Use of Artificial Illumination to Reduce Pacific Halibut Bycatch in a U.S. West Coast Groundfish Bottom Trawl

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Abstract

In the U.S. West Coast groundfish bottom trawl fishery, Pacific halibut (*Hippoglossus stenolepis*) bycatch can impact some fishers' ability to fully utilize their quota shares of groundfishes. In this study, we compared the catch efficiency for Pacific halibut and four commercially important groundfish species between an illuminated and non-illuminated trawl. The illuminated trawl caught significantly fewer Pacific halibut and sablefish than the non-illuminated trawl. For Dover sole (*Microstomus pacificus*), petrale sole (*Eopsetta jordani*), and lingcod (*Ophiodon elongatus*), the illuminated trawl caught fewer individuals than the non-illuminated trawl. However, this catch difference was not statistically significant. Physiological data collected on Pacific halibut caught in illuminated and non-illuminated trawl show blood levels of cortisol, a stress hormone, were significantly higher in fish caught in the illuminated trawl than in the non-illuminated trawl in the absence of differences in condition factor or fat content. While our results have obvious implications for the West Coast groundfish bottom trawl fishery, our findings could also have potential applications in Alaska and British Columbia, Canada trawl fisheries where Pacific halibut bycatch occurs.

Introduction

The directed commercial fishery for Pacific halibut (*Hippoglossus stenolepis*) is longline based in United States and Canadian waters from northern California to the Bering Sea. Pacific halibut are managed by the International Pacific Halibut Commission (IPHC) in collaboration with federal fisheries agencies and regional councils. Pacific halibut are a prohibited species in trawl fisheries and cannot be retained for commercial sale.

In the U.S. West Coast groundfish bottom trawl fishery, which is managed under a catch share program, fishers are allocated individual bycatch quota (IBQ) of Pacific halibut. If fishers reach their Pacific halibut IBQ, they are prohibited from fishing unless additional bycatch quota is obtained from another permit holder. However, obtaining additional bycatch quota can be challenging given the amount of quota needed, time of season, and cost of quota leases. As relatively limited bycatch quota is available to the groundfish bottom trawl fishery, Pacific halibut bycatch can affect the harvest of groundfishes such as sablefish (*Anoplopoma fimbria*), Dover sole (*Microstomus pacificus*), petrale sole (*Eopsetta jordani*), and lingcod (*Ophiodon elongatus*). For example, the 2019 West Coast trawl annual catch limit for sablefish, Dover sole, petrale sole, and lingcod was 4,571 MT, 50,000 MT, 2,908 MT, and 5,910 MT, respectively, compared to ca. 50 MT of Pacific halibut bycatch quota. Further, as the Pacific halibut stock is projected to gradually decrease between 2020 and 2023 due to low recruitment (IPHC, 2020), their bycatch is likely to continue to impact utilization of groundfish stocks as bycatch quota in the fishery (IPHC regulatory area 2A) is not anticipated to increase above current levels.

Sorting-grid bycatch reduction devices (BRDs) are capable of significantly reducing catches of larger Pacific halibut (>75 cm in total length) in the West Coast groundfish bottom trawl fishery (Lomeli and Wakefield, 2013, 2015, 2016; Lomeli et al., 2017). However, the devices are less effective at reducing catches of Pacific halibut that are similar in size to the target species. Therefore, reducing Pacific halibut bycatch of all sizes would depend on exploiting behavioral differences between Pacific halibut and other species during the capture process.

Vision plays a significant role in how fishes respond to trawls (Glass and Wardle, 1989; Olla et al., 1997; Kim and Wardle, 1998, 2003; Ryer et al., 2010). Under conditions where light levels are adequate for vision, studies have shown that fishes most often react actively to the gear with responses such as herding, orientation to the trawl, or maintaining their swimming position forward of or within the trawl (Rose, 1996; Olla et al., 2000; Ryer and Barnett, 2006; Ryer, 2008). However, under dark conditions where the visual capability of fish becomes limited or absent, their response to trawl gear becomes diminished. For BRDs that rely upon fish to use their visual system to direct their way through escape areas, the amount of available light could have a considerable impact on the gear performance.

Trawling often occurs at depths or times of day (i.e., night time, polar night) where fishes' visual capability to detect trawl gear is affected by light availability. In response, studies have begun exploring the effects of artificial illumination as a technique to enhance fishes' ability to escape (Nguyen and Winger, 2019). Examples include placing artificial illumination along open escape windows (Lomeli and Wakefield, 2019), on or near escape areas associated with sorting-grids (Hannah et al., 2015; Larsen et al., 2017, 2018), on the leading edge of a codend separator panel (Melli et al., 2018), and along the fishing line or headrope of trawls (Hannah et al., 2015; Lomeli et al., 2018ab, 2020; O'Neill and Summerbell, 2019). In the presence of artificial illumination, results from the above studies have ranged from increased (Hannah et al., 2015), status quo (Larsen et al., 2017, 2018), to reduced (Hannah et al., 2015; Lomeli and Wakefield, 2019) bycatch rates.

Research has suggested that Pacific halibut bycatch in the West Coast groundfish bottom trawl fishery could potentially be reduced using artificial illumination (Lomeli et al., 2018a). In a study investigating whether illuminating the headrope of a selective flatfish trawl could reduce bycatch of rockfishes (*Sebastes* spp.), results showed the illuminated trawl caught on average 57% less Pacific halibut than the non-illuminated trawl (Lomeli et al., 2018a). This result, however, was not significant likely due to the small sample size of Pacific halibut caught. For groundfish catches, results showed no significant difference in the catch efficiency between the non-illuminated and illuminated trawls for rockfishes, lingcod, English sole (*Parophrys vetulus*), and petrale sole. A significant difference in the catch efficiency was noted for sablefish and Dover sole with the illuminated trawl catching fewer fish on average. In the same study, light levels were measured at the center of the headrope and belly in the illuminated and non-illuminated trawls. Light levels at the altitude of the headrope showed the trawl groundgear often created mud clouds that rose above the headrope, which would likely affect fishes' ability to detect and respond to the illumination if the mud cloud duration was considerable. These results suggest there may be potential to reduce Pacific halibut bycatch using artificial illumination, but placement of lights on the trawl in areas that are less impacted by mud clouds (i.e., leading edge of doors, upper bridles, wing tips) could be a factor in their potential efficacy, necessitating further research.

The objective of this study is to determine whether artificial illumination can reduce Pacific halibut bycatch while maintaining or increasing groundfish catches and its relationship with the physiological condition and/or stress levels of captured Pacific halibut.

