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Artificial Illumination Of Trawl Gear Components To Reduce Pacific Halibut (Hippoglossus Stenolepis) Bycatch In The U.s. West Coast Groundfish Bottom Trawl Fishery

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Artificial illumination of trawl gear components to reduce Pacific halibut *(Hippoglossus stenolepis)* bycatch in the U.S. West Coast Groundfish Bottom Trawl Fishery

A Thesis

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

of the Requirements for the Degree of

Master of Science

by

Derek N. Jackson

January 2024

APPROVAL PAGE

This thesis is submitted in partial fulfillment of

the requirements for the degree of

Master of Science

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Abstract

Pacific halibut (*Hippoglossus stenolepis*) is a prohibited species for the U.S. West Coast Bottom Trawl Fishery and in the last decade, there has been a concentrated interest in the use of artificial illumination serving as a potential bycatch reduction device. Previous studies conducted off the coast of Oregon have found that the addition of green light-emitting diodes to the bridles of low-rise, cutback trawls greatly reduced the number of Pacific halibut caught. However, recent regulation changes now permit high-rise trawls, a gear configuration that fishes a very different volume of water than the previously permissible gear profile, in areas where they were once prohibited. No study to date has investigated the efficacy of artificial illumination to reduce Pacific halibut bycatch for this configuration. Field trials for this study were conducted off the Oregon Coast during August of 2022 and were designed to test a high-rise bottom trawl fitted with artificial illumination as a means to potentially reduce Pacific halibut bycatch. Length-dependent catch comparison and catch ratio analyses for trawls with and without illumination were conducted to determine if catches of Pacific halibut and three commercially important groundfish species differ between trawl treatments. Somatic fat content of Pacific halibut and physiological indicators of stress were also assessed via blood plasma samples to determine if there was a difference in physiological condition between Pacific halibut captured in either illuminated or non-illuminated tows. Additionally, an ethogram was constructed to quantify Pacific halibut behavior in response to an approaching high-rise trawl. Analyses were based on a simulated dataset based on previous flatfish behavioral studies and qualitative evidence from video and sonar recordings collected during field trials. While illuminated trawls caught fewer individuals than the non-illuminated trawls for all species in this study, the difference in catch was not statistically significant. Total catch size was found to have a significantly positive effect on glucose and lactate levels for Pacific halibut; however, no statistically significant differences between illuminated and non-illuminated tows were exhibited across all of the physiological parameters assessed in this study. I hypothesize that this lack of difference between treatment groups may have resulted from the change in gear configuration as Pacific halibut are more likely to rise off of the seafloor when responding to an approaching net. The higher headrope orientation used in a high-rise trawl configuration may be presenting too much of a challenge for halibut seeking to avoid the path of the trawl. It is also possible that the location of the lights was insufficient in triggering a change in avoidance behaviors. These findings are contrary to prior evidence and could have potential implications for the industry. Further investigation into Pacific halibut behavior is implored.

Artificial illumination of trawl gear components to reduce Pacific halibut *(Hippoglossus stenolepis)* bycatch in the U.S. West Coast Groundfish Bottom Trawl fishery

1. Introduction

Seafood is a staple in the diet for many around the world and the demand continues to grow. In 2020, approximately 112 million metric tons of marine life were harvested from the world’s oceans and over the last several decades the annual seafood consumption rate has outpaced the world population growth (FAO, 2022). The preservation of this resource is not only vital to the world economy but also to the food security of a nation. Sustainability- or the conservation of a resource to ensure its longevity- has thus become one of the main tenets of a “well-managed” fisheries. In order to ensure the health and longevity of desired fish stocks, several challenges must first be addressed.

Overfishing, or the process of removing more fish from a population than can be replaced, is one such challenge. The phenomenon of overfishing has been well-documented in numerous fisheries around the world. If left unchecked, overfishing can devastate an ecosystem as fish stocks diminish to unsustainable population sizes. In order to avoid this from happening, fisheries managers often set annual limits on the amount vessels can harvest before a season closure is enacted. How these limits are set and determined is dependent on the fishery itself, but often resource managers are reliant on tools like statistical models to carefully monitor the health and size of a fish stock. Limitations and controls on fishing pressure would then be decided collectively by a group of stakeholders, scientists, government agencies, and fishers. Notably, overfishing may still occur even in “well-managed fisheries”. Thus, meetings and stock assessments are often regularly conducted with the most up-to-date data to ensure the continued health of a stock and to potentially discuss any needed changes to the fishery.

In addition to species targeted by a fishery, managers may also be concerned about those species unintentionally captured. Bycatch, or the incidental capture of non-targeted species by fisheries, has been identified as a significant management issue for many fleets around the world (Hall, 2000). A recent assessment of global marine fisheries found that discards, those species caught incidentally, but are not retained, accounted for 9.1 million metric tons from 2010 to 2014 (Roda et al., 2019). Of that total discard, almost half came from trawl fisheries. These bycaught species are susceptible to the pressures of overfishing and often regulations are set in place to ensure that vulnerable species remain protected. National Standard Nine of the Magnuson-Stevens Act states that management of U.S.-based fisheries are called to take direct action to minimize the capture and mortality of incidentally caught fishes (ACT, 1996). Strategies for mitigating bycatch, however, may vary.

Rather than set broad annual catch limits that encompass an entire fishery, fisheries managers may elect to further divide the annual total allowable catch (TAC) into discrete units that are then allocated to individual vessels or owners as individual bycatch quotas (IBQs). These quotas then remove both the incentive to discard and prioritize individual accountability. The success of such a system has been demonstrated in the U.S. West Coast Groundfish Fishery where the annual number of discards for both quota and non-quota species saw substantial declines since the implementation of the catch share program (Somers et al., 2018).

In addition to IBQs, spatiotemporal closures can also be used by fisheries managers to set limits on fishing effort in areas and/or times in which bycatch species are known to be present. For example, in the Bering Sea (Alaska), rolling ‘hot spot’ closures are used to help fishers avoid areas that are known to have higher rates of Pacific salmon (*Oncorhynchus* spp.) bycatch in the walleye pollock (*Gadus chalcogrammus*) fishery. Spatial management strategies are also utilized for numerous tuna (*Thunnus* spp.) fisheries around the world to protect both juvenile target and incidentally captured species (Ban et al., 2014). However, the effectiveness of static spatial closures has been debated for some fisheries (Pons et al., 2021).

Additional strategies for mitigating bycatch include gear modification. Where in the field of conservation engineering, scientists and fishers often look to improve fishing gear and find ways to efficiently capture target species while simultaneously reducing the capture of bycatch species (i.e., increase selectivity). In the case of trawl gear, simple modifications to the codend mesh (e.g., orientation, mesh size and thickness) have been shown to have a profound effect on selectivity for numerous fisheries around the world (Herrmann et al., 2013; Tokaç et al., 2014; Petetta et al., 2020; Einarsson et al., 2021; Brinkof et al., 2022). Further mitigation can also be achieved by the development and utilization of bycatch reduction devices (BRD). These devices can take a variety of different shapes and sizes as they are dependent on the biology and behavior of the species of concern as well as the gear fishers use to interact with them. In the southeastern U.S., the inclusion of a sorting grid located within the extension of a trawl, often referred to as a turtle excluder device (TED), has been shown to be effective at reducing sea turtle bycatch within the shrimp trawl fishery (Shiode and Tokai, 2004).

Grid devices, like TEDs, are reliant on mechanically sorting catch based on physical size and shape. These sorts of devices are readily applicable when bycatch and target species have drastic differences in morphology, however, this is not always the case and at times other differences between species may need to be considered. Other devices may aim to exploit differences in the sensory nervous systems and behaviors found between marine organisms as they interact with gear. For BRDs to be successful at separating bycatch from target catch, an understanding of the behavior and physiology of the species of interest is critical. In the case of TEDs, investigators spent several decades developing the design of the grid and made gradual, incremental modifications over time. Fishers played a vital role in co-developing TEDs as their first-hand knowledge and experience were crucial in ensuring the practicality of the design, which led to both the efficient development of the TEDs design, and also further buy-in from the industry (Jenkins, 2023).

This thesis is part of an ongoing investigation into the potential for artificial illumination to serve as a means to reduce Pacific halibut (*Hippoglossus stenolepis*) bycatch in the U.S. West Coast Groundfish Bottom Trawl Fishery. The similar morphology between the targeted flatfish species and Pacific halibut can challenge the efficiency of traditional excluder devices. However, researchers hope to exploit differences in avoidance behaviors between the species by illuminating trawl gear components (Lomeli et al., 2018, 2021). In Lomeli et al. (2021), the addition of light-emitting diodes to the upper bridles of a low-rise (i.e., reduced trawl vertical opening), cutback (i.e., headrope moved aft of the footrope location) trawl saw a 58.7% reduction in the number of Pacific halibut captured when compared to tows with no illumination. Meanwhile, three out of the four target species assessed in that study saw no significant reductions in their overall catch efficiency. Since that study was conducted, however, regulations for the fishery have changed and high-rise (i.e., increased vertical opening) trawls are now permissible in areas they were once restricted off the U.S. West Coast (NOAA, 2018). Yet, no research to date has investigated the efficacy of artificial illumination as a means to reduce Pacific halibut bycatch for the recently permissible high-rise gear configuration.

Fieldwork for this project was conducted in collaboration with commercial fishers, fisheries technologists, and numerous stakeholder groups. Examination of this research question utilized a multi-pronged approach to explore the efficacy of artificial lights as a means to reduce Pacific halibut bycatch with efforts to understand the underlying behavioral drivers of fish response to artificial lights equipped on trawl nets as well as comparative field testing of trawls utilizing lights to mitigate bycatch. *Chapter One* reports on a field experiment conducted off the coast of Oregon designed to test a trawl fitted with artificial lights to reduce Pacific halibut bycatch. Length-dependent catch comparison and catch ratio analyses for trawls with and without lights provide an empirical basis for the evaluation of the efficacy of lights as a bycatch mitigation approach for this fishery. In addition to an examination of relative catch data, the physiological condition of Pacific halibut was evaluated as it could represent an indicator of their ability to avoid trawl capture. *Chapter Two* examines Pacific halibut behavior as they respond to an approaching trawl net via the construction of an ethogram. The ethogram was evaluated via a simulated dataset to approximate the behavioral response of Pacific halibut to an approaching bottom trawl.

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Chapter 1: Catch comparison and physiological assessment of Pacific Halibut *(Hippoglossus stenolepis)* interacting with an illuminated high-rise bottom trawl

2.1 Background

2.1.1 Artificial light serving as a bycatch reduction device

In the last decade, there has been a concentrated interest in the use of artificial illumination as a potential BRD for numerous fisheries around the world (Hannah et al., 2015; Ortiz et al., 2016; Bielli et al., 2020; Southworth et al., 2020; Cuende et al., 2022; Yochum et al., 2022). Artificial illumination leverages the physiological and behavioral responses of aquatic organisms to elicit a response that can in turn be utilized to meet a certain objective with respect to the capture process. Nguyen and Winger (2019) note in their review of artificial illumination as it relates to commercial fishing that the response of a marine organism to light can be categorized in four ways: phototaxis, photokinesis, aggregation, and vertical diurnal migration. Phototaxis and photokinesis have especially been considered when it comes to modifying fishing gear or implementing BRDs.

Fish that are identified as being positively phototactic are generally considered drawn to a light source, often seeking to move into proximity to it, whereas those species that are negatively phototactic are considered to be repulsed by light and tend to move away from the source. These opposing behaviors have been utilized in a variety of ways to attract target catch (Hazin et al., 2005; Marchesan et al., 2005; Nguyen et al., 2017; Afonso et al., 2021; Enever et al., 2022) and also prompt bycatch species to escape (Melli et al., 2018). If an organism exhibits a photokinetic reaction, they may become either suddenly active or inactive when exposed to a light source. Grimaldo et al. (2018) sought to exploit this response by using a light-emitting diode (LED) stimulation device placed within a trawl net to potentially trigger escape behavior for haddock (*Melanogrammus aeglefinus*) and cod (*Gadus morhua*). While there is some evidence to suggest it could be useful for haddock, this response is likely species-specific as cod exhibited little to no response towards the stimulus.

Characteristics of artificial illumination also impact species-level response. The color of a light source may also influence the behavioral response of an organism with studies such as Yochum et al. (2021) finding that a species can behave differently when exposed to a variety of different light factors such as color, intensity, and strobing. Many coastal fishes have a spectral sensitivity centered around blue-green light as colors with longer wavelengths like red and orange typically attenuate quickly as a function of depth (Bowmaker, 1990). Given this attribute, many studies exploring fish responses to light have focused on green or blue lights. Such was the case for Hannah et al. (2015), which explored adding green LEDs on an ocean shrimp (*Pandalus jordani*) trawler fishing off the northwestern coast of the United States as a means to potentially reduce finfish bycatch. However, other technical factors including the placement of those LEDs within the gear proved to be an important synergistic factor to consider. LEDs attached along the fishing line of a bottom trawler significantly reduced finfish bycatch by approximately 91% for some species but saw significant increases in bycatch when those same LEDs were attached near a Nordmøre sorting grid located deeper within the trawl. Subsequent work has sought to further explore the use of artificial light as a means of bycatch reduction for other fisheries throughout the region (Lomeli et al., 2018, 2020, 2021; Lomeli and Wakefield, 2019).

2.1.2 The U.S. West Coast Bottom Trawl Fishery and Pacific halibut

Bottom trawlers fishing off the U.S. West Coast are managed by the Pacific Fisheries Management Council (PFMC) and the National Marine Fisheries Service (NMFS). Since 2011, the Groundfish Trawl Catch Share Program has been utilized to regulate all U.S. West Coast trawl vessels targeting groundfish. Current vessel-level individual fishing quotas (IFQs) are allocated to owners based on annual catch limits for a variety of different groundfish found throughout the region (i.e., petrale sole (*Eopsetta jordani*), Dover sole (*Solea solea*), lingcod (*Ophiodon elongatus*), and sablefish (*Anoplopoma fimbria*)) (Jannot et al., 2020). In 2002, seven commercially important rockfish (*Sebastes* spp.) populations were classified as overfished (PSMC, 2008). Subsequent management actions set very restrictive regulations that greatly limited the fishing effort for bottom trawlers including the addition of a spatial closure identified as the rockfish conservation area (RCA) (Keller et al., 2013; Lomeli and Wakefield, 2015). Low-rise (i.e., reduced trawl vertical opening), cutback (i.e., headrope moved aft of the footrope location) trawls became the required gear configuration if trawling was conducted shoreward of the 100-fathom contour as it was effective at capturing species that typically associate with the sediment/water interface, like petrale sole and Dover sole, while reducing catches of rockfishes. In recent years, however, stock assessments have suggested that most rockfish populations have recovered to a stable size, and regulations have been modified to permit high-rise trawls (i.e., increased vertical opening), a net configuration that fishes a much different volume of water along the seafloor, in those areas they were once restricted (NOAA, 2018).

