area [Central]	2.29	-6.82	11.41	0.5460
Area [South]	n/a	n/a	n/a	n/a

Appendix 2. Fit statistics for the least squares regression model examining whether Pacific hake mean catch rates changed linearly with trawl configuration, light level, depth of catch, and/or area fished during August.

Term	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Trawl [Control]	39.06	1.55	76.58	**0.0429**
Trawl [16 LED]	-17.82	-42.09	6.45	0.1311
Trawl [32 LED]	-21.24	-52.19	9.70	0.1549
Light level	13.22	-29.54	56.00	0.5019
Depth of catch	-0.70	-1.85	0.43	0.1931
Area [North]	2.05	-24.62	28.72	0.8658
Area [Central]	-16.83	-44.51	10.84	0.2021
Area [South]	14.78	-15.51	45.09	0.2983

Appendix 3. Fit statistics for the least squares regression model examining whether Pacific hake mean catch rates changed linearly with trawl configuration, light level, depth of catch, and/or area fished during September.

Term	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Trawl [Control]	-37.69	-106.75	32.35	0.2041
Trawl [16 LED]	16.64	-17.40	50.69	0.2462
Trawl [32 LED]	21.05	-22.43	64.54	0.2501
Light level	-24.36	-69.11	20.37	0.2501
Depth of catch	-0.92	-2.55	0.70	0.1897
Area [North]	-17.38	-53.49	18.72	0.2523
Area [Central]	-0.72	-27.98	26.53	0.9445
Area [South]	18.11	-26.89	63.12	0.3264

Appendix 4. Fit statistics for the least squares regression model examining whether Pacific hake mean catch rates changed linearly with trawl configuration, light level, depth of catch, and/or area fished during October. n/a = zero fishing effort.

Term	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Trawl [Control]	7.10	-45.49	59.71	0.7265
Trawl [16 LED]	1.02	-36.69	38.74	0.9435
Trawl [32 LED]	-8.13	-30.71	14.44	0.3737
Light level	-0.75	-27.82	26.32	0.9423
Depth of catch	-0.22	-0.78	0.33	0.3288
Area [North]	n/a	n/a	n/a	n/a
Area [Central]	-6.26	-27.97	15.43	0.4676
Area [South]	6.26	-15.43	27.97	0.4676

Appendix 5. Fit statistics for the least squares regression model examining whether Chinook salmon mean bycatch rates changed linearly with trawl configuration, light level, depth of catch, and/or area fished during July. n/a = zero fishing effort.

Term	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Trawl [Control]	0.123	-0.350	0.597	0.5332
Trawl [16 LED]	-0.002	-0.350	0.354	0.9875
Trawl [32 LED]	-0.121	-0.530	0.287	0.4809
Light level	0.181	-0.296	0.659	0.3743
Depth of catch	<0.001	-0.019	0.020	0.9664
Area [North]	0.163	-0.112	0.439	0.1889
Area [Central]	-0.163	-0.439	0.112	0.1889
Area [South]	n/a	n/a	n/a	n/a

Appendix 6. Fit statistics for the least squares regression model examining whether Chinook salmon mean bycatch rates changed linearly with trawl configuration, light level, depth of catch, and/or area fished during August.

Term	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Trawl [Control]	0.339	-0.211	0.890	0.1968
Trawl [16 LED]	0.456	0.099	0.813	**0.0177**
Trawl [32 LED]	-0.796	-1.250	-0.341	**0.0033**
Light level	0.279	-0.348	0.907	0.3406
Depth of catch	-0.007	-0.024	0.009	0.3318
Area [North]	-0.792	-1.184	-0.400	**0.0013**
Area [Central]	0.314	-0.091	0.721	0.1138
Area [South]	0.478	0.032	0.923	**0.0380**

Appendix 7. Fit statistics for the least squares regression model examining whether Chinook salmon mean bycatch rates changed linearly with trawl configuration, light level, depth of catch, and/or area fished during September.

Term	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Trawl [Control]	-0.973	-2.219	0.272	0.0960
Trawl [16 LED]	0.449	-0.165	1.063	0.1123
Trawl [32 LED]	0.524	-0.260	1.309	0.1374
Light level	-0.678	-1.486	0.129	0.0800
Depth of catch	-0.001	-0.030	0.028	0.9190
Area [North]	-0.346	-0.997	0.305	0.2145
Area [Central]	0.528	0.036	1.020	**0.0407**
Area [South]	-0.182	-0.994	0.630	0.5676

Appendix 8. Fit statistics for the least squares regression model examining whether Chinook salmon mean bycatch rates changed linearly with trawl configuration, light level, depth of catch, and/or area fished during October. n/a = zero fishing effort.

Term	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Trawl [Control]	6.252	-3.765	16.269	0.1582
Trawl [16 LED]	-4.364	-11.548	2.818	0.1699
Trawl [32 LED]	-1.887	-6.186	2.411	0.2898
Light level	2.583	-2.572	7.738	0.2366
Depth of catch	0.017	-0.088	0.123	0.6670
Area [North]	n/a	n/a	n/a	n/a
Area [Central]	1.234	-5.367	2.898	0.4536
Area [South]	-1.234	-2.898	5.367	0.4536