Materials and Methods

Trawl, Gear trials, and Sampling

We used an Eastern 400 trawl for this study (Fig. 1). The headrope was 40.3 m in length. The 31.2 m chain footrope was covered with rubber discs 20.3 cm in diameter, and outfitted with rubber rockhopper discs 35.6 cm in diameter placed approximately every 58 cm along the footrope length. By design, the trawl headrope runs behind the footrope (e.g., cutback headrope) and fishes approximately 1.3 m above the seafloor. The wingspread of this trawl is approximately 20.8 m. The low-rise and cutback headrope features of this trawl are designed to reduce bycatch of benthopelagic rockfishes when targeting flatfishes and other demersal groundfishes (King et al., 2004; Hannah et al., 2005). In the West Coast groundfish bottom trawl fishery, this trawl design is termed a selective flatfish trawl (King et al., 2004; PFMC, 2019). The design and dimensions of this trawl are typical of selective flatfish trawls used in the groundfish fishery. The upper bridles consisted of 25.4 mm Spectra^{TM} rope and were 2.4 m in length, whereas the lower bridles consisted of chain covered with rubber discs 20.3 cm in diameter (Fig. 1). The sweeps were combination wire 91.4 m in length and were outfitted with ten 17.8 cm diameter disc clusters spaced at 8.2 m intervals along their entire length (Lomeli et al., 2019). The trawl was spread using Thyborøn type-11 doors. A T90 mesh codend (127 mm nominal mesh size, 6.0 mm double twine, 88 meshes in circumference and 100 meshes in length) was used.

We used a single trawl with artificial illumination as the only experimental treatment. The trawl was fished along bottom depth contours with and without illumination in an alternating order to create paired tows. Green LED fishing lights (Lindgren-Pitman Electralume®, centered on 519 nm [Nguyen et al., 2017]) were used to illuminate the upper bridles and wing tips of the trawl. As Lomeli et al. (2018a) found the trawl groundgear often created mud clouds that rose above the trawl headrope, we selected to illuminate the trawls upper bridles and wing tips as these gear components are typically less effected by mud clouds. Green LEDs were selected for the following reasons: (1) they allow for a comparison of results with Lomeli et al. (2018a), (2) blue-green light is the predominant spectral component of coastal waters (Jerlov 1976; Bowmaker 1990; Britt 2009), and (3) use of green lights in the ocean shrimp (*Pandalus jordani*) trawl fishery has shown to reduced fish bycatch (Hannah et al., 2015; Lomeli et al., 2018b, 2020). For the illuminated trawl, the fishing lights were grouped into clusters of three using twine to connect each light end to end. Three LED clusters were attached along each of the wing tips and upper bridles (Fig. 1). In total, six LED clusters were attached to each the port and starboard side. The lights were attached to the trawl before deployment and then removed following retrieval to avoid damaging them when winding the gear onto the net reel. Attachment points on the trawl were marked with shock cord and orange twine to assure that the tow-to-tow attachment point of each LED cluster was consistent across tows. Light levels and water temperatures at the trawl's breastline were measured using a Wildlife Computers TDR-MK9 archival tag. The MK9 tag was positioned in the same location on the port breastline, with the light sensor facing forward towards the bridles. The MK9 tag was not used on tows 1 and 2 as we accidentally forgot to deploy the tag. The relative light units for the calibrated MK9 tag were converted to irradiance units (e.g., μmol photons m^{-2} s^{-1}) using the calibration function presented in Lomeli et al. (2018a). Collecting these data is recommended by the International Council for the Exploration of the Sea to improve comparability of results between light studies (ICES, 2018).

Gear trials occurred off Oregon (Fig. 2) in August aboard the F/V *Last Straw* (a 23.2 m long, 540-hp trawler). Towing occurred during daylight hours from 0630 to 1900 at bottom fishing depths from 97 to 238 m. The average bottom fishing depth was 168 m (SE ± 6.3). Towing speed over ground ranged from 1.1 to 1.3 m/s (2.2 to 2.6 knots). Target tow duration was 60 minutes, and time on bottom was measured once deployment of the trawl warps stopped. However, due to time constraints and anticipated large catches some paired tows were of 30 and 45 min. in duration. Within each pair, the tow duration was kept consistent.

Our study site (Fig. 2) was selected based on known groundfish and Pacific halibut abundances. After each tow, all fishes were sorted to species and weighed using a Marel M1100 motion compensated marine platform scale that was calibrated before each sampling event. Fishes were measured to the nearest cm using total length for flatfishes and lingcod, and fork length for sablefish. Subsampling was avoided when possible; however, time constraints and relatively large catches required subsampling at times. For Pacific halibut, data on fish condition and somatic fat content was collected on all individuals caught. Fish condition from all Pacific halibut caught in illuminated and non-illuminated trawls was estimated using Fulton's Condition Factor (K) (Le Cren, 1951), which describes the relationship between fish total length (L) measured in cm, weight (W) measured in grams, and a scaling factor (c; representing the reciprocal of the average value of K) to approximate K to 1, as described by Eq. 1:

$$K = c * \frac{W}{L^3} \qquad (1).$$

Somatic fat content from all Pacific halibut caught in illuminated and non-illuminated trawls was estimated using a Distell Fish Fatmeter (Model FFM 692), using Distell's Sea Bass II standard calibration. The Fatmeter is a non-invasive tool that utilizes low-power microwave emission to estimate subdermal lipid content based on the water content of tissues (Kent, 1990). Two readings were obtained from both sides (eyed and blind sides) of each fish, the first one taken inside the arch of the lateral line (slightly posterior from the pectoral fin) and the second one taken at a position anterior to the caudal peduncle (coinciding with the end of the dorsal fin) and above the lateral line. The two readings from each site were averaged and the grand mean of the averaged readings from each of the four sites (e.g., two sites per side) were applied to a fat calibration curve developed for Pacific halibut (unpublished results). To investigate if the physiological condition of Pacific halibut differs between fish caught in the illuminated and non-illuminated trawls, we measured the levels of physiological stress indicators in their blood. Blood samples were collected from tows 17-34 on the vessel back deck by caudal puncture and then centrifuged for 15 minutes at 3,000 rpm in a temporary lab space configured in the vessel's galley. The resulting plasma samples were stored at -20°C until use. The levels of glucose, lactate, and cortisol were measured directly in the plasma using commercial kits (glucose, EIAGLUC, Invitrogen; lactate, MET-5012, Cell Biolabs; cortisol, ELISA 500360, Cayman). Statistical differences between mean values of physiological parameters from the illuminated and non-illuminated trawls were analyzed by unpaired two-sample T-test using R Studio package (version 1.2.5033) for R (version 3.6.2). Results are expressed as mean ± standard deviation and considered to be statistically significant at $p < 0.05$.

To capture the behavior of Pacific halibut and target groundfishes as they encountered the illuminated trawl, we placed a video camera (GoPro Hero 4) aft of the trawl's port breastline (looking toward the port bridles) on four tows, and a DIDSON (Dual-frequency Identification SONar) imaging sonar near the trawl footrope (looking towards the port wing tip and bridles) on five tows. The only source of illumination for the video were the experimental LED clusters.