The U.S. West Coast Groundfish Bottom Trawl Fleet is annually allocated individual bycatch quotas (IBQs) for Pacific halibut (*Hippoglossus stenolepis;* hereafter referred to as "halibut"). Management of halibut is overseen by the International Pacific Halibut Commission (IPHC), an international organization established by a convention between Canada and the U.S. This species is prohibited for the U.S. West Coast Groundfish Bottom Trawl Fishery, meaning it cannot be retained, as evidence has suggested that juvenile halibut are susceptible to overexploitation by trawl nets and this gear type has a high probability of discard mortality (Stewart et al., 2021; Jannot et al., 2022). The annual bycatch quota, which was initially based on historical catches, is limited and bycatch limits are estimated via fishery observer and electronic monitoring data resulting in a near-real-time catch accounting system. A vessel may not fish with a deficit in quota and if they are to continue fishing in pursuit of target species, they must first acquire more IBQ. This process could be quite costly for captains and vessel owners. In this instance, there then is a need both ecologically and economically to find ways to reduce the bycatch of halibut.

2.1.3 Halibut bycatch reduction

Scientists and fishers have sought to reduce halibut bycatch through a variety of different methods. The implementation of BRDs is one technical approach that has shown promise and in Alaska, a rigid sorting grid placed near the codend of a trawl had a 94% escapement rate of halibut (Rose and Gauvin, 2000). Similarly, a flexible sorting grid, designed for the U.S. West Coast Groundfish Bottom Trawl Fishery, was found to reduce the number of halibut caught by 57% with minimal reduction in the target catch (Lomeli and Wakefield, 2013). While both grid designs were considered successful at significantly reducing bycatch, it is worth noting that fish would still have to interact with the trawl gear before potentially escaping. Kennelly and Broadhurst (2021) note that bycatch reduction devices for demersal trawls typically are implemented in one of four distinct zones within the gear: spreading mechanisms (e.g., trawl doors), headline/foot rope/ ground gear, trawl wings and body, or extension/codend (**Fig. 1**). Deterring bycatch before they enter the extension, like in areas near the sweeps or bridles, could greatly reduce the risks of overexertion, physiological stress/ injury, and potential mortality of bycatch species.

Studies conducted off the coast of Oregon have found that the addition of green LEDs to the bridles of low-rise cutback trawls greatly reduced the number of halibut caught (Lomeli et al., 2018, 2021). In particular, Lomeli et al. (2021) found that the addition of LEDs had a significant effect with illuminated trawls catching on average 58.7% less halibut than the non-illuminated trawls. Additionally, three out of the four target species assessed in that study saw no significant reductions in the overall catch efficiency. Somatic fat content readings and blood samples were also collected from captured halibut to assess the physiological condition as it could be related to their ability to avoid trawl capture. Halibut caught in the illuminated trawls were found to have significantly higher cortisol levels relative to halibut captured in non-illuminated trawls. Notably, cortisol levels in the blood plasma are thought to be a physiological indicator of stress. It was hypothesized that this increase in cortisol could be related to the presence of these lights, however, the investigators acknowledged that further investigation would be required to understand the underlying cause of the observed difference. Overall, it was concluded that these LEDs have the potential to efficiently reduce halibut bycatch.

Prior to this thesis, research has not investigated the efficacy of artificial illumination as a means to reduce halibut bycatch for the recently permissible high-rise gear configuration. In a lab setting, halibut have demonstrated a tendency to act less like other flatfishes that rely on cryptic behavior and hide near the seafloor and instead behave more like a roundfish that exhibit an escape response and often swim away or over an approaching net (Ryer, 2008). Given this behavior, higher bycatch rates could be realized for high-rise trawls whose hooded configuration (having the headrope forward of the footrope when fishing) would present a physical challenge for fish trying to swim up and over the net. Furthermore, the authors note that halibut could have escaped capture by going either above or below the illuminated bridles of the low-rise trawl (Lomeli et al., 2021). If so, a bridle system for a high-rise trawl could be modified to mimic the bridle configuration of the low-rise trawl used in the previous study and could potentially find similar success at reducing bycatch.

2.1.4 Objective and hypotheses

The objective of this study was to examine the efficacy of artificial light on a high-rise bottom trawl as a means to reduce Pacific halibut bycatch while maintaining target catch rates. Additionally, this project aimed to build on previous research that explored the physiological condition of halibut after being captured as it could be related to their ability to avoid trawl capture.

The working hypotheses for this study were:

1. *Illuminated trawls will catch fewer halibut than non-illuminated trawls.*
2. *Halibut caught in illuminated trawls will show higher cortisol levels in their blood samples than in the non-illuminated trawls*.

2.2 Methods

2.2.1 Trawl and sampling design

A two-seam high-rise demersal trawl was used for this study. The circumference for the mouth of the trawl was 180 meshes, but gradually tapered down over 77.5 meshes to a codend circumference opening that was 88 meshes wide (11.4 cm mesh size). A T90 mesh codend (127 mm nominal mesh size, 6.0 mm double twine, 88 meshes in circumference, and 75 meshes in length) was used. The headrope was 24.1 m long and the footrope (24.7 m long) incorporated 20.3 cm diameter rubber disks, with 45.7 cm rockhopper discs placed approximately every 73.7 cm. Each lower bridle was 30.5 m in length and consisted of steel cable covered with 7.5 cm rubber discs. The sweeps used in this study were elevated, 91.4 m in total length, and made of

4.8 cm combination wire with steel bobbins 25.4 cm in diameter placed every 30.5 m. Thyborøn type-11 low-aspect-ratio doors (size = 4.8 m^2; weight = 995 kg) were used.

The methodology for catch sampling was based on procedures in Lomeli et al. (2021). Fieldwork for this project was conducted off the Oregon Coast in August of 2022 aboard the F/V Last Straw (23.2 m long, 540-hp stern trawler). The study site was determined based on known groundfish and halibut abundances. For every tow, the catch was sorted by species and weighed with a Marel M1100 motion-compensated marine platform scale that was calibrated before each sampling event. Length measurements were recorded to the nearest centimeter (cm) for halibut and three target species: Dover sole, petrale sole, and sablefish. Total length was recorded for the flatfishes, whereas fork length was recorded for sablefish. For tows in which there was a relatively large catch, total catch typically greater than 500 kg, lengths were subsampled to account for time and space constraints on the vessel (**Table 1**). Subsampling protocols specified that every second or third basket for the selected target species would be retained for measurement (depending on the overall catch size) up to a maximum limit of ten baskets for each species.

2.2.2 Artificial illumination and abiotic conditions

Green Lindgren-Pitman Electralume® LED fishing lights centered on 519 nm (Nguyen et al., 2017) were used for artificial illumination in this study. Green lights were chosen because: (1) green-blue light is the predominant spectral component of coastal waters in our study region, (2) this color is assumed to be the range of light in which halibut exhibit sensitivity (Brill et al., 2008), and (3) the color and light manufacturer are the same type used in previous studies (Lomeli et al., 2018, 2021) and would facilitate a comparison of the results. All LEDs were tied together end-to-end in clusters of three with twine (**Fig. 2**). Five clusters were placed on a 12 mm

Spectra rope approximately 3.96 m in length that was connected from the breastline to a hammer lock that connected the footrope extension to the beginning of the lower bridle on either side of the trawl to mimic the bridle configuration of the trawl used in the Lomeli et al. (2021) study **(Fig. 3).** Trials were conducted with an alternating pattern (ABBA) between illuminated and non-illuminated tows, starting each day with a different treatment. For example, if the first tow of the day was an illuminated tow, then the next two tows would have no illumination. LEDs would then be added for the last tow of the sequence.

With the exception of tows 9 and 16, a Wildlife Computers TDR-MK9 archival tag was placed on the portside wing of the trawl to record ambient light levels during fishing operations while a Sea-Bird 19plus CTD profiler placed near the codend recorded additional abiotic parameters (e.g., turbidity, depth, temperature, dissolved oxygen). All CTD files were then later processed, and profiles of the water parameters were constructed for every tow. Only values in which fishing was actively occurring along the seafloor were extracted for analysis. Similar processes were conducted for the MK9 data. The MK9 tag was initially calibrated using the function presented in Lomeli et al. (2018) and the relative light units were converted to irradiance units, µmol photons $m^{-2}s^{-1}$.

2.2.3 Physiological assessment

A Distell Fish Fatmeter (Model FFM 692) was used to record somatic fat content. The Fatmeter is a non-invasive tool that estimates subdermal lipid content based on the water content of tissues by utilizing low-power microwave emissions (Kent, 1990). Before each sea day, the device was calibrated according to Distell's Sea Bass II standard. Readings were taken at two locations on the eyed-side for every halibut: above the pectoral fin, but inside the lateral line and anterior to the caudal peduncle (**Fig. 4**). At each location, two readings were taken. The average of those readings was then applied to a fat calibration curve developed for halibut (IPHC, unpublished results).

Blood samples were taken to assess physiological stress indicators for halibut caught during both illuminated and non-illuminated tows. Samples were opportunistically collected from the caudal peduncle of 148 halibut and then centrifuged for 15 min at 3,000 rpm. The resulting plasma samples were stored at −20 ◦C until being sent to the IPHC to be tested. Glucose, lactate, and cortisol levels were all measured directly in the plasma using commercial kits (glucose, EIAGLUC, Invitrogen; lactate, MET-5012, Cell Biolabs; cortisol, ELISA 500360, Cayman). Samples were tested in replicate and the average values were recorded. Dilutions were made 10, 50, and 500 times for samples testing glucose, lactate, and cortisol levels, respectively. In some cases, different dilutions were evaluated in order to get values within the acceptable confirmation range of the standard curve. Caudal fin clips were also sent to the IPHC, where two genetic assays were used to determine the sex from a subset of all sampled halibut.

A two-sample t-test was used to compare the somatic fat content and physiological indicators of stress of halibut caught in the illuminated versus the non-illuminated tows (α=0.05) using the R Studio package for R (version 4.2.2, R Core Team, 2020). A general linear model was used to further assess the relationship between catch weight and tow duration across all physiological stress indicators. Model assumptions were tested using the ‘car’ R package (Fox et al., 2012) and potential interactions between the predictor variables were assessed. For those parameters in which the assumption of normality could not be met, a generalized linear model was used with the ‘glmmTMB’ R package (Brooks et al., 2023). Any outlying tows with a Cook’s Distance > 4/n (where n is the total number of data points) were removed from the analysis (Cook, 1977). For generalized linear models, Poisson and negative binomial distributions were considered for potential candidate models. Akaike Information Criterion (AIC) values were used to determine the best model (Akaike, 1974). Models were compared using the AICtab function from the 'bbmle' R package (Bolker, 2014), in which the model with the lowest value was used for analysis. Additional residual diagnostics for best fitting models were evaluated with the use of the 'DHARMa' R package (Hartig, 2022).

2.2.4 Catch comparison and catch ratio analyses

SELNET is a statistical software used to evaluate catch ratio analyses and conduct length-dependent catch comparisons (Sistiaga et al., 2016; Herrmann et al., 2012, 2017; Grimaldo et al., 2018; Larsen et al., 2018a, b; Santos et al., 2020; Fakioglu et al., 2022). The use of this software was initially considered for this project since it was notably used in previous studies investigating catch comparisons between illuminated and non-illuminated tows (Lomeli et al., 2018, 2021). Data generated by this type of study assumes a binomial distribution as an individual fish can be captured in one of two gears (e.g., the illuminated versus non-illuminated trawl). The resulting relative length-dependent catch comparison proportion (CC_l) of changing from non-illuminated and illuminated trawls was determined with the use of the following equation:

$$CC_l = \frac{\sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{i=1}^{mc}\left\{\frac{nc_{li}}{qc_i}\right\}+\sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\right\}} \tag{1}$$

where nc_{li} and nt_{lj} are the numbers of fish measured in each length class l for the non-illuminated (c) and illuminated (t) trawl in tow i and j, respectively. Terms qc_i and qt_j are the related subsampling factors (fraction of the caught fish being length measured), and mc and mt are the number of tows carried out with the non-illuminated and illuminated trawl, respectively.

Within SELNET, the maximum likelihood estimation was used to attain the functional form of the catch comparison proportion *CC(l,v)*, which was expressed in Eq. 1. This was done by minimizing the following equation:

$$-\sum_{l}\left\{\sum_{i=1}^{mc}\left\{\frac{nc_{li}}{qc_i}\times ln[1.0\ -\ CC(l,v)]\right\}\ +\ \sum_{j=1}^{mt}\left\{\frac{nt_{lj}}{qt_j}\times ln[CC(l,v)]\right\}\right\} \qquad (2)$$

The ‘v’ in Eq. 2 represents the vector of parameters that describe the catch comparison curve for the observed catch proportion. This equation is similar to the model defined in Millar (1992). When the catch efficiency of the non-illuminated and illuminated trawls are equal (*mc* = *mt)*, the expected value for the summed catch comparison rate would be 0.5. However, this study had an unequal number of illuminated and non-illuminated tows (27 to 25, respectively). The expected value would therefore be equal to 0.52. Estimated values below 0.52 would suggest there is a significant catch effect with fewer fish on average caught with the illuminated trawl, and vice versa for a catch comparison proportion above 0.52. Therefore, this baseline can be applied to judge whether there is a difference in catch efficiency between the two trawl designs. The experimental CC_l was modeled by the function *CC(l,v)* using the following equation:

$$CC(l,v)\ =\ \frac{exp[f(l,v_0,\ldots,v_k)]}{1+\ exp[f(l,v_0,\ldots,v_k)]} \qquad (3)$$

The value of “f" is a polynomial of order k with coefficients v_0-v_k, such that v = ($v_0,\ldots,v_k$). The values of the parameters “v” describing *CC(l,v)* were taken from the minimization of Eq. 2. The value of “f" was considered up to an order of 4 based on previous studies (Sistiaga et al., 2018; Lomeli et al., 2021) and the combination of these parameters, v_0-v_4, resulted in a total of 32 candidate models to select from. The catch comparison proportion was estimated using the multi-model inference to obtain a combined model (Herrmann et al., 2017). Models were ranked and weighted in the estimation according to their AICc values (Burnham & Anderson, 2002). Models with AICc values within +10 of the model with the lowest AICc value were considered for the estimation of *CC(l,v)* following the procedure described in Katseanevakis (2006) and Herrmann et al. (2015). Multi-model averaging and calculation was determined in the following equation to generate the combined model used in the final results:

$$CC(l,v) \; = \; \sum\nolimits_i w_i \; \times \; CC(l,v_i) \; withw_i \; = \; \frac{exp(0.5 \times (AICc_i - AICc_{min}))}{\sum_j exp(0.5 \times (AICc_j - AICc_{min}))} \qquad (4)$$

The ability of the combined model to describe the data was quantified by examining the difference between the experimental data and the model and calculating the probability that the observed deviation between the two would occur if the model was accurate (Herrmann et al., 2017). If the model sufficiently described the observed data, the fit statistics should reflect a *p* value >0.05, and a deviance value within approximately two times the degrees of freedom value. If the selected model produced fit statistics that were not within the acceptable range, the predicted curve of the model was plotted against the experimental rates to visually inspect for deviations between the model and the data. If no clear pattern was evident, the poor fit statistics would be due to overdispersion rather than the model's inability to describe the data (Wileman et al., 1996; Melli et al., 2023).

The following catch ratio *CR(l,**v**)* equation was used to provide a direct relative value of the catch efficiency between fishing with the non-illuminated and illuminated trawl:

$$CR(l,v) = \frac{CC(l,v)}{[1-CC(l,v)]} \qquad (5)$$

A double bootstrap method was used to account for the uncertainty due to between tow variation (Herrmann et al., 2017). For this method, the same number of hauls were randomly resampled with replacement as can be found in the dataset. Data for each length class within the resampled hauls were then also randomly resampled in an inner bootstrap for each resampled tow. This would account for the associated uncertainty for a tow due to the finite number of fish being caught and measured. Efron 95% confidence intervals (CIs) were calculated after 1,000 bootstrap repetitions were performed (Efron, 1982; Lomeli et al., 2018, 2021).

If the catch efficiency of both trawl designs are equal, the *CR(l,**v**)* will be 1.0. An overall value for the catch ratio was then estimated directly from the observed catch data using the following equation:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{mt} \left\{ \frac{nt_{lj}}{qt_j} \right\}}{\sum_l \sum_{i=1}^{mc} \left\{ \frac{nc_{li}}{qc_i} \right\}} \tag{6}$$

The percent improvement in average catch efficiency between fishing with the non-illuminated and illuminated trawl is then estimated using the following equation:

$$\Delta CR_{average} = 100 \times \left(CR_{average} - 1.0 \right) \tag{7}$$

Eq. 7 provides an overall value for the effect of changing from non-illuminated and 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.

2.3. Results

2.3.1 General overview

Over the course of three consecutive fishing trips, for an overall total of 10 days of fishing, 52 tows were completed for this project (27 illuminated and 25 non-illuminated tows) (**Fig. 5**). Daily fishing operations were conducted during daylight hours from 0600 to 2030 at a mean depth of 168 m (Standard Error ± 0.045) and a range from 96 to 342 m. The target tow duration was 30 minutes, however, time varied for some tows due to a variety of factors (i.e., time constraints and anticipated large catches). The average tow duration was approximately 33 minutes (±1.22) with a range of 20 to 45 minutes. Tow speed over ground ranged from 3.13 to

6.94 km/hr (1.69-3.75 kts). Sampling for this study initially intended to pair alternating tows with an illuminated and non-illuminated spectra rope. However, after low catch sizes and fishing days with odd numbers of tows, the data from the illuminated and non-illuminated tows were pooled into two groups for analysis. On average, total catch for illuminated tows was approximately 751 kg (± 99.7) and approximately 1767 kg (± 442) for non-illuminated tows. Relative light levels as measured by the MK9 sensors for illuminated tows were on average far greater than non-illuminated tows (**Fig. 6**). The mean natural light level measured for the non-illuminated tows was 7.40e-06 µmol photons $m^{-2}s^{-1}$ (± 0.04). Whereas the mean light level for illuminated tows was 5.01e-04 µmol photons $m^{-2}s^{-1}$ (± 0.037). Based on the CTD values, abiotic conditions were consistent for both illuminated and non-illuminated tows (**Fig. 7**).

2.3.2. Catch comparison and catch ratio analyses

For all species except petrale sole, the fit statistics for the combined *CC(l,v)* model exhibited a p-value <0.05 (**Table 2**). While the *p*-values for those species were all less than 0.05, deviance values were within two times the degrees of freedom. Additionally, plots of the predicted curve against the experimental rates suggest that the difference between the observed data and the models was due to overdispersion rather than improper fit (Herrmann et al., 2017; Wileman et al., 1996).

Illuminated tows demonstrated a decrease in catch efficiency compared to non-illuminated tows (values below zero) for all species examined in this study (**Fig. 8**). For Dover sole and petrale sole, the illuminated tows caught 38.3% and 46.2% less fish than the non-illuminated tows, respectively. Additionally, illuminated tows caught 56% less halibut and 21.5% less sablefish than non-illuminated tows. However, none of these results were statistically significant as the 95% CIs extended across zero. Similarly, mean catch comparison and catch ratio curves had broad confidence intervals and no significant differences in catch between illuminated tows and non-illuminated tows were found for any length class (**Figs. 9 and 10**).

Out of the 152 halibut captured from non-illuminated tows, approximately 51% were caught in two tows (tows 1 and 7). To examine the effect of these two tows, an additional catch comparison and catch ratio analysis was performed with these tows excluded from the dataset. The new dataset then had 27 illuminated tows and 23 non-illuminated tows. Similar to the original pooled analysis, no statistically significant difference was found between illuminated and non-illuminated tows (**Figs**. **11 and 12**). However, upon removal of the two tows with the highest halibut catches (> 20 halibut per tow), illuminated tows only caught 19.2% less halibut than non-illuminated tows.

2.3.3 Physiological condition

Overall, 226 halibut were caught (74 with illumination and 152 with no illumination). Halibut lengths ranged from 54-112 cm and weights ranged from 1.1-16.4 kg. Of the 146 caudal fin clips sampled, assays confirmed 67 were female and 62 were male. The remaining samples either had a disagreement between the assays or the results were ultimately inconclusive. Female halibut were on average 4.46 kg (± 0.015) and 71.9 cm long (± 1.42), whereas male halibut had a mean of 4.47 kg (± 0.238) and 71.9 cm (± 1.20).

The mean fat content between halibut caught in the illuminated tows versus non-illuminated tows was 1.89 (± 0.038) and 1.89 (± 0.03), respectively. No significant difference between halibut caught in illuminated tows versus those caught in the non-illuminated tows was found for any of the physiological stress indicators or somatic fat percentage (**Table 3**). However, the total catch size was found to have a significant positive relationship with lactate and glucose levels ($p < 0.01$, **Table 4**). As catch size increased, glucose and lactate levels would tend to increase as well. Tow duration was found to have no statistically significant relationship with any of the physiological stress parameters.

2.4 Discussion

The use of artificial illumination on high-rise trawl bridle components did not have a statistically significant effect on halibut bycatch. These results were not only contrary to the initial hypothesis, but also to the findings of Lomeli et al. (2021). There was, however, a general trend of illuminated tows to be less efficient relative to non-illuminated tows (**Fig. 8**). While not statistically significant, this pattern of reduction does parallel the trends seen by Lomeli et al. (2018) in which results showed that low-rise trawls with an illuminated headrope caught on average 57% less halibut than non-illuminated trawls, but possessed confidence intervals too broad to conclude a statistical difference. For this study, the use of artificial illumination did exhibit a reduction in halibut when compared to non-illuminated tows, albeit with a reduction that was less than previously observed by Lomeli et al. (2021). While the illuminated trawl did capture fewer halibut, the same trend was also evident for target species. This would challenge the overall effectiveness of these devices as fishers would have to compensate by increasing fishing efforts to offset this reduction.

Based on values collected from the MK9 archival tag, illuminated tows were shown to be typically brighter than non-illuminated tows (**Fig. 6**). This trend was also seen in Lomeli et al. (2021) in which the mean natural light for non-illuminated tows was 2.6e–05 (±3.2e–06) µmol photons m^{-2} s^{-1} and the mean light level for illuminated tows was 1.4e–02 (±1.6e–03) µmol photons m^{-2} s^{-1}. Notably, the mean light level for illuminated tows in this study was darker than previously exhibited. However, the placement of the archival tag in the trawl has been shown to affect the recorded light levels as the tag can be influenced by external factors like sediment clouds or trawl obstruction (Hannah et al., 2015; Lomeli et al., 2018). A difference in mean values could be explained by a difference in tag location between the two studies in which different gear configurations were utilized. While light levels for illuminated tows were on average two orders of magnitude greater than non-illuminated tows, it is possible that the increase in light levels that the LED provided was not enough to elicit a change in halibut behavior responding to the approaching trawler (Brill, personal communication, 2023). How halibut perceive and respond to these additional light sources on an approaching trawl net is further discussed in *Chapter Two* of this thesis. If halibut had difficulty perceiving the trawl, even with LEDs attached to a spectra rope, the ability to escape the path of the trawl would be challenging and could explain the lack of reduction exhibited in this study.

Tows for this study were conducted in similar environmental conditions and typically within close proximity of each other (**Figs. 5 and 7**). Any external stressors generated from the environment would thus be expected to be omnipresent throughout sampling. Notably, oxygen levels for both illuminated and non-illuminated tows were at times reaching near-hypoxic conditions (< 1.4 mL/L) according to the CTD data. This could have resulted from a mechanical error as the probe may have been obstructed by the trawl and prevented an accurate reading. However, hypoxic zones are regularly detected every summer in the Northeast Pacific Ocean and are driven by physical and biological processes (Franco et al., 2023). Furthermore, fish that occupy regions with low-oxygen concentrations have been shown to be more susceptible to trawl capture (Thambithurai et al., 2019). If the CTD data is believed to be true, it is possible that fishing occurred in regions with lower oxygen concentrations. This could partially explain the results between illuminated and non-illuminated tows, as halibut occupying those low-oxygen regions during this study could have been more susceptible to capture regardless of trawl treatment. Unfortunately, it remains unknown whether the Lomeli et al. (2021) study experienced similar oxygen levels as no CTD data from the tow locations are available for comparison.

There was no statistical evidence to reject the null hypothesis that the cortisol levels found in the illuminated tows were different from those levels found in non-illuminated tows. The same is also true for all other physiological parameters assessed in this study (**Table 3**). The sample size for this analysis was almost three times larger than in the previous Lomeli et al. (2021) study, while the significance level was kept the same ($\alpha=0.05$). By increasing the sample size, the statistical power was also increased which means that the analysis is less likely to have been underpowered. It is possible that the difference in the observed results in this study versus those found in Lomeli et al. (2021) could be attributed to a difference in vessel operations and handling protocols. However, sampling protocols for this study were intentionally based on the previous study to reduce potential biases.

Total catch size was also found to have a significant effect on both lactate and glucose levels in halibut (**Table 4**). Lactate levels in Atlantic cod caught by a bottom trawl in the North Atlantic Ocean were also found to be influenced by total catch size (Olsen et al., 2013). The researchers hypothesized that this correlation was due to post-mortem glycolysis in which the anaerobic degradation of glycogen and hydrolysis of ATP caused the lactic acid levels to increase. Since larger catch sizes would take longer to process, fish were more likely to suffocate and trigger these post-mortem processes. Similar processes may have occurred in this study. Additionally, total catch size has been shown to affect the degree of injury an individual can endure (Digre et al., 2010). Larger total catch sizes could mean more fish were in the codend for longer periods of time. This in turn can further stress the individual and ultimately influence the levels of lactate and glucose found in the blood. While tow duration has also been shown to influence physiological stress parameters, such was not the case for this study. There was a limited range in tow duration (20 to 45 minutes) as this parameter was kept relatively constant across illuminated and non-illuminated tows. Trends may have been different if more tows were conducted.

This study marked the first attempt at the utilization of artificial illumination on a high-rise trawl, whereas previous trials used a low-rise, cutback configuration. While the spectra rope was attached to this new configuration in such a way as to mimic the previous bridle system, it is possible that this attempt was unsuccessful. This change in gear configuration could have elicited a different behavioral response. Halibut have been shown to rise up off the seafloor more often than other flatfish (Ryer et al., 2008). It is possible that a high-rise configuration presents too much of a challenge for fish seeking to rise up over an approaching net. Further research investigating the interaction between trawl design and halibut behavior is needed to better understand the potential these light devices can have in reducing bycatch. How halibut behave in response to the gear configuration used in this study will be further addressed in *Chapter Two*.

The development of all BRDs is often a protracted process in which researchers continuously modify devices to maximize selectivity. In order for a BRD to be successful at separating bycatch from target catch, a robust comprehension of the behavior and physiology for the species of interest is paramount. In addition, understanding the behavior of the fishery and the roles that stakeholders can play in furthering the utilization of these devices can often be just as important (Jenkins, 2023). Even if a device is highly consistent at reducing bycatch, if the industry ultimately does not buy in, the BRD is functionally ineffective (Northridge et al., 2013).

This project was conducted aboard a commercial fishing vessel and in close partnership with several stakeholder groups. While the results from this study were ultimately not significant, they do provide valuable information to the industry that can be used for future decision-making and research. The general trend of illuminated tows catching less halibut suggests that artificial light may still have an impact on avoidance behavior. Further research into how halibut respond to artificial light is implored.

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2.6 Figures

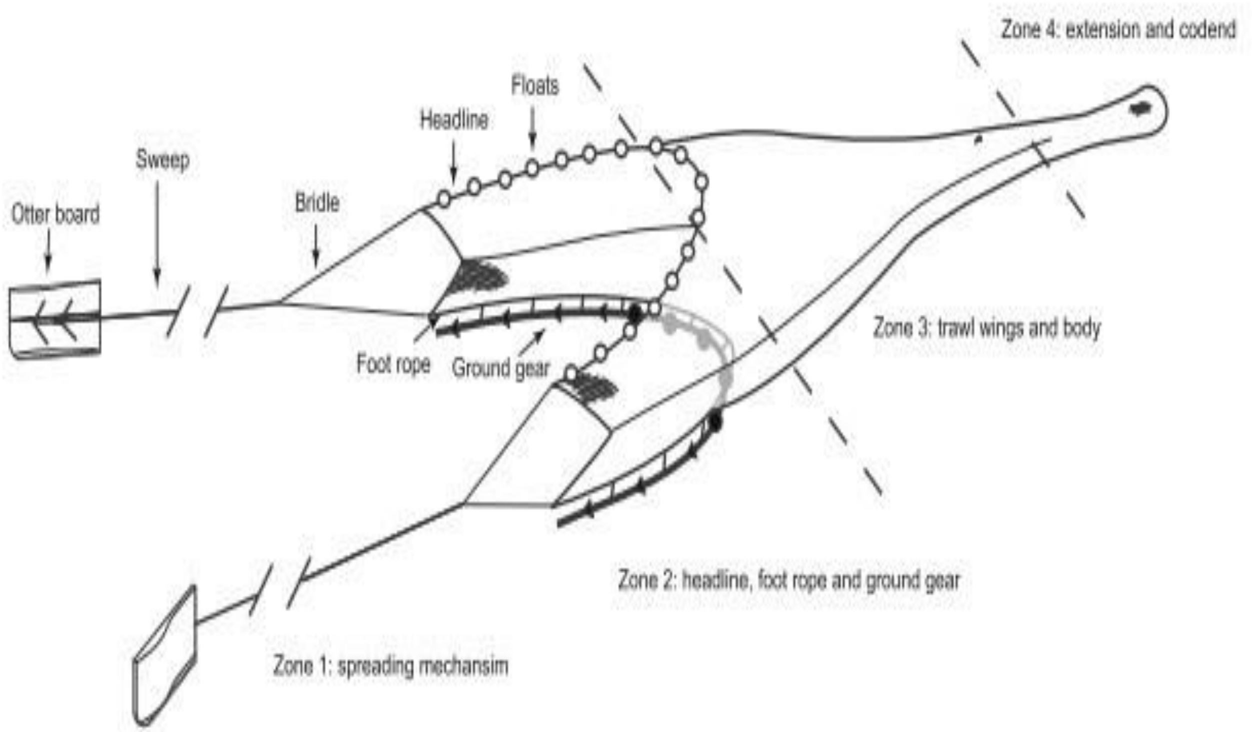

Fig. 1. Four categorized zones of where gear modification can occur for a typical demersal trawl (Reprinted from Kennelly and Broadhurst, 2021).