Estimating relative catch efficiency between illuminated and non-illuminated trawls

We conducted length-dependent catch comparison and catch ratio analyses (Sistiaga et al., 2015; Lomeli et al., 2018a, 2019) to determine whether there was a difference in catch efficiency and/or fish length between the illuminated and non-illuminated trawl. To assess the relative length-dependent catch comparison proportion (CC_l) of changing from non-illuminated to illuminated trawl, we used Eq. 2:

$$CC_l = \frac{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}+\frac{nc_{lj}}{qc_j}\right\}} \tag{2}$$

where nt_{lj} and nc_{lj} are the number n of fish measured per length class l for the illuminated (t) and non-illuminated (c) trawl, respectively, in pair j of the alternated tows. Terms qt_j and qc_j are the subsampling ratios. Parameter m is the number of tows made with the illuminated and non-illuminated trawl. The functional form of the catch comparison proportion *CC(l,**v**)* expressed by Eq. 2 was attained using maximum likelihood estimation by minimizing Eq. 3:

$$-\sum_{l}\left\{\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j}\times ln[1.0-CC(l,\boldsymbol{v})]\right\}+\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\times ln[CC(l,\boldsymbol{v})]\right\}\right\} \tag{3}$$

where ***v*** represents the parameters describing the catch comparison curve defined by *CC(l,**v**)*. Equation 3 is similar in structure to the SELECT model (Millar, 1992) for data pooled over hauls which is often applied in analysis of fishing gear size selectivity (Wileman et al., 1996). Minimizing Eq. 3 is equivalent to maximizing the likelihood for the observed data based on a formulation of the negative log likelihood for binominal data. When the catch efficiency of the two trawls are equal, the catch comparison proportion would be 0.5. A catch comparison proportion value with 95% confidence intervals (CIs) below 0.5 would imply there is a significant catch effect with fewer fish on average caught in the illuminated trawl, and vice versa for a catch comparison proportion above 0.5. The experimental CC_l was modeled by the function *CC(l,**v**)* using Eq. 4:

$$CC(l,\boldsymbol{v})=\frac{exp[f(l,v_0,\ldots,v_k)]}{1+exp[f(l,v_0,\ldots,v_k)]} \tag{4}$$

where *f* is a polynomial of order *k* with coefficients v_0-v_k, such that $\boldsymbol{v} = (v_0,\ldots,v_k)$. The values of the parameters ***v*** describing *CC(l,**v**)* are estimated by minimizing Eq. 3. We considered *f* of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4 as our experience from prior studies (Krag et al., 2015; Santos et al, 2016; Sistiaga et al., 2018) have demonstrated that this provides a model that can sufficiently describe the catch comparison curves between two fishing gears. Leaving out one or more of the parameters $v_0 \ldots v_4$, at a time resulted in 31 additional candidate models for the catch comparison function *CC(l,**v**)*. Among these models, the catch comparison proportion was estimated using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017; Harrison et al., 2018). Specifically, the models were ranked and weighted in the estimation according to their AICc values (Burnham and Anderson, 2002). The AICc is calculated as the AIC (Akaike, 1974), but it includes a correction for finite sample sizes in the data. Models that resulted in AICc values within +10 of the value of the model with lowest AICc value (AICc_{min}) were considered for the estimation of $CC(l,\boldsymbol{v})$ following the procedure described in Katsanevakis (2006) and in Herrmann et al. (2015). We use the name combined model for the result of this multi-model averaging and calculated it using Eq. 5:

$$CC(l,\boldsymbol{v}) = \sum_i w_i \times CC(l,\boldsymbol{v}_i) \quad with \quad w_i = \frac{exp\left(0.5\times\left(AICc_i - AICc_{min}\right)\right)}{\sum_j exp\left(0.5\times\left(AICc_j - AICc_{min}\right)\right)} \tag{5}$$

where the summations are over the models with an AICc value within +10 of AICc_{min}. The ability of the combined model to explain the observed data was based on the *p*-value, which is calculated based on the model deviance and degrees of freedom (Wileman et al., 1996; Herrmann et al., 2017). Thus, suitable fit statistics for the combined model to describe the observed data sufficiently well should be a p-value >0.05 and a deviance value within approximately two times the degrees of freedom.

To provide a direct relative value of the catch efficiency between fishing with and without illumination, the following catch ratio $CR(l,\boldsymbol{v})$ equation was used:

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

Thus, if the catch efficiency of both trawls is equal, the $CR(l,\boldsymbol{v})$ will be 1.0.

We used a double bootstrapping method to estimate the CIs for the catch comparison and catch ratio curves. This technique accounts for uncertainty due to between tow variation by selecting *m* tows with replacement from the *m* tows available during each bootstrap repetition. Within each resampled tow, the data for each length class are resampled in an inner bootstrap to account for the uncertainty in the tow due to a finite number of fish being caught and length measured in the tow. We performed 1,000 bootstrap repetitions and calculated the Efron 95% CIs (Efron, 1982).

We estimated directly from the observed catch data an overall value for the catch ratio using Eq. 7:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \left\{ \frac{nt_{lj}}{qt_j} \right\}}{\sum_l \sum_{j=1}^{m} \left\{ \frac{nc_{lj}}{qc_{ij}} \right\}} \qquad (7).$$

Based on Eq. 7, we then estimated the percent improvement in average catch efficiency between fishing with and without illumination using Eq. 8:

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

We used Eq. 8 to provide an overall value for the effect of changing from non-illuminated to illuminated trawl on the catch efficiency. If the illuminated trawl has an increase in catch efficiency, then the $\Delta CR_{average}$ value will be above zero. On the contrary, if the illuminated trawl has a decrease in catch efficiency, then the $\Delta CR_{average}$ value will be below zero.

The analyses described above were performed using the software SELNET (Sistiaga et al., 2010; Herrmann et al., 2012, 2016).

Results

Sampling conditions

Fishing occurred over three consecutive fishing trips each of four days in length. The duration between each fishing trip was two days. We completed 34 tows representing 17 consecutive pairs each with catch data from one illuminated and one non-illuminated trawl. The mean distance between paired tow lines was 1.3 km (SE ± 0.2). The mean natural light level measured in the non-illuminated trawl was $2.6e^{-05}$ ($\pm 3.2e^{-06}$) µmol photons m^{-2} s^{-1}. In the illuminated trawl, the mean light level measured increased to $1.4e^{-02}$ ($\pm 1.6e^{-03}$) µmol photons m^{-2} s^{-1}. Mean light levels per tow for the non-illuminated and illuminated trawl are shown in Figure 3. The mean water temperature was 7.4°C (±0.005) and ranged from 7.0-7.9°C.

Fit statistics

The species caught in sufficient numbers for use in the catch efficiency analyses were Pacific halibut, Dover sole, petrale sole, sablefish, and lingcod (Table 1). The combined $CC(l,\mathbf{v})$ models described the observed data well for Dover sole, petrale sole, and sablefish as shown by their fit statistics (Table 2). For Pacific halibut and lingcod, which had a fit statistic p-value <0.05, inspecting the fit between the observed catch comparison data and the modeled mean curve showed that the poor fit statistics were probably due to overdispersion of the data as opposed to the model's inability to sufficiency describe the data.

Pacific halibut bycatch and biological data

Bycaught Pacific halibut ranged from 58-127 cm in length and 2.0 to 25.7 kg in weight. When examining if an increase in average catch efficiency occurred, results show the illuminated trawl caught on average 58.7% less Pacific halibut than the non-illuminated trawl (Fig. 4). This difference in catch efficiency was statistically significant. The analyses also detected a significant length-dependent catch efficiency effect for Pacific halibut 62-126 cm in length with the illuminated trawl catching on average only 36.8% of the number of Pacific halibut compared to the non-illuminated trawl (Figs. 5 and 6).