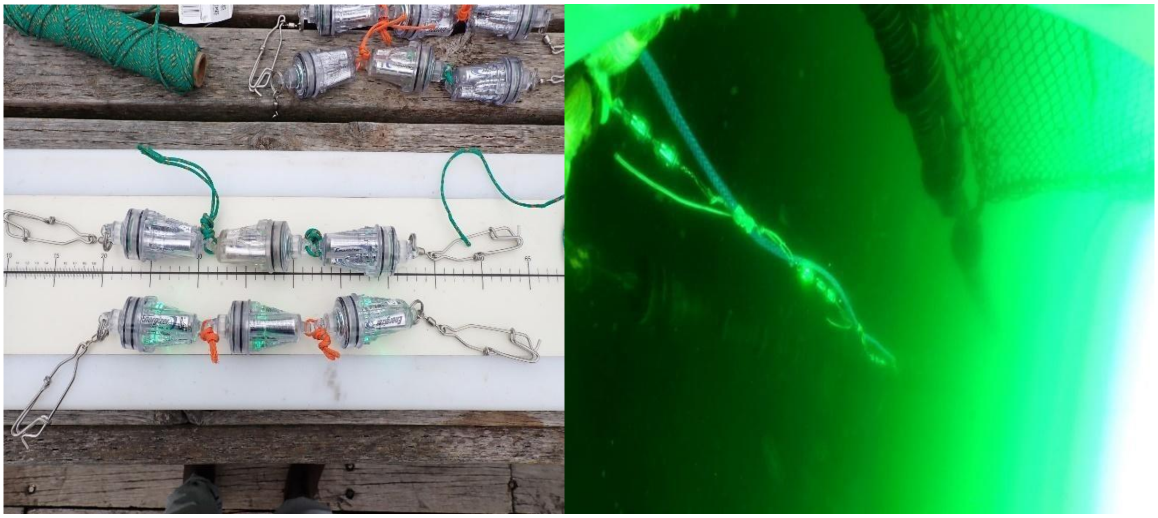

Fig. 2. (Left Photo) Electralume LEDs tied together in groups of three with snaps attached to either end for easy attachment and removal between tows. **(Right photo)** Five LED clusters were attached to either side of the trawl along a 2.4-meter-long spectra rope that ran from the breastline to a hammerlock that connected the footrope extension to the beginning of the lower bridle. The photo was taken as the gear was being deployed.

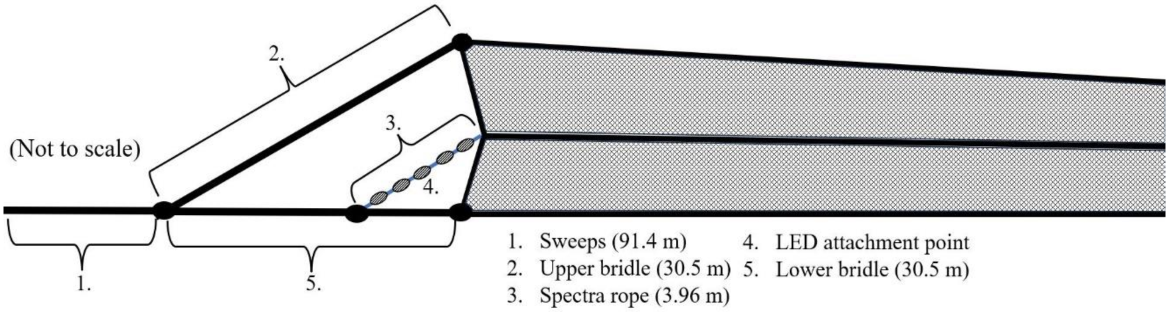

Fig. 3. Side profile of the two-seam high-rise trawl used in this study.

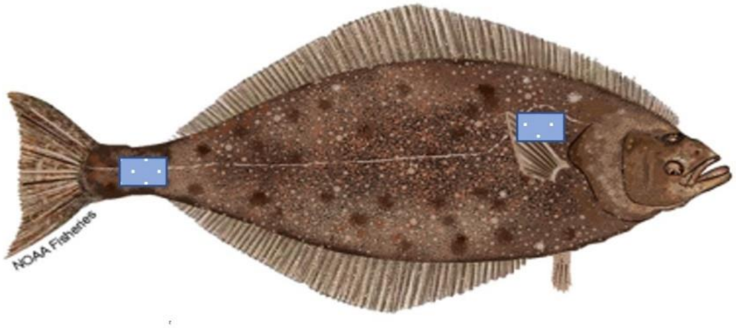

Fig. 4. Blue shaded regions represent locations in which somatic fat content was measured on halibut. Each location was measured twice for every halibut.

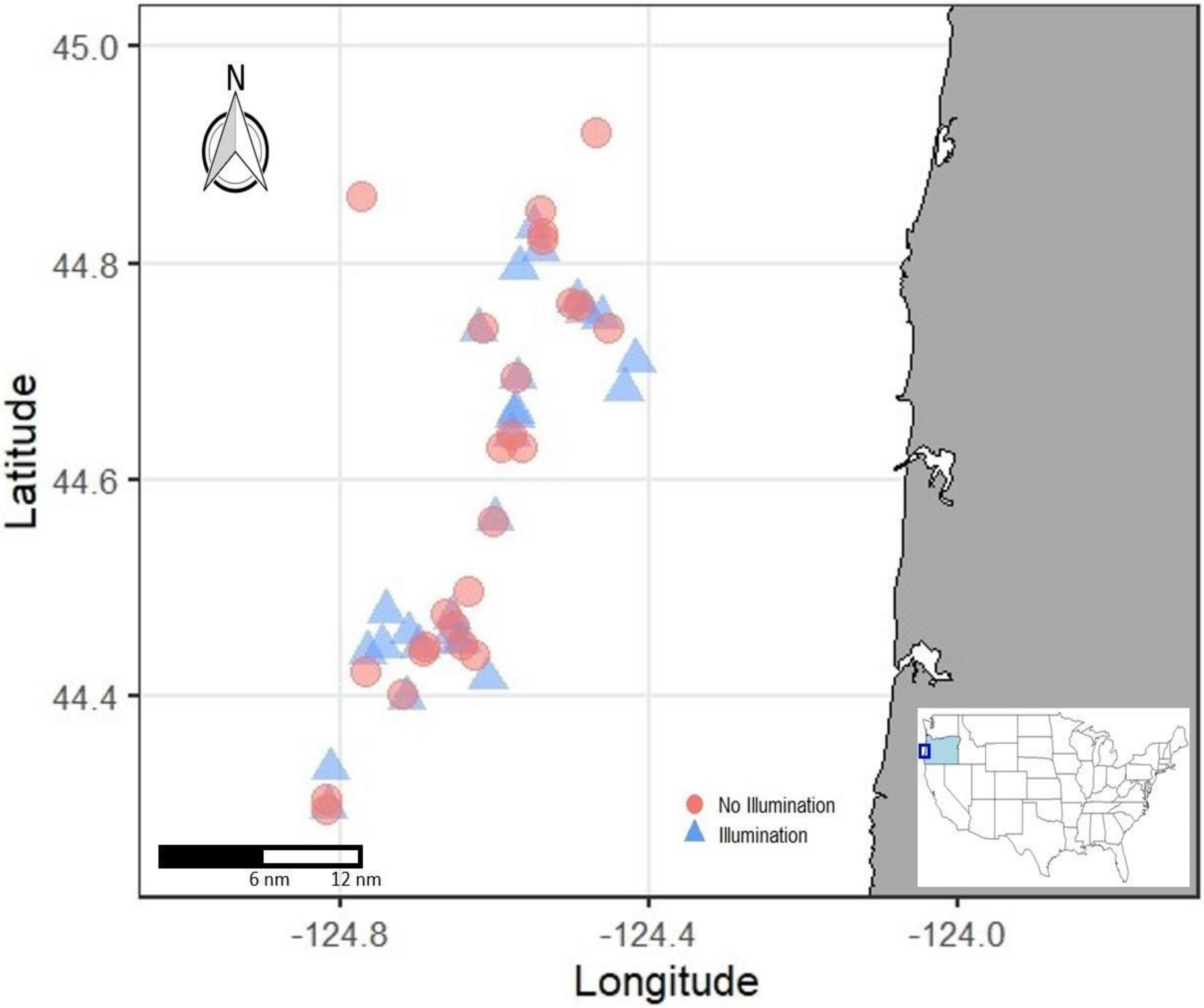

Fig. 5. Map of the tow starting locations for sea trials.

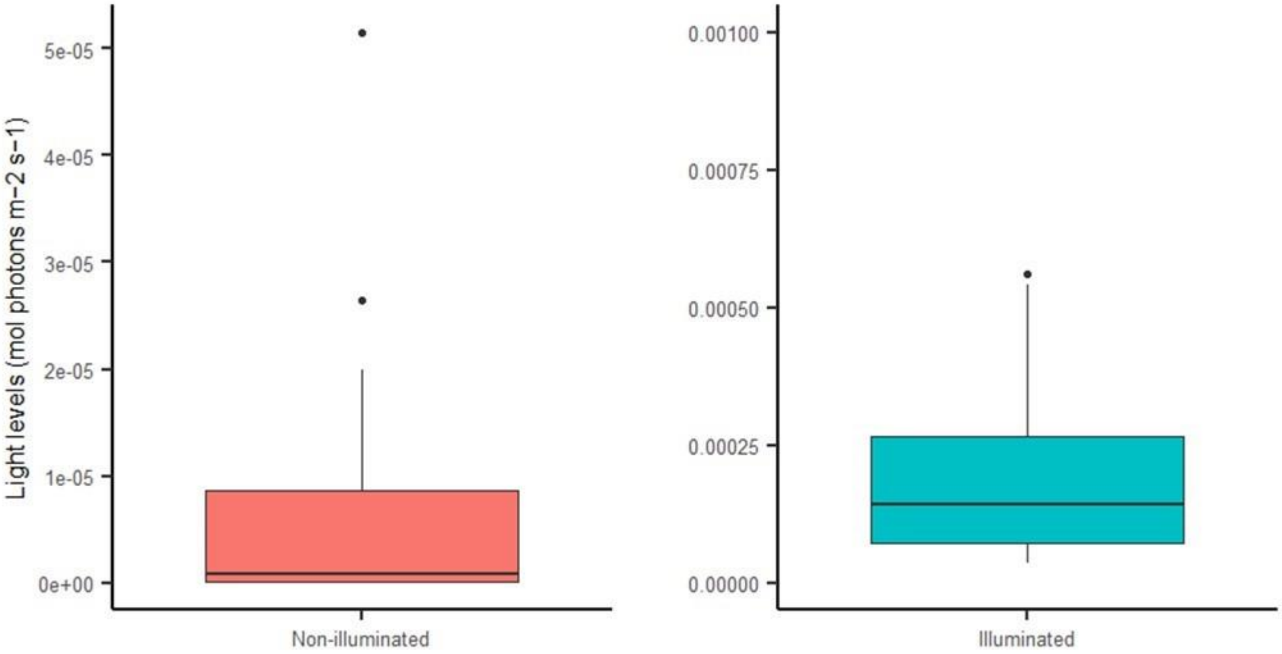

Fig. 6. The difference between light levels recorded by the Wildlife Computers TDR-MK9 archival tag for illuminated and non-illuminated tows.

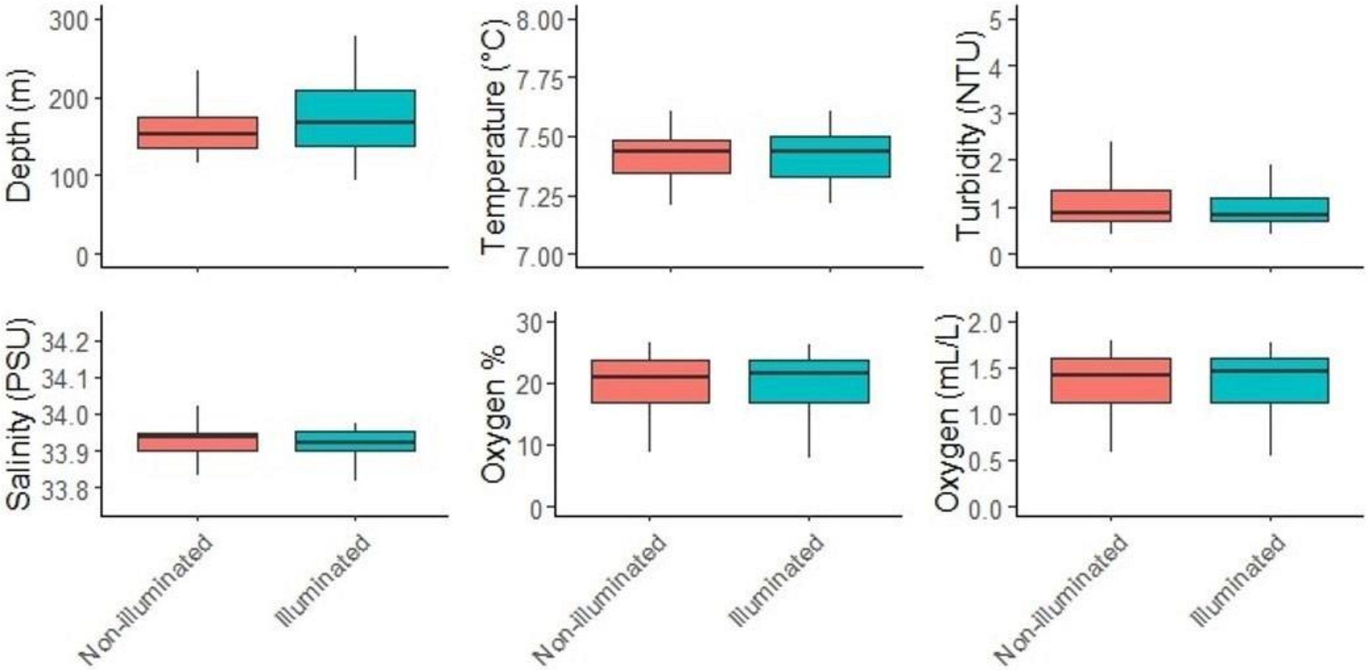

Fig. 7. Abiotic conditions taken from CTD profiles while actively fishing for both illuminated and non-illuminated tows.

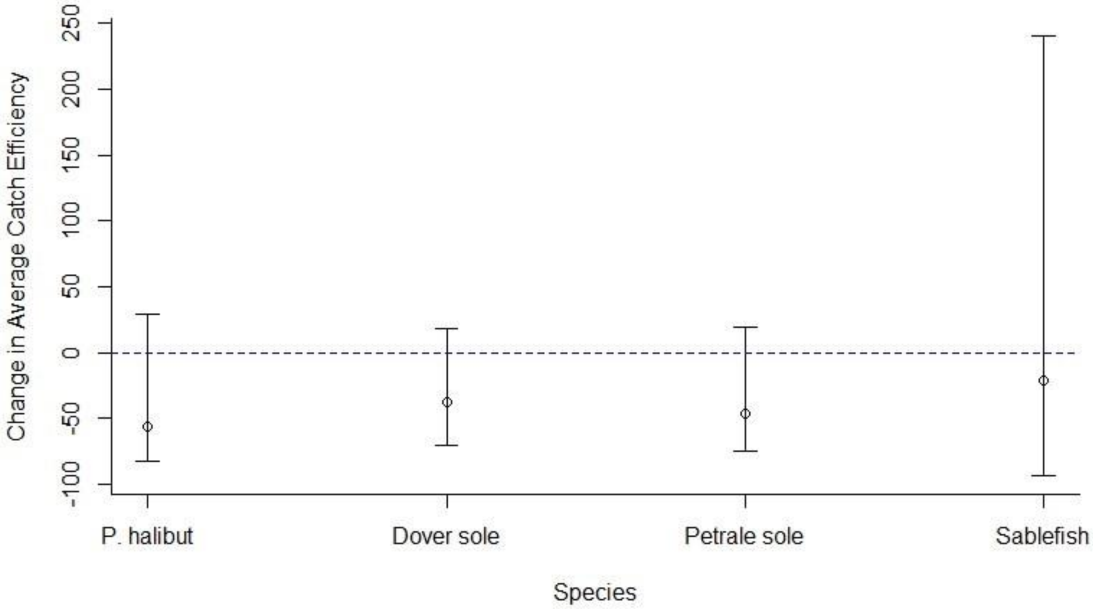

Fig. 8. Change in average catch efficiency based on values from Eq. 4. The baseline catch efficiency value of zero, represented as a dashed line, is indicative of equal catch efficiency between the two trawls. Values below zero indicate the illuminated trawl has a decrease in catch efficiency compared to the non-illuminated trawl. Conversely, values above zero indicate the illuminated trawl has an increase in catch efficiency compared to the non-illuminated trawl. Circles represent mean values. The bars represent 95% CIs.

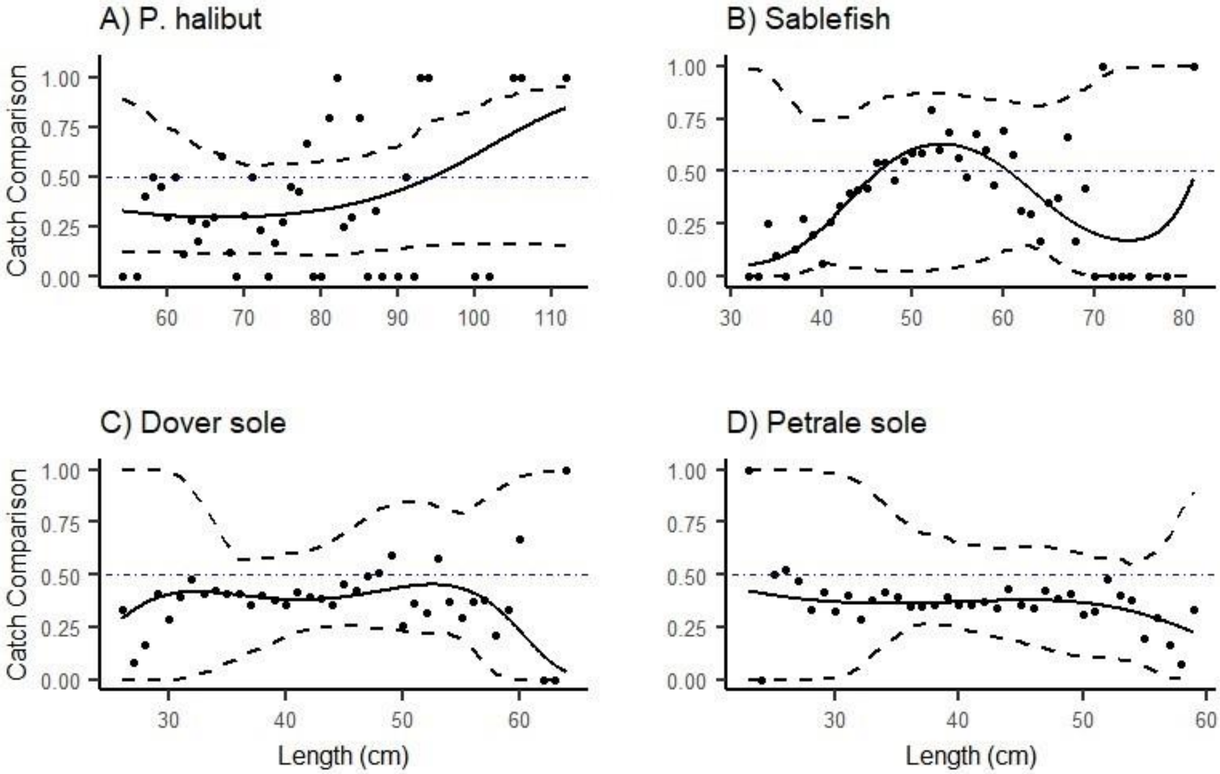

Fig. 9. Mean catch comparison curves between the illuminated and non-illuminated tows. The observed data are represented by the black circles; fitted solid lines are the modeled values; dashed lines are 95% CIs; dotted straight lines depict the baseline catch comparison proportion of 0.52 indicative of the catch rates between the two trawls.

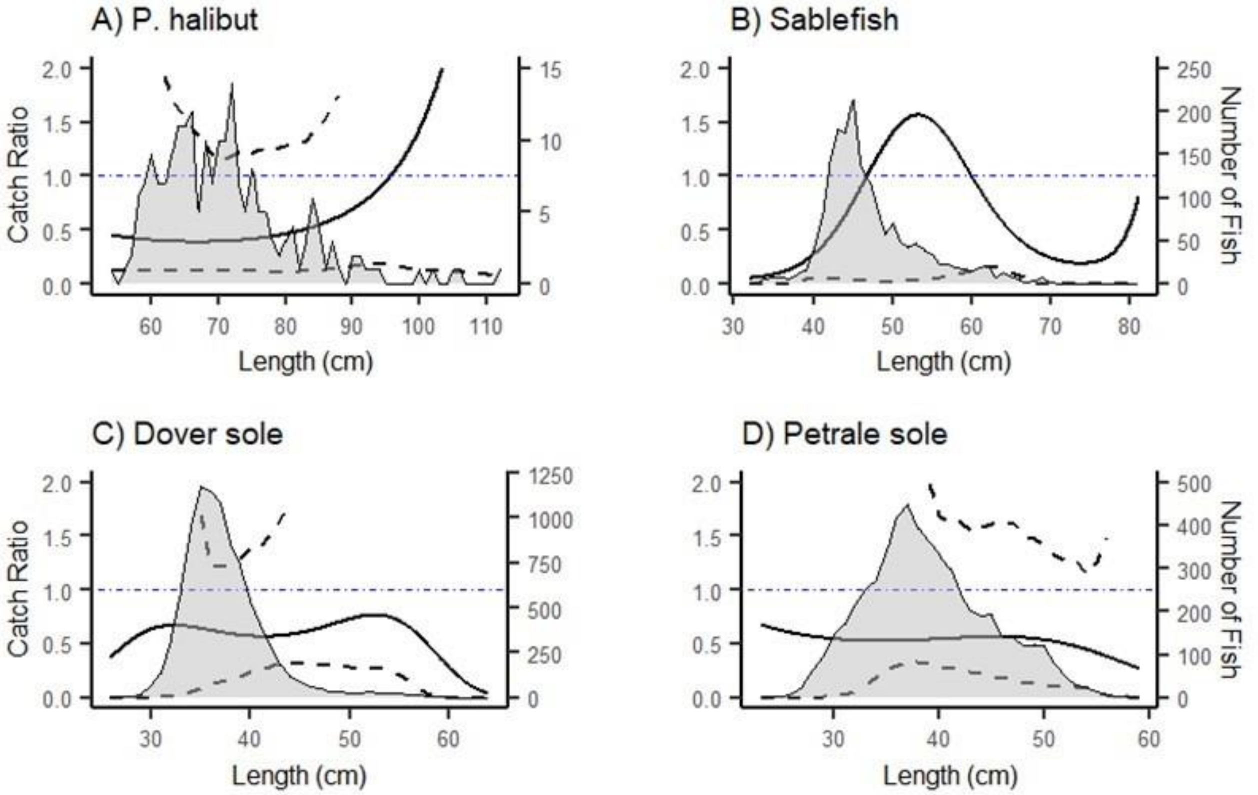

Fig. 10. Mean catch ratio curves between the illuminated and non-illuminated tows. The modeled values are represented by the solid black line, the dashed lines are 95% CIs, and the dotted straight lines depict the baseline catch ratio of 1.0 indicating equal catch efficiencies between the two trawls. The shaded regions represent the length distribution for all measured fish.

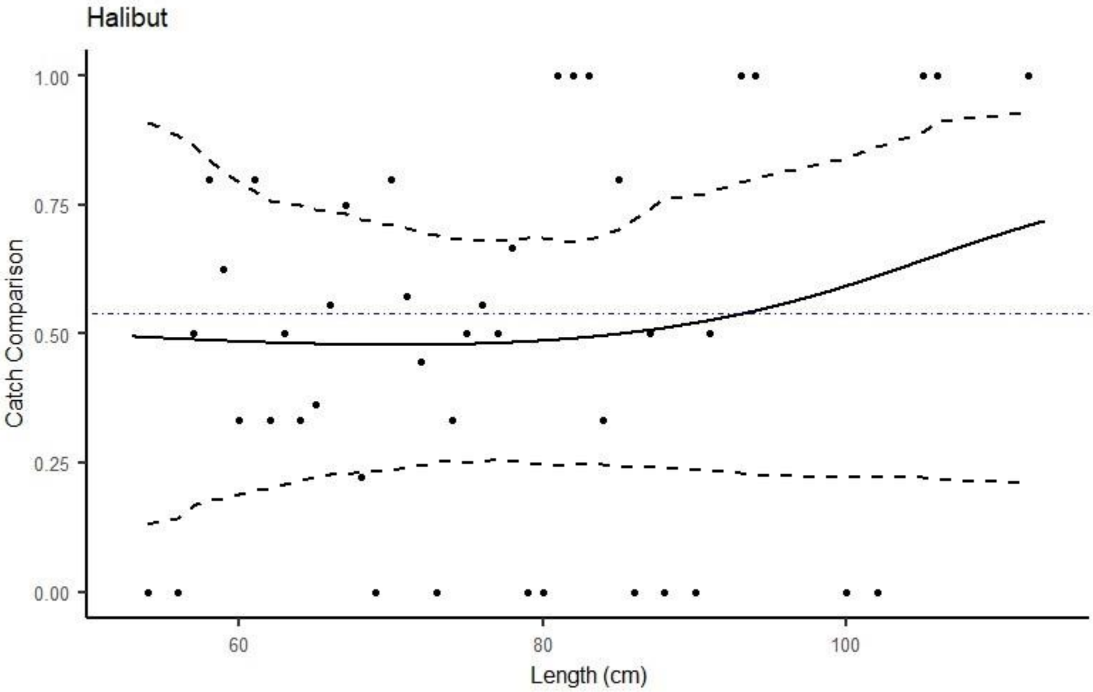

Fig. 11. Mean catch comparison curves between the illuminated and non-illuminated tows (with the exception of outlying tows 1 and 7). The observed data are represented by the black circles; fitted solid lines are the modeled values; dashed lines are 95% CIs; the dotted straight line depicts the baseline catch comparison proportion of 0.54 indicative of the catch rates between the two trawls using the subset of tows.

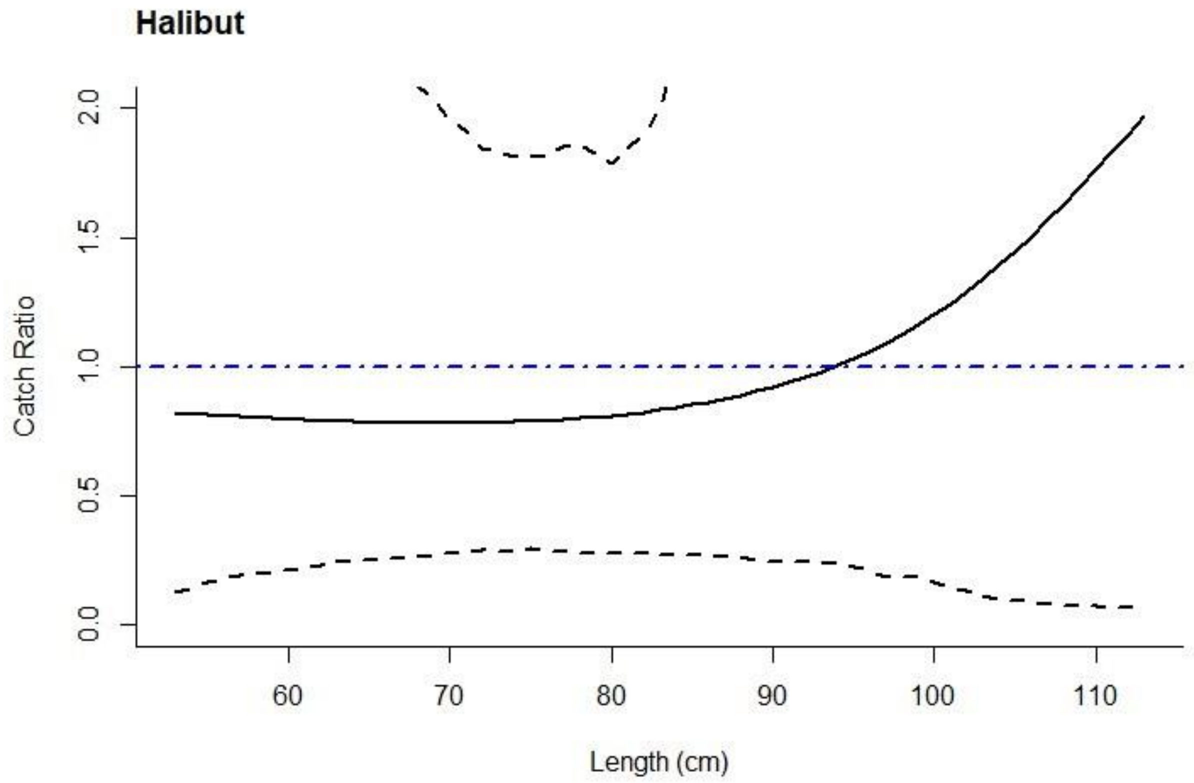

Fig. 12. Mean catch ratio curves between the illuminated and non-illuminated tows (with the exception of tows 1 and 7). The modeled values are represented by the solid black line, the dashed lines are 95% CIs, and the dotted straight lines depict the baseline catch ratio of 1.0 indicating equal catch efficiencies between the two trawls.