Condition factor and fat content, two measures indicative of the physiological condition of fish, did not differ significantly for Pacific halibut caught between the illuminated and non-illuminated trawl (Table 3). Among the physiological stress indicators measured in their blood, the levels of the metabolites lactate and glucose did not differ significantly for fish caught between the illuminated and non-illuminated trawl. However, the blood levels of cortisol, a stress hormone, were significantly higher (two-sample T-test [$t=2.24$, $df=41$, $p<0.05$]) in Pacific halibut caught in the illuminated trawl than in the non-illuminated trawl (205.1 ± 116.1 and 138.4 ± 65.1 ng/ml, respectively; Table 3). No relationship was found between catch weight and tow duration and the various physiological parameters measured, including blood cortisol levels (data not shown).

Dover sole, petrale sole, sablefish, and lingcod catches

Our catch ratio analysis shows a significant length-dependent catch effect occurred for Dover sole with the illuminated trawl catching on average fewer individuals 25-29 cm in length and 48-53 cm in length than the non-illuminated trawl. For Dover sole 30-47 cm in length and 54-55 cm in length, no significant length-dependent catch effect occurred between the two trawls (Figs. 5 and 6). When evaluating if an increase in average catch efficiency occurred, results show that the illuminated trawl caught 6.2% less Dover sole than the non-illuminated trawl. However, this result was not significant as shown by the 95% CIs of the mean value extending across the value of zero (Fig. 4). For petrale sole, similar findings occurred with the illuminated trawl catching significantly fewer fish 42-51 cm in length than the non-illuminated trawl (Figs. 5 and 6). While the illuminated trawl caught 26.9% less petrale sole than the non-illuminated trawl, the result was not significant.

A significant length-dependent catch effect occurred in sablefish 44-52 cm in length with the illuminated trawl catching on average only 65.1% of the number of sablefish compared to the non-illuminated trawl (Figs. 7 and 8). In terms of increase in average catch efficiency, the illuminated trawl caught significantly fewer sablefish (35.2%) than the non-illuminated trawl (Fig. 4). For lingcod, our analyses detected no significant length-dependent effect of changing from non-illuminated to illuminated trawl (Figs. 7 and 8). When examining if an increase in average catch efficiency occurred, our results show that the illuminated trawl caught 19.0% less lingcod than the illuminated trawl; however, this difference was not statistically significant.

Discussion

Developing approaches and technologies that can minimize bycatch would be beneficial to fishers, management, and fishery resources. In our study, we showed the ability to significantly reduce Pacific halibut bycatch before trawl capture by placing LEDs along the wing tips and upper bridles of a selective flatfish trawl. These findings contribute new data on the efficacy of artificial illumination to reduce Pacific halibut bycatch, but also their ability to reduce their bycatch before trawl capture. Capture-escape processes can lead to unobserved and unaccounted post-release mortality caused from physiological stress, fatigue, and injuries (Chopin and Arimoto, 1995; Davis and Olla, 2001, 2002; Ryer, 2004; Davis, 2005). Reducing Pacific halibut bycatch before trawl capture would likely have a positive effect on lowering this mortality.

Use of BRDs often create economic tradeoffs that fishers need to consider when seeking to reduce bycatch. In our study, sablefish catches were significantly reduced in the illuminated trawl. However, this result was moderate in effect as the mean $\Delta CR_{average}$ upper 95% CI nearly extended to the $\Delta CR_{average}$ ratio value of zero. For Dover sole, petrale sole, and lingcod, the illuminated trawl on average caught fewer individuals than the non-illuminated trawl, but not to a significant level. Under such catch losses, whether nominal or significant in value, a fisher using an illuminated trawl would need to increase their fishing effort to maintain target species catches

(Table 4). Their increased fishing effort would result in an increase of Pacific halibut bycatch and fuel consumption, among other considerations. Based on the catch relationships noted in our study (Fig. 4), Table 4 shows catch scenarios for various increased tow durations in the illuminated trawl and its effect on groundfish catches and Pacific halibut bycatch. It is worth noting that the values presented in Table 4 for Dover sole, petrale sole, and lingcod are nominal values. Furthermore, these values do not account for changes in trawl performance that may occur as tow durations increase (e.g., a fishes' herding duration, fatigue, etc.).

While the illuminated trawl on average caught fewer sablefish, this reduction in catch may not necessarily be undesirable as fishers targeting Dover sole and petrale sole over the continental shelf often encounter smaller-sized sablefish that are of lesser economic value. Ex-vessel prices for sablefish increase with fish weight classes and can range from \$0.65 to \$9.57 USD/kg, with fish ≥3.2 kg (~45 cm in length) exhibiting the highest ex-vessel values (i.e., \$4.25-9.55 USD/kg). It is over the outer continental shelf and upper slope where the trawl allocation of sablefish is primarily utilized in the DTS (Dover sole-thornyhead-sablefish) complex fishery where sablefish are larger-sized (upwards to 95 cm in total length [Lomeli et al., 2017; Haltuch et al., 2019]) and of higher ex-vessel value. Thus, reducing catches of smaller-sized sablefish for fishers trawling over the continental shelf could improve their economic utilization of the sablefish resource by having more quota available to apply to the DTS complex fishery. Further, depending on the amount of Pacific halibut IBQ that a fisher has, and the magnitude of Pacific halibut bycatch reduction needed, use of artificial illumination in the DTS complex fishery may or may not be beneficial and would create economic tradeoffs between catch composition and bycatch reduction.

We found that placing illumination along the wing tips and upper bridles of a selective flatfish trawl was an effective technique for reducing Pacific halibut bycatch. This finding supports research by Lomeli et al. (2018a) suggesting that their bycatch could be reduced using artificial illumination. However, the processes resulting in Pacific halibut bycatch reduction in the presence of artificial illumination remain uncertain. The various ways that Pacific halibut (and sablefish) could avoid capture include passing under the footrope, rising over the wings or upper bridles of the trawl, passing over the sweeps forward of the bridles, or out swimming the trawl. We attempted to gain insights on how Pacific halibut and groundfishes interact with the illuminated trawl using video and a DIDSON imaging sonar, but were unsuccessful for the following reasons: 1) the LEDs did not provide sufficient illumination to support suitable imagery, and 2) movement of the fishing line and footrope during the tow created an unstable platform for the DIDSON to capture suitable imagery for identifying fish or making behavioral observations. Further, it remains unknown how Pacific halibut might respond to artificial illumination used on trawls with overhanging headropes and larger wings (King et al., 2004; Hannah et al., 2005). Data on phototaxis and visual cues in Pacific halibut are also lacking. Thus, research investigating the interactions between illumination, trawl design, and Pacific halibut bycatch is needed to better understand the mechanisms contributing to our observed results.