2.7 Tables

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 multiplied by the offset for tow duration. Values in brackets are the range in length measurement subsample ratios multiplied by the tow duration offset.

Species	Illuminated	Non-illuminated
Halibut	74 (0.70 [0.44 - 1.0])	152 (0.78 [0.44 - 1.0])
Dover sole	4024 (0.56 [0.16 - 1.0])	5150 (0.49 [0.14 - 1.0])
Petrale sole	2564 (0.55 [0.25 - 1.0])	2983 (0.53 [0.08 - 1.0])
Sablefish	696 (0.68 [0.18 - 1.0])	1059 (0.72 [0.20 - 1.0])

Table 2. Catch Comparison fit statistics.

	p-value	Deviance	DF
Halibut	0.038	56.02	39
Dover sole	0.003	59.68	33
Petrale sole	0.157	39.99	32
Sablefish	0.021	61.35	41

Table 3. Physiological parameters of halibut caught in the illuminated and non-illuminated tows. Somatic Fat (%) represents the content of fat in the somatic muscle tissue of halibut as determined by a Distell Fish Fatmeter. Mean values for three physiological stress indicators (plasma lactate, glucose, and cortisol) are presented with their standard deviations, as well as the number of fish per group in parentheses. Units of lactate and glucose are in milligrams per deciliter of plasma, whereas cortisol units are in nanograms per milliliter of plasma. A two-sample T-test was used to compare the physiological parameters of halibut caught in the illuminated and non-illuminated tows (α=0.05).

Parameters	**Illuminated Tows**	**Non-illuminated Tows**	**t- statistic**	**p-value**
Somatic Fat (%)	1.89 ± 0.346 (65)	1.89 ± 0.344 (128)	-0.064018	0.9491
Plasma Lactate (mg/dL)	11.7 ± 8.67 (62)	14.8 ± 10.7 (77)	-1.8978	0.05983
Plasma Glucose (mg/dL)	23.1 ± 14.3 (61)	32.3 ± 40.2 (75)	-1.8466	0.06788
Plasma Cortisol (ng/mL)	160.0 ± 91.6 (58)	143.0 ± 91.6 (70)	1.0873	0.279

Table 4. General linear model results for the physiological parameters collected from halibut. SE.= standard error.

Lactate Model:	*GLMM (Negative Binomial)*			
	Estimate	**SE**	**z-value**	**p-value**
Intercept	1.42	0.332	4.26	2.03e-05
Total Catch Size	0.00047	0.0002	2.86	0.004
Tow Duration	0.010	0.011	0.927	0.354

Cortisol Model:	*GLM (Gaussian)*			
	Estimate	**SE**	**t-value**	**p-value**
Intercept	173.0	51.5	3.36	0.003
Total Catch Size	-0.017	0.027	-0.634	0.532
Tow Duration	-0.467	1.68	-0.279	0.783

Glucose Model:	*GLM (Gaussian)*			
	Estimate	**SE**	**t-value**	**p-value**
Intercept	8.93	3.60	2.48	0.021
Total Catch Size	0.009	0.002	4.70	9.9e-05
Tow Duration	0.078	0.115	0.676	0.506

Chapter 2: Behavioral analysis of Pacific Halibut *(Hippoglossus stenolepis)* bycatch interacting with an illuminated high-rise bottom trawl

3.1. Background

3.1.1 Ethograms and observational studies

Understanding the mechanisms that drive fish behavior can be complicated due to the multitude of variables that drive decision-making when reacting to stimuli. Researchers often approach the topic in a variety of ways, including hypothesis testing both in a laboratory and *in situ* settings, complex modeling, and direct observational studies. One or any combination of these approaches enables researchers to draw inferences on how fish perceive the world as influenced by behavioral and physiological factors, which can lead to further research or technological application. Ethograms represent useful tools in the field of behavioral ecology that enable researchers to quantify observations of complex behaviors. These tools categorize and then utilize a list of highly defined behaviors, often referred to as a ‘repertoire’, to document the number of unique traits exhibited during a given interaction. The occurrence of these behaviors then can be further analyzed and quantified to draw inference relative to a given ecological question. For fisheries technologists, the utilization of ethograms can be a powerful tool when observing how fish respond to commercial fishing gear (Kim and Wardle, 2003; Ryer and Barnett, 2006; Bayse et al., 2016; Yochum et al., 2021).

3.1.2 Fish behavior in relation to trawl gear

Fishing gear is often designed to exploit the behavioral responses of fishes to artificial stimuli (He, 2010). Leveraging these responses, in turn, can facilitate an outcome with respect to the probability of capture. In trawl gear, for example, the sweeps, bridles, and wings of a trawl are thought to corral fishes towards the center of an approaching net. The diverse visual and acoustic capabilities for the suite of species that interact with the gear can play a crucial role in their initial detection and response (Winger et al., 2010). Yet, the distance at which fish react to the approaching fishing gear is based on a number of cost-benefit decisions. These risk-avoidance behaviors exhibited when interacting with a trawl are thought to be very similar, if not the same as, predator-prey avoidance behaviors (Fernö and Huse, 2003; Winger et al., 2010).

Fishes are reliant on their evolutionary adaptations when considering the trade-offs between fleeing or hiding from potential threats. For example, roundfish typically swim away from an approaching trawl much sooner than flatfish (Bublitz, 1996; Ryer, 2008). Flatfish are more reliant on cryptic behavior, such as hiding close to the seafloor, when feeling threatened and will often only choose to rapidly flee from a predator as a last resort. These are generalizations and there are exceptions to this behavior even within a morphologically similar species group (e.g., flatfishes). Ryer et. al. (2004) found that juvenile Pacific Halibut (*Hippoglossus stenolepis;* hereafter, 'halibut') were more likely to sprint away from potential predators relative to other flatfish species when studied in a lab.

Given enough ambient light, fish often will orient themselves in a relatively fixed position in relation to a moving trawl net. This behavior, often referred to as the "optomotor response", is thought to be dependent on visual cues provided by the trawl net and surrounding environment (Kim and Wardle, 2003). Once corralled towards the center of the trawl, fish typically exhibit herding behaviors and will swim in front of the mouth of the net for extended periods of time before either tiring and falling back into the net or escaping below the footrope. Typically, the time a flatfish will swim at the mouth of the net before either falling back or dropping below the footrope is only a few seconds. Yet, the species-specific trait for halibut to grow much larger than most other flatfishes may give them a physiological advantage (Ryer, 2010). Halibut have been shown to swim in front of the net for upwards of 8 minutes (Rose, 1996; Ryer, 2008).

In addition to the length of time that halibut will swim at the mouth of the net, halibut have rarely been seen avoiding capture by going below a footrope (Weinberg et al., 2002). These behaviors, however, may be related to external factors. Ryer and Barnett (2006) found that halibut had a strong tendency to rise over a footrope rather than swim under, away, or simply hop over when tested in a lab setting. That tendency to rise was thought to be influenced by ambient light levels, as individuals were more likely to seek to swim away from the rope when conditions were brighter. Yet, despite these insights, documenting halibut behavior in environments far less controlled than those found in a laboratory has proven difficult to quantify consistently and accurately given the number of variables fish consider when potentially responding to an approaching trawl net.

3.1.3 Objective and hypothesis

Video and imaging sonar recordings in Lomeli et al. (2021), were unable to be utilized to observe halibut behavior in response to an approaching low-rise cutback trawl, yet a significant reduction in halibut bycatch was observed. It was hypothesized that halibut may be escaping capture by either going above or below the illuminated bridles of that low-rise trawl. A bridle system for a high-rise trawl was thus modified to mimic the previous low-rise cutback configuration. This chapter of my thesis sought to further investigate how halibut reacts to an approaching trawl net with illuminated bridles. Based on this prior knowledge, *a working hypothesis is that when the bridles are illuminated, the halibut avoid capture by going over the bridles of the trawl.* To test this hypothesis an ethogram was constructed to analyze the behavioral responses of halibut in relation to an approaching trawl net. Data was derived from a simulated dataset based on prior flatfish behavioral studies as well as qualitative evidence provided by video and sonar recordings.

3.2. Methods

3.2.1. Behavioral observations with video and sonar

In an effort to capture the behavior of halibut and target species, both video and sonar technologies were employed during data collection as described in *Chapter One*. A video camera (GoPro Hero 4 in a ruggedized housing) was placed less than one meter aft of the trawl's starboard breastline looking forward towards the starboard bridles for six tows in order to observe the behavior of halibut and target species interacting with the approaching trawl gear (**Fig. 1**). The camera for the first tow with video, tow 11, was attached to the inside of the trawl. All subsequent tows had it placed at the same location, but on the outside of the trawl to improve viewing. The experimental LED clusters served as the only source of illumination for the video footage. Similarly, a DIDSON (Dual-frequency IDentification SONar) imaging device was later used for nine tows (**Fig. 2**). The device emits a combination of low and high-frequency sound waves. If an object moves into the path of those soundwaves, sound then bounces off of that object and back to the sonar transducer on the device. An image of that object against its surrounding environment is then generated. The initial placement of this device matched that of the video camera. A preliminary review of the recordings suggested that this positioning was not optimal and should be moved. The device was then centered on the inside of the top panel of the trawl and focused on the port wing.

All recordings were then reviewed twice, and times of potential interactions with fish were recorded. Video recordings were analyzed with the use of the VLC media player, whereas in-house software from Sound Metrics, Corp. was utilized for the sonar files. The playback speed for all interactions was reduced to frame by frame to determine species identification. Additional image processing was utilized to alter the light intensity and contrast in those recordings taken with low ambient light levels. All observations were recorded by one reviewer for this study.

3.2.2. Constructing the ethogram

All behavioral observations were quantified using an ethogram, which was divided into two categories: “Locomotion” and “Event” (**Table 1**). Behavioral traits within each of these categories were based on the findings of previous flatfish behavioral studies (Bublitz, 1996; Kim and Wardle, 2003; Ryer and Barnett, 2006). The category of “Locomotion” was divided into four distinct behaviors: “rise”, “run”, “under”, and “variable”. These behaviors are defined by the perceived movements of halibut as they interact with the approaching trawler. For example, “rise” and “under” were selected if the halibut was perceived to move at least a quarter of its body length in either an upward or downward direction, respectively. In the case of “run”, however, the halibut exhibits no vertical directionality in its swimming and instead sustains swimming speed forward of the net. Conversely, a halibut that exhibited rapid changes in its vertical orientation both upwards and downwards, exceeding a quarter of its body length over the course of the interaction, would be classified as “variable”. Lengths of each halibut were estimated based on the known, fixed distance between light clusters on the spectra rope.

The “Event” category refers to the velocity at which the halibut move and is further defined as either “constant” or “erratic”. If the orientation and swimming intensity of the halibut were to change rapidly over the course of the interaction event (i.e., sudden changes in orientation >30° in 1 second or rapid increase or decrease in the number of body undulations per second), then the behavior would be listed as “erratic”. If body orientation and swimming intensity were relatively constant throughout the interaction event, the behavior would be classified as “constant”. Body orientation was determined by the position of the head in relation to the direction of the approaching trawl. For example, a fish facing directly away from the camera, in the direction of the tow, would have an orientation of 0°. A fish swimming directly perpendicular to the camera, towards the mouth of the net, would have a position of 90 or 270°. Based on a preliminary review of the video and sonar recordings, most interactions lasted only a few seconds (< 3 sec). Interaction events were thus recorded from the time of initial detection until the fish moved out of view of the camera. Body orientation was recorded at the beginning and end of each interaction. A halibut was noted as potentially captured if its final orientation was in the direction of the approaching trawl (180° to 270°) or last seen falling back into the net. Additionally, halibut initially spotted swimming forward past the camera were excluded from observation to avoid potentially counting the same halibut multiple times.

3.2.3. Constructing a simulated dataset

For the simulated dataset, 500 behavioral observations were randomly assigned to both illuminated and non-illuminated treatment groups. Each “Locomotion” category was then assigned a conditional probability of occurrence. If artificial lights were present, the likelihood of the behavior being “rise” or “run” was set to appear approximately 30% of the time, whereas, “under” and “variable” behaviors would occur at approximately 20%. If tows were not illuminated, conditions were set so that halibut would exhibit “rise” approximately 35% of the time, whereas, “run” and “under” would occur 20% and “variable” would be approximately 15%. These probabilities were set based on a combination of previously established behavioral traits exhibited during lab studies (Ryer and Barnett, 2006; Kim and Wardle, 2003) and the behaviors that appeared during the video and sonar recording review.

The estimated likelihood of an individual halibut potentially being captured by the net (final orientation being within 180° to 270°) was conditional on whether it was in illuminated or non-illuminated tows. Out of the 500 behavioral observations per group, approximately 375 halibut would be captured in non-illuminated tows and about 190 in illuminated tows. This was done to approximate the results seen in *Chapter One*. Similarly, the estimated lengths for each halibut were randomly generated from the observed range of 50 to 120 cm since no statistical difference in length was found during the field trials. All interaction times were presumed to be of the same length.

The outcome for the "Event" category in the Ethogram was also randomly generated for each interaction. However, any interaction with a 'variable' condition was automatically assigned to "erratic" as prescribed by the ethogram. Likewise, if the event was classified as "constant", the final orientation of the halibut was set to be within 30° of the initial orientation. All other orientation positions were randomly generated between 0° and 359°. A Chi-square test of independence was used to assess the relationship between tow group (i.e., illuminated vs. non-illuminated tows) and "Locomotion" and "Event" behaviors. The construction of the simulated dataset and subsequent analysis was completed in R (version 4.2.2, R Core Team 2020).

3.3. Results

3.3.1. Behavioral analysis from video and sonar review

Video footage was recorded for six tows in which the spectra rope was illuminated with the LED clusters (*Chapter One* data collection). For most of the footage, sediment clouds produced from the bridles drastically reduced visibility. With the exception of one sablefish spotted crossing over the spectra rope during tow 11, species were nearly impossible to determine. It is worth noting that with the exception of tow 22, no halibut was caught during those video-recorded tows. Most fish that were detected in the footage were small and unlikely to have been halibut. Fish were often observed as they were either rising over the spectra rope or falling back toward the direction of the approaching net.

DIDSON recordings were analyzed for nine tows. Similar to the video footage, species identification of fishes interacting with the gear was improbable. For several of the tows, the DIDSON was either obstructed by the trawl or in a poor location. Fish that were observed, however, were often seen rising over the ground gear.

3.3.2. Analysis of simulated data

Based on the simulated data, there was a significant relationship between tow group and the locomotion behavior ($\chi^2 = 16.28$, $p < 0.001$; **Table 2**). Halibut that interacted with illuminated tows exhibited "run" behavior 31% of the time (**Fig. 3**). Whereas "rise", "under", and "variable" made up 29.2%, 20.2%, and 19.6% of the interactions, respectively. For interactions with non-illuminated tows, "rise" behavior constituted 37.6% of the interactions. The locomotion interactions of "run", "under", and "variable" were exhibited in 26.2%, 23%, and 13.2% of the interactions, respectively. For both groups, "erratic" behavior was more likely to be exhibited than "constant" (**Fig. 4**). However, the null hypothesis of no difference between event behavior and tow group was not rejected ($\chi^2 = 0.266$, $p = 0.606$). For non-illuminated tows, 280 out of the 500 halibut interactions exhibited this trait whereas 315 out of 500 exhibited erratic behavior when interacting with illuminated tows. Overall, a total of 182 halibut were classified as potentially captured by illuminated tows based on their final orientation. Conversely, 363 halibut were potentially captured by non-illuminated tows.

3.4. Discussion

Species identification was unable to be determined due to low image quality in both video and sonar recordings. For the video recordings, the green LED clusters served as the only source of additional illumination. Studies investigating fish behavior as it relates to trawl gear have previously sought to use red lights to illuminate the study area (e.g., Yochum et al., 2021). Red light is often outside the visual range of coastal fishes and is thought to have minimal influence on fish behavior (Raymond and Widder, 2007; Fitzpatrick et al., 2013). Halibut, and the other species that the fishery targets, are associated with moderately deep coastal waters and have been shown to be unable to perceive the longer wavelengths within the spectrum of visible light (Brill et al., 2008). However, there is some contrary evidence to suggest that some species of fish can still perceive and react to sources of red light (Widder et al., 2005). Given that the goal of this thesis was to better understand how fish respond to green light (519 nm), the introduction of an additional source of illumination could potentially have added a confounding factor when observing fish behavior. Thus, the utilization of additional illumination sources was ultimately ruled out. The results in my study, however, match that of the previous Lomeli et al. (2021) investigation which also did not include additional sources of light. Future studies may need to consider adding red or infrared lights to further improve visibility. Other cameras with low light sensitivities should also be considered.

Sonar imagery has been utilized in the past to study fish behavior in low-light settings (Rakowitz et al., 2012; Martignac et al., 2015; Lomeli et al., 2021). However, as with the video analysis, effectively analyzing the sonar recordings for this study was challenging. For several of the tows, the location of the device was not optimal as the device was either obstructed by the net or unable to record fish as they approached the mouth of the trawl. Yet, one tow was successful. Files from that tow provided a clear image of the port wing as it moved along the seafloor. Smaller fish, highly unlikely to have been halibut based on morphology, were observed erratically rising up and away from the sediment/water interface as the net approached. As fishing continued, however, a large sediment cloud near the sediment/water interface greatly obscured any potential interactions occurring near the sediment/water interface. Sediment clouds are not only commonly generated by trawl gear, but are thought to be a useful mechanism that helps to further corral fishes towards the mouth of the net and ultimately increase the probability of capture (Winger et al., 2010). These sediment clouds were also present in the video analysis and at times would greatly reduce image clarity. Thus, it is possible that the presence of these sediment clouds could have influenced the perception of fish to the artificially illuminated spectra rope and could explain the lack of difference exhibited between treatment groups.

A simulated dataset was constructed based on observations provided by video and sonar analyses and findings from previous lab studies that assessed halibut behavior. This dataset, while species-specific, is limited in its ability to inform as to how halibut respond in a natural setting. It does, however, demonstrate the usefulness of the constructed ethogram and highlights key behavioral differences between those halibut caught in illuminated tows versus those caught in non-illuminated tows. The goal of this chapter was to better understand how halibut respond to an approaching trawl with illuminated bridles and to consider how quantifiable behavior data could inform the mechanism for facilitating capture avoidance, and the differences among the halibut light studies. I hypothesized that halibut would avoid capture when illumination was present by going over the bridles of the trawl. The constructed ethogram was focused on describing the vertical movements and speed of halibut as they react to an approaching net.

In reality, halibut behavior is unlikely to be confined to just the few parameters in which I defined them. More complex models have been attempted in the past to further exemplify the complicated and chaotic nature of decision-making for a fish as it responds to an approaching trawl (Kim and Wardle, 1998, 2005). The use of such models, however, seemed to go beyond the scope of this thesis. If a comprehensive dataset derived from *in situ* observations was available, the utilization of behavior accumulation curves (BAC) to quantify the completeness of the behavioral repertoire would represent a robust approach to describe the response of halibut to trawl gear by quantifying the number of behaviors observed per interaction event and using an asymptotic model to describe the relationship between the sampling effort and behavioral observations (Dias et al., 2009; Bolgan et al., 2016). The use of this standardized method could then allow for comparison from future studies.

From the simulated dataset, a significant relationship was observed between tow group and locomotion behavior. In lab studies, halibut behavior has been shown to be affected by the amount of ambient light in the environment (Ryer and Barnett, 2006). When light levels are low, halibut are more likely to rise. Notably, a high-rise trawl was utilized for this study as they are now permissible within the 150-fathom contour (NOAA, 2018). Tow speed observed during the field trial portion of the project, returned an average vessel speed over ground when towing the trawl net that ranged from 1.69- 3.75 knots, or 3.13- 6.94 km/hr. Flatfish often rely on cryptic behavior and only react to an approaching trawl once it is less than a few meters away (Bublitz, 1996; Ryer and Barnett, 2006; Ryer, 2008). Unfortunately, video and sonar imagery could not establish this startle distance due to the low image quality and device angle. It is possible that halibut that chose to rise up off of the seafloor when trying to avoid an approaching trawl were unable to do so fast enough to rise over the headrope and were more likely to be captured. Nonetheless, this hypothesis could also explain why illuminated tows were less effective at reducing halibut bycatch than previous studies that utilized low-rise cutback trawls.

For illuminated tows within the simulated dataset, the ‘run’ response was the most prevalent behavior. Halibut have been shown to have a stronger propensity to demonstrate a flight response from a trawl if ambient light levels are relatively high (Ryer and Barnett, 2006). The field trials portion of the project found a significant difference in ambient light conditions between illuminated and non-illuminated tows; however, it is unclear whether the difference between the observed light levels was enough to trigger a change in avoidance behavior in a natural setting. Previous studies have suggested that the contrast between an object and its background may be more important than the brightness of an object (Wardle, 1987; Wardle and Pitcher, 1993). Therefore, the addition of lights could be useful at increasing the contrast between the approaching net and surrounding water to better enable halibut to see the approaching trawler and potentially escape.

The capability of fish to detect a moving image is dependent on its visual acuity, the ability to resolve and see fine details of an object, and the time it takes to mentally process an image (persistence time) (Arimoto et al., 2010). Visual acuity is an attribute that can greatly vary between species and has been shown to increase as a function of fish size (Arimoto, 2010). It is possible that the physiology of halibut, their larger size and perceptive capabilities, would have given them an advantage over other, smaller targeted species when it comes to avoiding approaching trawls. Further investigation into halibut vision and perception is needed.

The study of fish behavior requires an abundance of detail-oriented observations before any inferences can be made. Field trial efforts to gather this level of detailed behavioral information was limited and hindered the ability to quantify halibut avoidance behaviors. From a conceptual standpoint, the use of a constructed ethogram did allow for the development of a framework that is capable of analyzing such behaviors. The application of a simulated dataset highlights the utility of the ethogram when wanting to accurately quantify complex behaviors. The use of such a tool could prove useful for future research.

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3.6. Figures

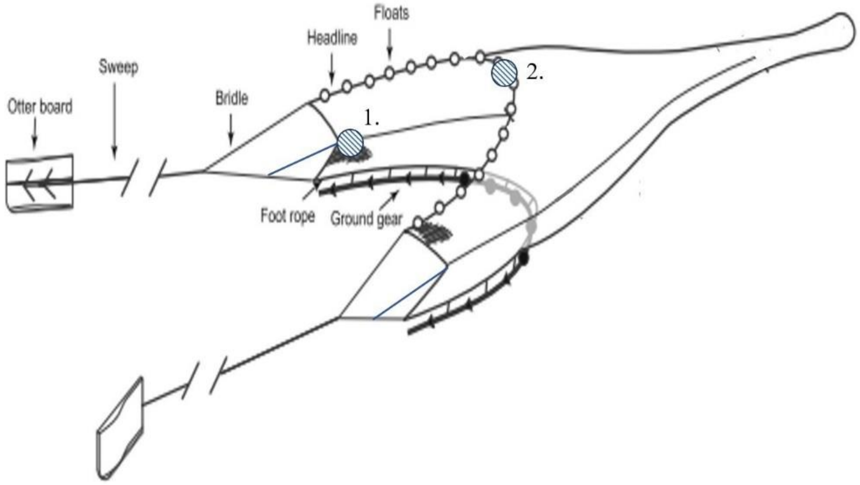

Fig. 1. Locations of video and sonar recording devices (modified from Kennelly and Broadhurst, 2021). Both the GoPro Hero 4 video camera and the Dual-Frequency Identification Sonar (DIDSON) device were initially placed at *Location 1*. The GoPro Hero 4 was at first placed on the inside of the trawl but was later moved to outside of the net and directed towards the spectra rope. The DIDSON device was later moved to *Location 2* and focused on the port wing of the trawl.

Fig. 2. DIDSON (Dual-frequency IDentification SONar) imaging device and apparatus centered on the top panel and focused on the port wing.

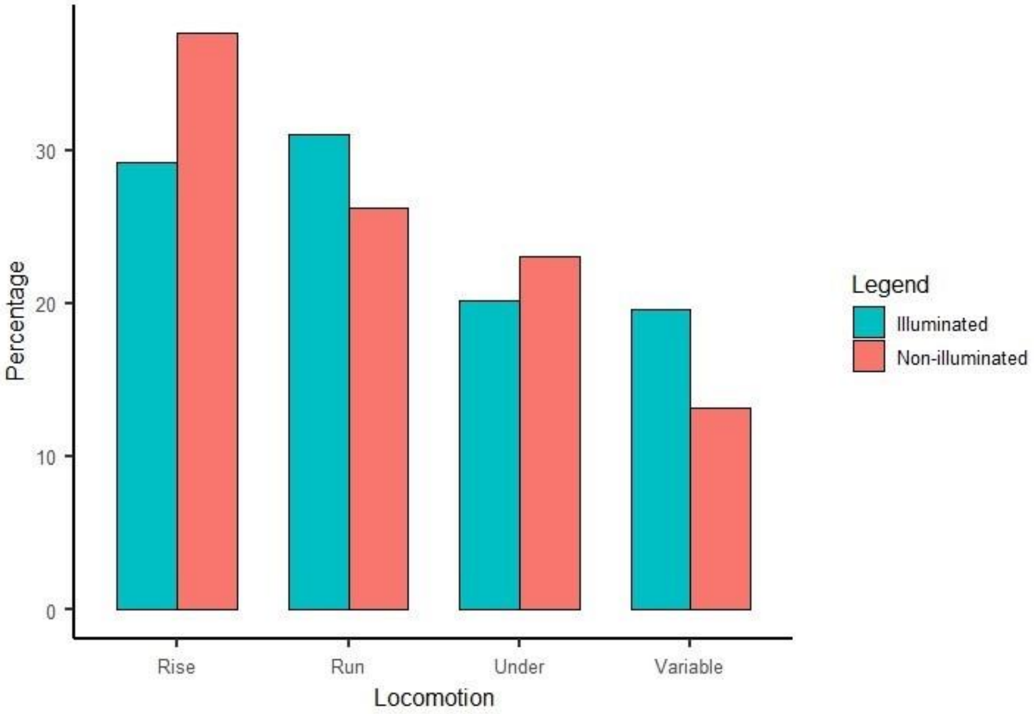

Fig. 3. Percentage of the various **"**Locomotion" behaviors exhibited by halibut that interacted with either an illuminated or non-illuminated tow.

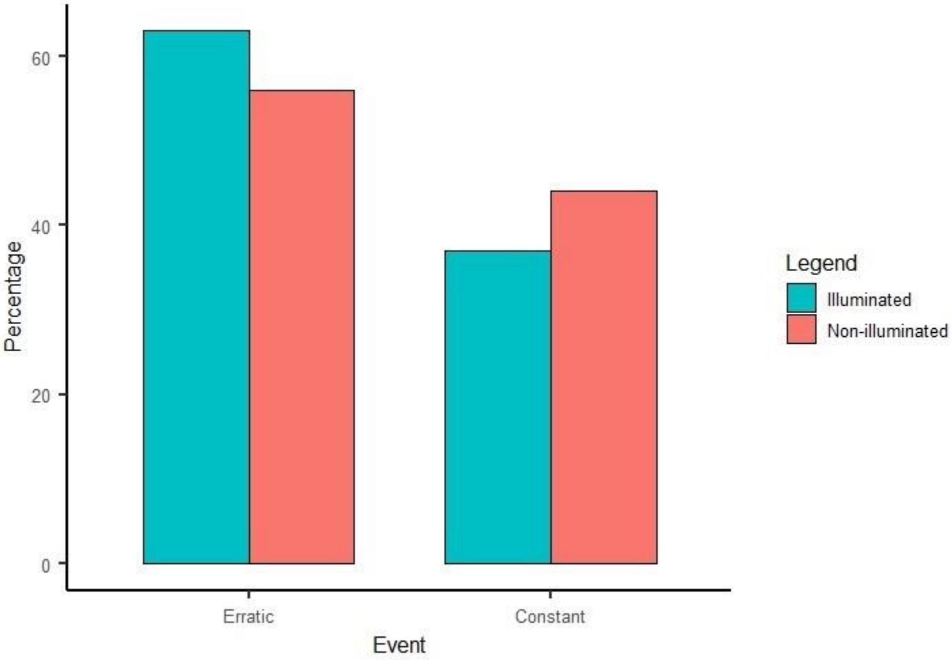

Fig. 4. Percentage of the "Event" behaviors exhibited by halibut that interacted with either an illuminated or non-illuminated tow.