In Alaska groundfish bottom trawl fisheries, such as the eastern Bering Sea flatfish and Pacific cod (*Gadus macrocephalus*) fisheries, Pacific halibut bycatch occurs (NPFMC, 2018, 2019). While fishers employ excluders to reduce their bycatch and deck sorting methods that reduce discard mortality rates, Pacific halibut bycatch continues to constrain these fisheries (NPFMC, 2018, 2019). Findings from our research could have potential applications in these fisheries to further reduce Pacific halibut bycatch. As fishers and managers seek collaborative efforts to minimize Pacific halibut bycatch (Rose and Gauvin, 2000; NOAA, 2014, 2019), research testing the ability of artificial illumination to reduce Pacific halibut bycatch could result in positive fishery impacts on Alaska groundfish bottom trawl fisheries. However, in Alaska larger vessels deploying larger-sized trawl gear may limit transferability.

Examination of the levels of physiological stress indicators in the blood from Pacific halibut in the illuminated trawl revealed significantly higher levels of cortisol, a corticosteroid hormone produced by the interrenal gland of fish as the primary response to a stressor (Schreck et al., 2016). The higher levels of cortisol, combined with the trend towards higher plasma glucose levels in fish in the illuminated trawl (although not statistically significant), suggest higher levels of stress in these fish when compared to those in the non-illuminated trawl. Parallel increases in plasma cortisol and glucose are consistent with the notion that stress-induced cortisol elevates plasma glucose levels through the mobilization of glycogen reserves in order to provide glucose as an energy substrate to meet the higher energy demands imposed by stress in fish (Rodnick and Planas, 2016). These observed differences in physiological stress indicators between illuminated and non-illuminated trawls occur in the absence of differences related to the physiological condition of Pacific halibut, as assessed by condition factor and somatic fat content, or to indicators of physical exhaustion, as assessed by plasma lactate levels. Similarly, the differences were independent of catch volume or tow duration. Therefore, the observed differences in stress levels of Pacific halibut between illuminated and non-illuminated trawls appear to be related to differences in conditions experienced during trawl entrapment and not to differences in the physiological condition of fish before trawl capture. Given that the presence or not of illumination is the major difference between the two experimental set-ups, we hypothesize that the presence of artificial illumination may have been responsible for the higher stress levels in fish in the illuminated trawl. This possibility is supported by a number of studies showing that acute or chronic exposure to artificial illumination of different intensities and wavelengths can affect stress or stress responses in a variety of fish species in a species-specific manner (Owen et al., 2010; Maia and Volpato, 2013; Heydarnejad et al., 2017). As stated above, although the precise behavioral response of Pacific halibut to the type of artificial illumination used in the present study is not known, exposure to artificial illumination during trawl capture may have increased stress in captured Pacific halibut. In view of the significant reduction of Pacific halibut bycatch using artificial illumination, the potential effects on the survivability of captured and discarded Pacific halibut in illuminated versus non-illuminated trawls represent an interesting topic for further investigation.

Results from our study and Lomeli et al. (2018a) show similar findings. For sablefish, both studies noted a significant catch reduction in the presence of artificial illumination. For Pacific halibut, Dover sole, and lingcod, the illuminated trawl caught fewer individuals than the non-illuminated trawl. However, this result was only significant for Pacific halibut in the current study and Dover sole in Lomeli et al. (2018a). For petrale sole, we found that the illuminated trawl caught 26.9% fewer fish than the non-illuminated trawl while the Lomeli et al. (2018a) study found that the illuminated trawl caught 51.4% more petrale sole than the non-illuminated trawl. However, these catch results were not significant in either study. This comparison between similar studies illustrates the importance of continued research in commercial fisheries to develop a better understanding of how artificial illumination affects Pacific halibut bycatch and groundfish catches, and fishers potential use of illuminated trawls.

Studies have demonstrated that fish behavior and catchability can change between light and dark conditions (Hannah et al., 2005; Petrakis et al., 2001; Ryer and Barnett, 2006; Ryer et al., 2010; Lomeli and Wakefield, 2019). In our study, we focused our fishing effort during daylight hours as resources (e.g., available vessel budget, scientific staff) were not available to fish day and night to examine if diel changes in the catchability of Pacific halibut and target groundfishes occurs between illuminated and non-illuminated trawls. As fishers' in the West Coast groundfish bottom trawl fishery trawl under day and night conditions, it should be mentioned that the results we observed may differ under night conditions.

In conclusion, this study demonstrated the ability to significantly reduce Pacific halibut bycatch by illuminating the wing tips and upper bridles of a selective flatfish trawl. As Pacific halibut bycatch is likely to continue to constrain some fishers' ability to fully utilize their quotas of healthy groundfish stocks, results from our study provide fishers a simple gear modification that can reduce Pacific halibut bycatch. Further, this study was able to reduce their bycatch before trawl capture potentially reducing unobserved and unaccounted post-release mortality that can occur from capture-escape processes within the trawl. Although these results are positive, it is important to note that fishers would need to consider economic tradeoffs between bycatch reduction and increased fishing effort needed to offset any reduction in catch caused by artificial illumination. Lastly, testing the efficacy of artificial illumination to reduce Pacific halibut bycatch in Alaska and British Columbia, Canada trawl fisheries and under day and night conditions is encouraged.

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Table 1. Number of fish measured for the catch comparison and catch ratio analyses. Values in parentheses are the mean length measurement subsample ratios from the total catch. Values in brackets are the range in length measurement subsample ratios.

	No. measured	
Species	Illuminated trawl	Non-illuminated trawl
Pacific halibut	57 (1.0 [1.0-1.0])	138 (1.0 [1.0-1.0])
Dover sole	1,255 (0.72 [0.23-1.0])	1,348 (0.73 [0.43-1.0])
Petrale sole	1,728 (0.46 [0.21-1.0])	1,627 (0.32 [0.13-1.0])
Sablefish	695 (0.52 [0.22-1.0])	910 (0.43 [0.33-1.0])
Lingcod	668 (0.48 [0.25-1.0])	628 (0.48 [0.29-1.0])

Table 2. Catch comparison curve fit statistics.

	p-value	Deviance	DF
Pacific halibut	0.0387	55.9	39
Dover sole	0.3540	27.0	25
Petrale sole	0.0587	43.0	30
Sablefish	0.1252	47.0	37
Lingcod	0.0012	103.8	64

Table 3. Physiological parameters of Pacific halibut caught in the illuminated and non-illuminated trawl. Fulton's Condition Factor is a measure of the relationship between fish total length and weight, with values above and below 1 indicating fish with high and low fitness, respectively. Fat (%) represents the content of fat in the fish skeletal muscle as determined by the Distell Fish Fatmeter. Plasma lactate, glucose, and cortisol represent physiological stress indicators. Values are presented with their standard deviations, with the number of fish per group in parentheses. An asterisk indicates statistically significant differences between the illuminated trawl and non-illuminated trawl groups (unpaired two-sample T-test; $p \leq 0.05$). Units of lactate, and glucose are in milligrams per deciliter of plasma; cortisol units are in nanograms per milliliter of plasma.