3.7 Tables

Table 1. Ethogram describing the movement of halibut when reacting to an approaching trawl net.

Behavior Category	Behavior Name	Code	Description	Context
Locomotion	Rise	1	Sustained swimming w/ perceived upward movement at least ~1/4 body length of individual	
	Run	2	Sustained swimming w/ no perceived vertical movement	
	Under	3	Sustained swimming w/ perceived downward movement at least ~1/4 body length of individual	
	Variable	4	Sudden vertical movement; changes direction over the course of the observation period	Rapid movements either up or down (> 1/4 body length)
Event	Constant	A	Orientation and swim intensity maintained throughout observation period	
	Erratic	B	Orientation and swim intensity variable over observation period	Sudden changes in orientation (>30 degrees in 1 second) or rapid increase or decrease in body undulations

Table 2. Results from the Chi-squared analyses used to test independence between tow group (illuminated or non-illuminated) and ‘Locomotion’ and ‘Behavior’ behaviors.

Behavior	Chi-squared (χ^2)	Degrees of Freedom	p-value
Locomotion	16.276	3	0.0009955
Event	0.26601	1	0.606

4. Conclusions

Contrary to the initial hypothesis, no statistical significance was detected between the number of halibut caught in illuminated tows and those halibut caught in non-illuminated tows. However, general trends in catch reduction across the suite of species analyzed persist which suggests that the viability for artificial light to serve as a BRD is still plausible. Future studies investigating the behavioral response of halibut to artificial light on trawl bridles is implored. The change in gear configuration for this study, with the headrope now much higher up in the water column when fishing than previously required, may present too much of a challenge for halibut seeking to avoid the approaching net.

Video analysis was ultimately inconclusive. Based on what could be seen from the video review and the findings of previous lab studies, however, it is possible that halibut avoid capture by moving out of the path of trawl far sooner than target species. Furthermore, the physiological advantages halibut possess may allow them to respond to an approaching trawler faster and more consistently than the smaller flatfish species that the fishery is targeting. More research is needed to better understand the visual acuity of halibut and how trawl net modifications can impact the mechanisms that trigger avoidance behaviors.

In order for BRDs to be successful at separating bycatch from target catch, a robust comprehension of the behavior and physiology for the species of interest is paramount. Additionally, working in close partnership with commercial fishers and stakeholder groups can further improve the relationship the scientific community can have with industry and promote future collaborations towards the ultimate goal of achieving sustainable fishing practices. This thesis is part of an ongoing investigation into the potential for artificial illumination to serve as a tool for fishers to use to reduce unwanted bycatch. While findings from this study were statistically insignificant, they do provide valuable information to the industry which can be used for future decision-making and research.

5. Appendix

5.1 SelFisher

5.1.1 Estimating relative catch efficiency between illuminated and non-illuminated tows using SelfFisher

The ‘selfisher’ package in R was used in addition to using SELNET to assess the validity of the results regarding the relative catch efficiency between illuminated and non-illuminated tows for the data set presented in *Section 2.3.1* of this thesis. Like SELNET, SelFisher is designed to analyze fishing gear selectivity data from a number of experimental designs, including: covered codends, paired gear, and catch comparisons (Brooks et al., 2022). The latter was used for this analysis using SelFisher. The two programs use similar equations; however, the free and open-source nature of ‘selfisher’ has allowed it to be more accessible than SELNET and could potentially allow for more user control when analyzing data. SelFisher models the relative retention probability which directly relates to the proportion of fish retained by one gear versus those fish retained by another. The proportion of the total catch expected to be retained and sampled in either gear is expressed as the probability of fish entering the first gear configuration and being retained and sampled divided by the probability of entering, being retained, and sampled in either of the two gear configurations (*see **Equation 1** in Chapter One*). SelFisher, like SELNET, is capable of accounting for subsampling and uncertainty due to between tow variation can be addressed by using the double bootstrap method. All analyses were completed in R (version 4.2.2, R Core Team 2020).

5.1.2 Results and discussion

Similar to SELNET, SelFisher analyses found no statistically significant difference between halibut, petrale sole, and Dover sole caught in either illuminated or non-illuminated tows (**Fig. 1 and 2**). There was, however, a significant difference for sablefish. Similar to Lomeli et al. (2021), smaller-sized sablefish were less likely to be captured in illuminated tows. Yet, the number of sablefish caught at these length classes was far less than any other size. In looking over the data, those size classes only represent a few tows and would potentially be mis-representing the true distribution.

5.2 SELNET paired analysis

5.2.1 Methods

A paired analysis was initially considered for this thesis as it is commonly used in catch comparison studies (Wileman et al., 1996). However, after low catch sizes and fishing days with odd numbers of tows, the data from the illuminated and non-illuminated tows were ultimately pooled into two groups for further analysis. For my paired analysis, I only considered tow pairs that were conducted within close time and proximity of each other and represented both an illuminated and non-illuminated tow. Analysis of these pairs is similar to the methodology described in *Chapter One*. The equations used within SELNET to analyze this data are further defined in Lomeli et al. (2021).

5.2.2 Results and discussion

Overall, I had 18 viable pairs from which I could conduct my analysis. Similar to my pooled analysis, I found no statistically significant differences between petrale sole and Dover sole caught in either illuminated or non-illuminated tows (**Figs. 3 and 4**). I did, however, find a significant difference for halibut and sablefish. Yet, in using this analysis, I removed 16 tows from my original dataset. This would potentially reduce my statistical power. Additionally, fit statistics for this analysis were inferior relative to those generated from the pooled analysis

(**Table 1**). For those reasons, the pooled data configuration rather than use the results from my paired analysis was presented.

5.3 References

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5.4 Figures

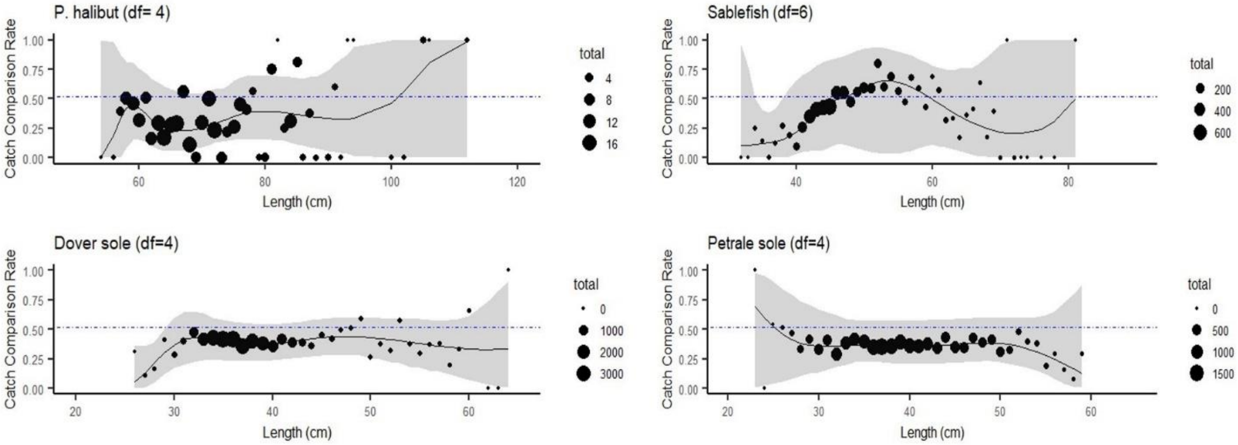

Fig. 1. Mean catch comparison curves between the illuminated and non-illuminated tows from Selfisher analysis. The observed data are represented by the black circles; fitted solid lines are the modeled values; shaded regions are 95% CIs; dotted straight lines depict the baseline catch comparison proportion of 0.52 is indicative of the catch rates between the two trawls.

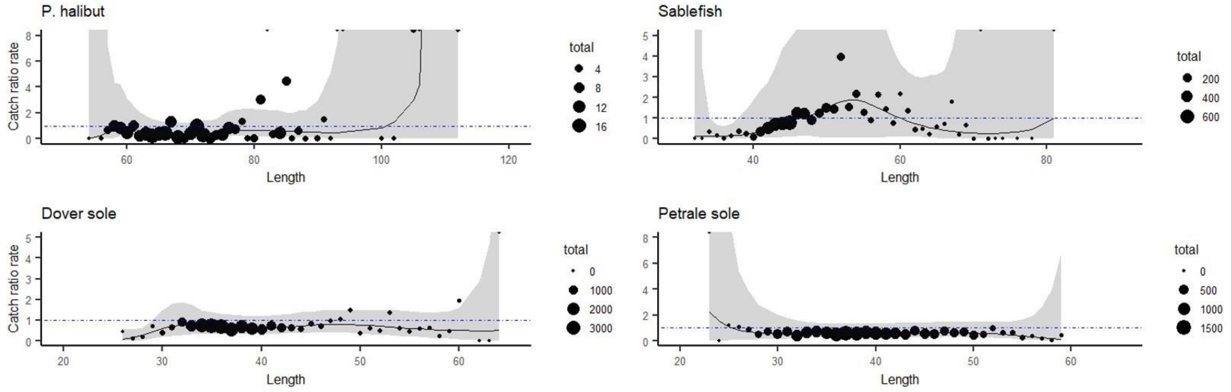

Fig. 2. Mean catch ratio curves between the illuminated and non-illuminated tows from a SelFisher analysis. The modeled values are represented by the solid black line, the shaded regions are 95% CIs, the black circles represent the number of observations for a given length class, and the dotted straight lines depict the baseline catch ratio of 1.0 indicating equal catch efficiencies between the two trawls.

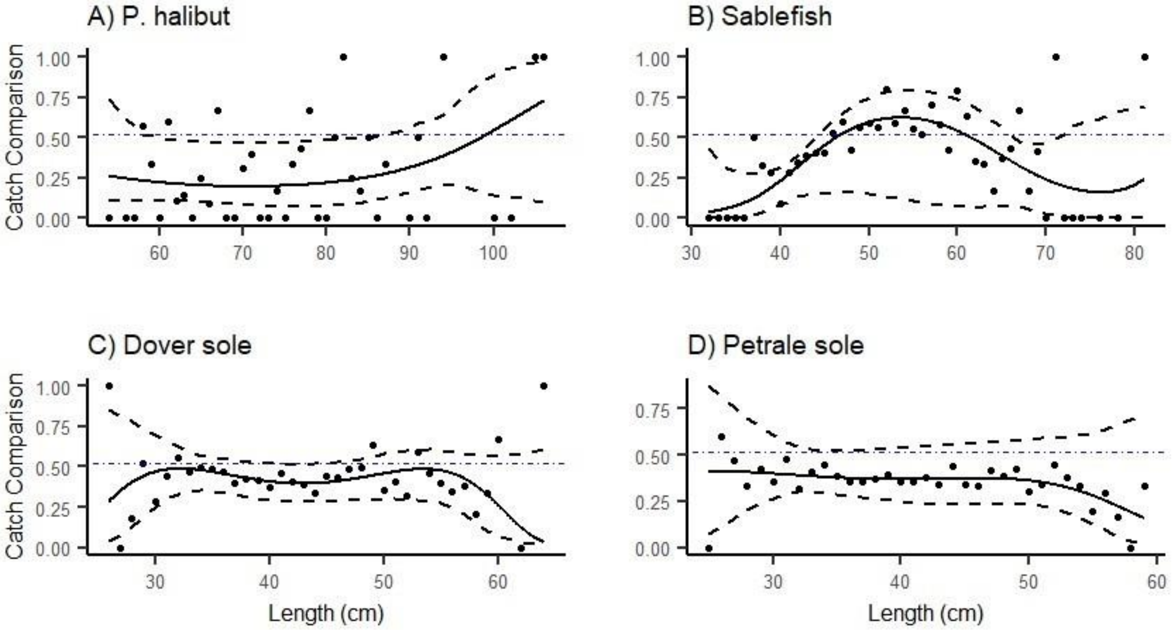

Fig. 3. Mean catch comparison curves between the illuminated and non-illuminated tows for a paired analysis. The observed data are represented by the black circles; fitted solid lines are the modeled values; dashed lines are 95% CIs; dotted straight lines depict the baseline catch comparison proportion of 0.52 indicative of the catch rates between the two trawls.

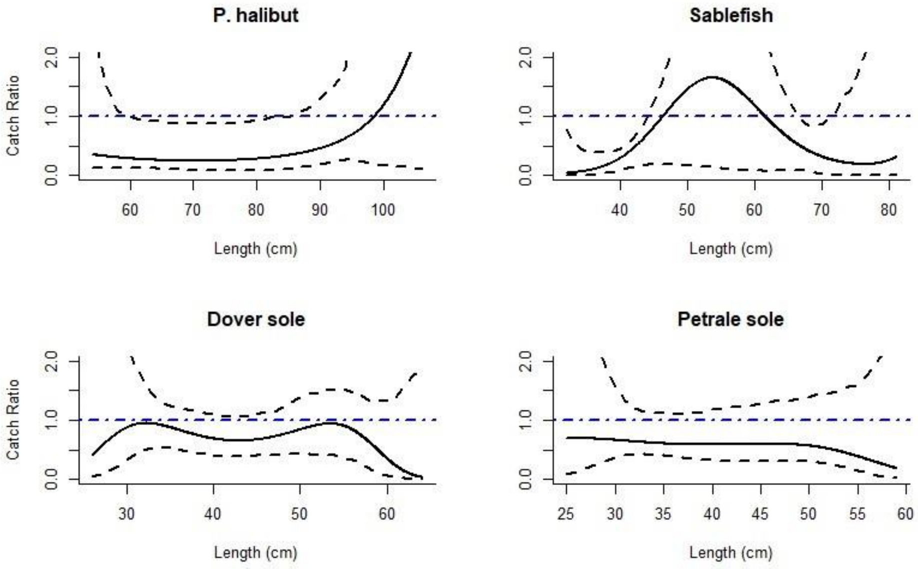

Fig. 4. Mean catch ratio curves between the illuminated and non-illuminated tows for a paired analysis. The modeled values are represented by the solid black line, the dashed lines are 95% CIs, and the dotted straight lines depict the baseline catch ratio of 1.0 indicating equal catch efficiencies between the two trawls.

Table 1. Catch Comparison fit statistics for paired analysis.

	p-value	**Deviance**	**DF**
Halibut	0.0063	60.62	36
Dover Sole	0.0007	63.93	32
Petrale Sole	0.317	33.14	30
Sablefish	0.0248	60.60	41