Parameters	Illuminated trawl	Non-illuminated trawl
Fulton's Condition Factor (*K*)	0.99 ± 0.78 (59)	1.00 ± 0.14 (145)
Fat (%)	2.33 ± 0.64 (59)	2.24 ± 0.61 (142)
Plasma lactate (mg/dL)	30.30 ± 17.8 (9)	31.10 ± 18.5 (33)
Plasma glucose (mg/dL)	41.70 ± 29.8 (8)	35.40 ± 22.4 (30)
Plasma cortisol (ng/mL)	205.10 ± 116.1 (9)*	138.40 ± 65.1 (34)*

Table 4. The effect of illuminated tow durations (above a 60 minute baseline) on catch efficiencies of groundfishes and Pacific halibut bycatch as compared to those of non-illuminated tows. Zero values in the improvement in average catch efficiency (%) refer to equal catch levels between the two trawls.

Increased tow duration		Improvement in average catch efficiency (%)				
%	min.	Dover sole	Lingcod	Petrale sole	Sablefish	Pacific halibut
0	0	-6.2	-19.0	-26.9	-35.2	-58.7
7	4.2	0	-13.3	-21.7	-30.6	-54.6
23	13.8	+15.3	0	-10.1	-20.2	-45.2
37	22.2	+28.5	+11.0	0	-11.2	-36.9
54	32.4	+44.4	+24.7	+12.6	0	-27.0
142	85.2	+133.1	+114.8	+103.5	+91.7	0

Figure 1. Image of six LED cluster locations (numbered) on the selective flatfish trawl along the port side upper bridle and wing tip (upper left image); image of the selective flatfish trawl without LED clusters along its upper bridles and wing tips (upper right image); image of the selective flatfish trawl being deployed with LED clusters along its upper bridles and wing tips (bottom images).

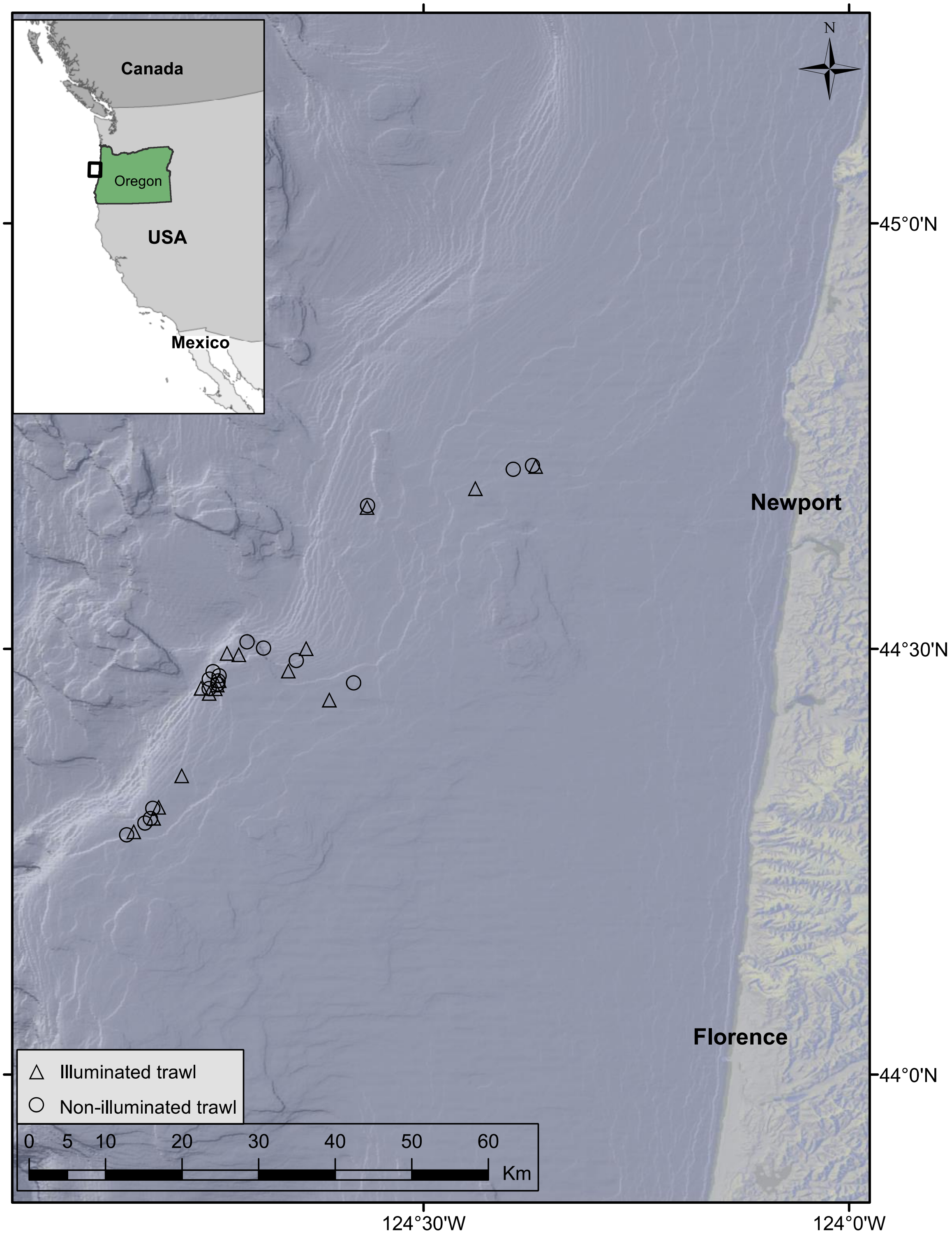

Figure 2. Map of the area off Oregon where sea trials occurred. Symbols represent tow start locations for the illuminated trawl (triangles) and non-illuminated (circles) trawl.

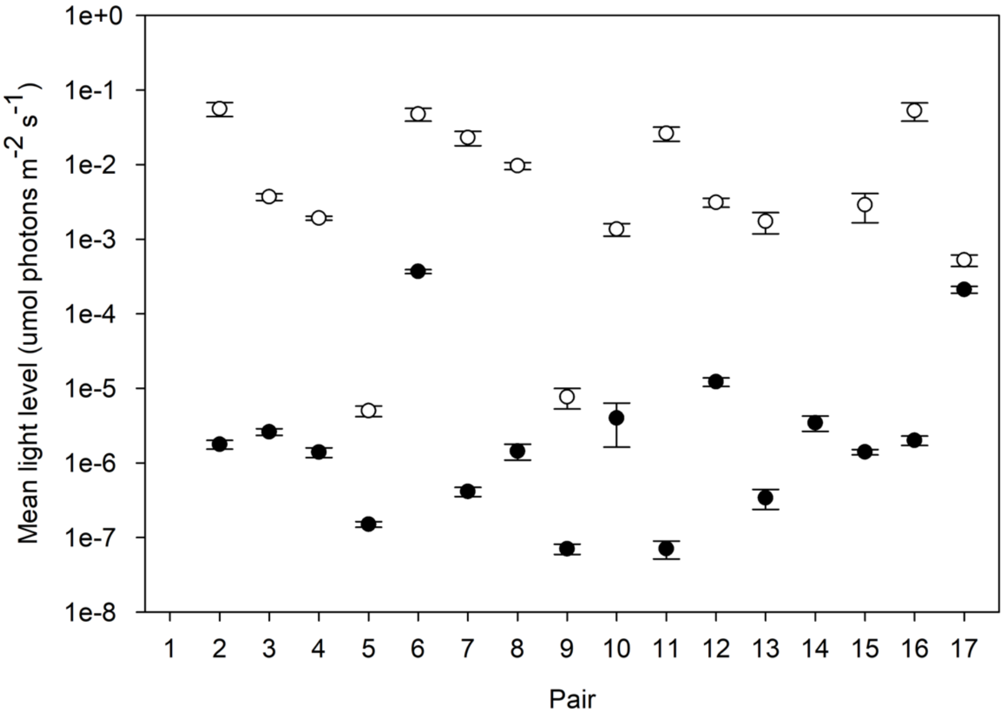

Figure 3. Mean light level measured for the illuminated trawl (open circles) and non-illuminated trawl (closed circles) per tow pair. Bars are standard errors.

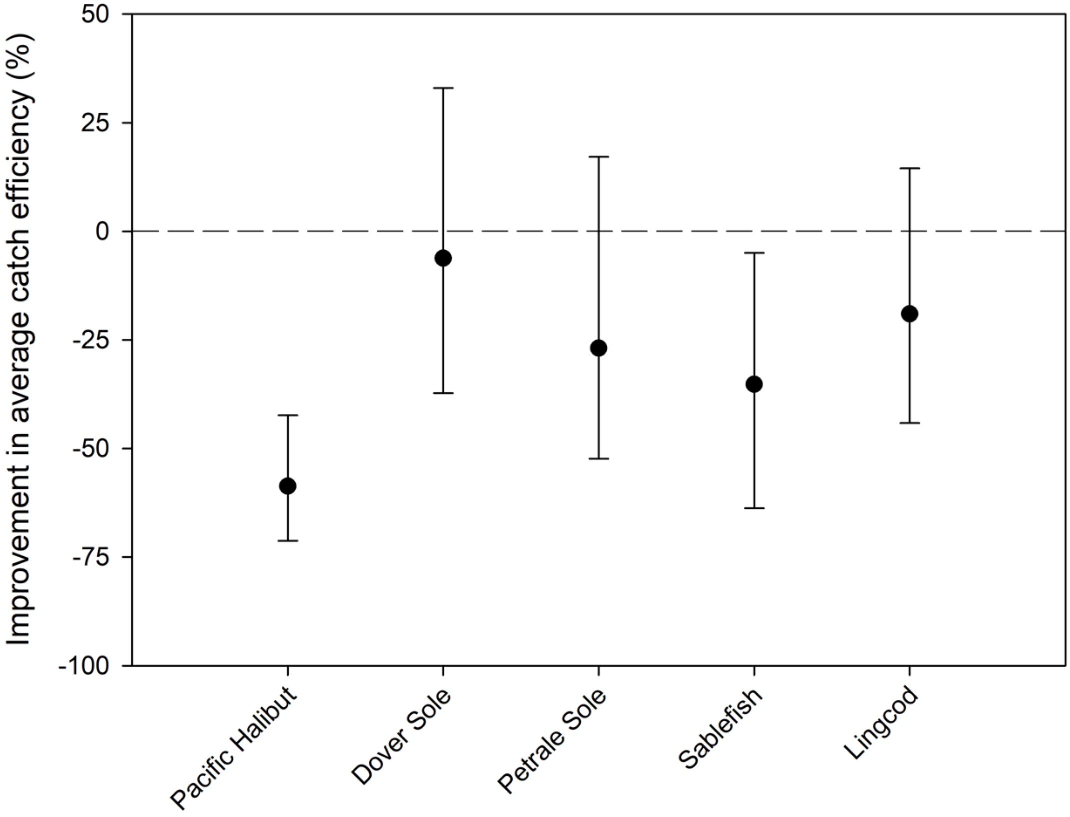

Figure 4. Improvement in average catch efficiency ($\Delta CR_{average}$, see Eq. 8) between the illuminated and non-illuminated trawl. The dashed line depicts the baseline catch efficiency value of zero indicating equal catch efficiency between the two trawls. Values below zero indicate the illuminated trawl has a decrease in catch efficiency compared to the non-illuminated trawl. Values above zero indicate the illuminated trawl has an increase in catch efficiency compared to the non-illuminated trawl. Bars are 95% CIs.

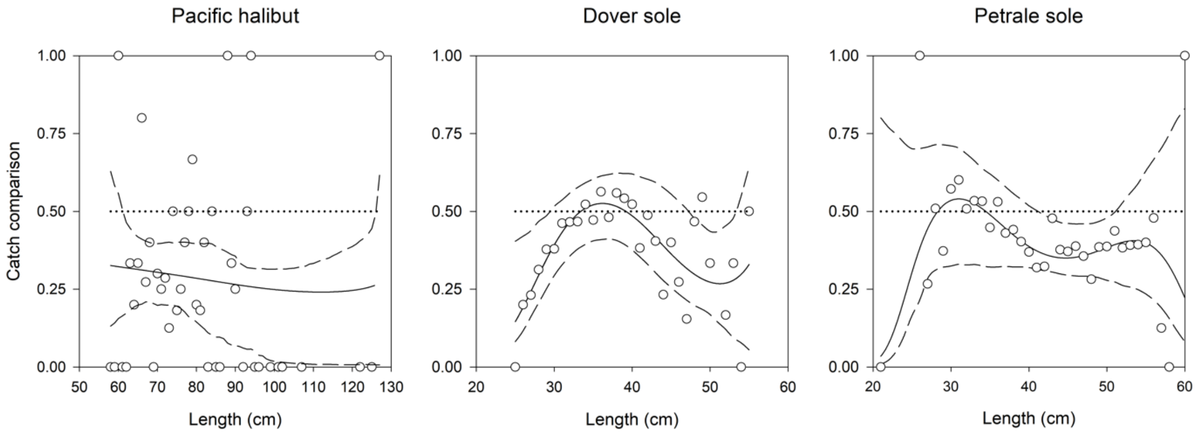

Figure 5. Mean catch comparison curves for Pacific halibut, Dover sole, and petrale sole between the illuminated and non-illuminated trawl. Circles are the observed data; fitted solid lines are the modeled values; dashed lines are 95% CIs; dotted straight lines depict the baseline catch comparison proportion of 0.5 indicating equal catch rates between the two trawls.

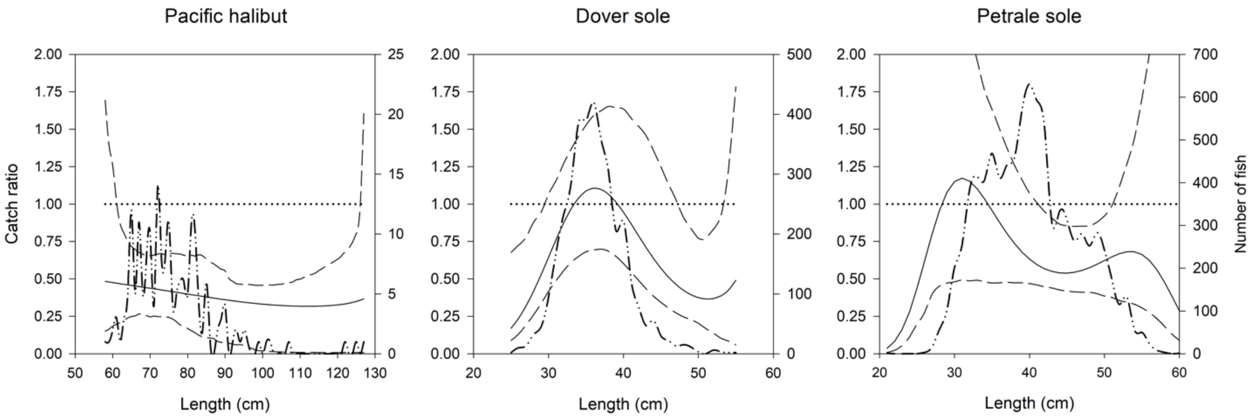

Figure 6. Mean catch ratio curves for Pacific halibut, Dover sole, and petrale sole between the illuminated and non-illuminated trawl. Fitted solid lines are the modeled values; dashed lines are 95% CIs; dash-dot lines are number of fish caught; dotted straight lines depict the baseline catch ratio of 1.0 indicating equal catch efficiencies between the two trawls.

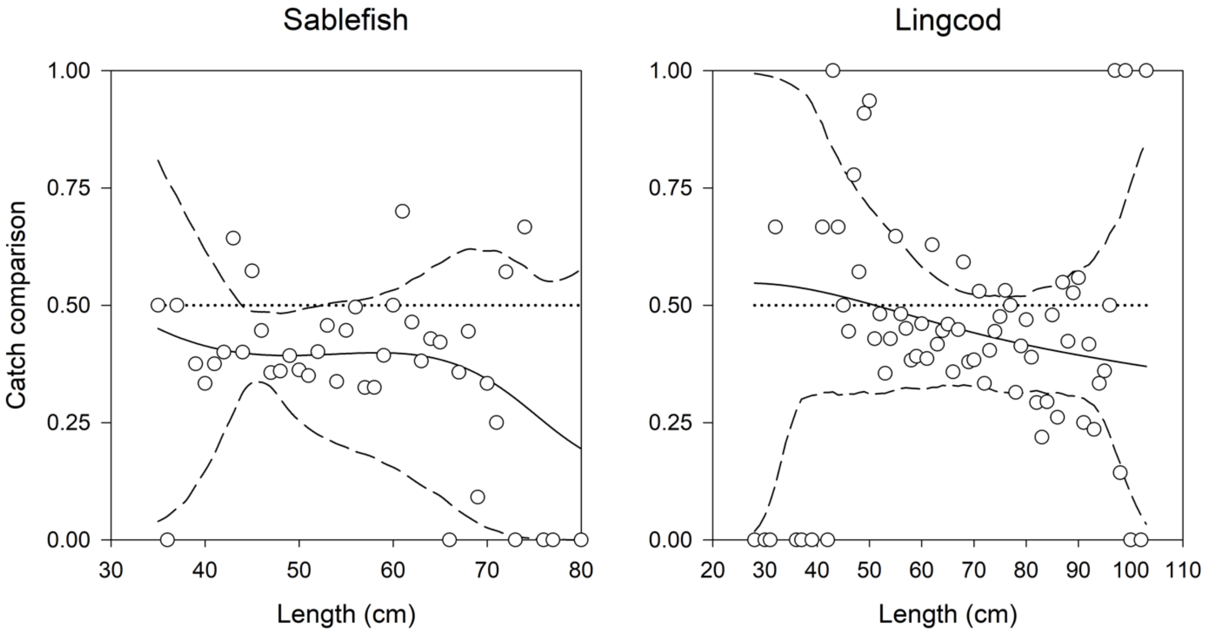

Figure 7. Mean catch comparison curves for sablefish, and lingcod between the illuminated and non-illuminated trawl. Circles are the observed data; fitted solid lines are the modeled values; dashed lines are 95% CIs; dotted straight lines depict the baseline catch comparison proportion of 0.5 indicating equal catch rates between the two trawls.

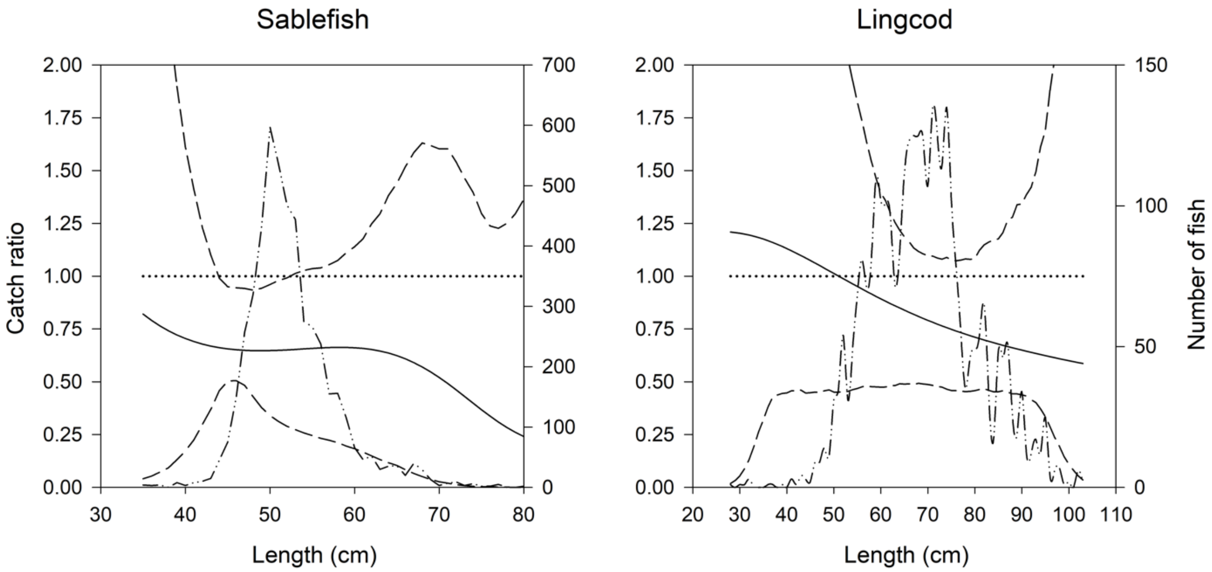

Figure 8. Mean catch ratio curves for sablefish, and lingcod between the illuminated and non-illuminated trawl. Fitted solid lines are the modeled values; dashed lines are 95% CIs; dash-dot lines are number of fish caught; dotted straight lines depict the baseline catch ratio rate of 1.0 indicating equal catch efficiencies between the two trawls.

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*Declaration of Interest Statement

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☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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