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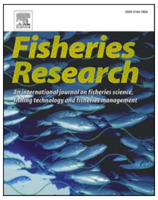

The effects of LED handline attachments on Atlantic cod (*Gadus morhua*) catch efficacy and bycatch

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ABSTRACT

Catch efficacy and bycatch are critical factors that determine the sustainability, practicality, and profitability of fishing gears. Inshore Atlantic cod (*Gadus morhua*) fisheries commonly use gillnets, cod-pots, longlines and handlines. Owing to their efficiency, selectiveness, and low effort, gillnets are the most widely used gear. Gillnets however are prone to bycatch and low-quality catch. Handlines benefit from low capital investment, live high-quality fish, low bycatch, and low carbon footprint. Enhancements to handlines that could increase catch rate or size of catch would be considered beneficial and could promote uptake by harvesters using other gear types. Previous pilot research has shown that LED handline attachments that target the visual sensitivity of cod increased the catch rate of Atlantic cod. The present study builds upon this finding, incorporating three participating commercial crews and vessels. We found no significant effect of LED handline modifications on catch efficacy for Atlantic cod or bycatch. The bycatch of Atlantic wolffish (*Anarhichas lupus*) in our study was found to decrease with the use of green LEDs, but the data precludes complex statistical analysis. We discuss how these findings are relevant to small-scale fishers and provide an empirical reference regarding the use of such devices in the commercial fishery.

1. Introduction

Following the collapse of Atlantic cod (*Gadus morhua*) stocks in eastern Canada, the commercial fishery was closed in 1992 (Hutchings and Myers, 1994). Explanations for the collapse are varied, but it appears overfishing was compounded by biophysical and socio-economic factors (Hutchings and Myers, 1994; Myers et al., 1996; Milich, 1999). A major contributing influence was increasing technological advancement, such as rapid improvements in vessel design, fish-finding capability, and fishing gear technology, including the widespread use of monofilament nylon gillnets (Hutchings and Myers, 1994; Myers et al., 1996; Montgomerie, 2015). Gillnets are prone to bycatch, which is the incidental catch of non-target fish (Shester and Micheli, 2011), corals (Dias et al., 2020), turtles (Alfaro-Shigueto et al., 2018), marine mammals (Reeves et al., 2013), and seabirds (Tasker et al., 2000, 2013; Hedd et al., 2015). Efforts to reduce bycatch have investigated acoustic and visual deterrents and reduced soak times (Melvin et al., 1999; Rouxel et al., 2021) but effective means to reduce bycatch in gillnets remain elusive (Field et al., 2019; Montevecchi et al., 2022). Gillnet removal and gear-switching is a viable and effective option for bycatch mitigation (Northridge, 1991; Regular et al., 2013; Slooten, 2013; O'Keefe et al., 2021). Baited cod pots have proven to be effective in both Canada (Meintzer et al., 2017, 2018) and western Europe (Bryhn et al., 2014; Anders et al., 2017), however uptake has been slow due to higher capital investments required.

Handlining is a traditional fishing practice still used today (Hutchings and Myers, 1994; Montgomerie, 2015), with high quality catch and sustainability compared to gillnets. Handlines eliminate seabird and marine mammal bycatch, however handlines have the potential for low catch rates and undersized fish (Rouxel and Montevecchi, 2018). In the Northwest Atlantic, handlines may infrequently catch wolffish (*Anarhichas* spp.), of which all three species that can occur in the region are Species of Concern (SARA, Committee on the Status of Endangered Wildlife in Canada COSEWIC, 2012).

Artificial light has been used in fishing practices for centuries to exploit the visual capabilities of target species (review by Nguyen and

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Winger, 2018). Modern commercial applications of light in fisheries include squid, shrimp, snow crab, and Atlantic cod (Bryhn et al., 2014; Nguyen et al., 2017; Humborstad et al., 2018; Larsen et al., 2018). Fishes are influenced by the visual environments they inhabit, whereby the habitat light-scape influences the evolution and development of physiological and behavioural characteristics. The visual systems of fishes inhabiting specific pelagic zones have evolved such that visually-driven behaviours maximize the potential use of available light. Marine light environments are relatively constant and predictable, given the absorption of the available ambient light through the water column (Levine and MacNichol, 1982; Mann and Lazier, 1991), so visual ecology can be useful for understanding the interactions of animals and fishing gears (Blackmore et al., 2021), particularly those modified with artificial light devices.

Northern or Atlantic cod (*Gadus morhua*) is a typical benthopelagic fish species that inhabits both demersal and open ocean environments throughout its life (Rose, 2019). Its visual system possesses blue (446 nm) and green (517 nm) sensitive photopigments corresponding to the light availability below 50 m (Anthony and Hawkins, 1983; Douglas and Djamgoz, 1990; Bowmaker, 2008; Valen et al., 2014). Cod's dichromatic visual system provides sensitivity for specific wavelengths of light (colours) to carry more information that is behaviourally relevant (Gerl and Morris, 2008). Utne-Palm et al. (2018) tested the influence of light on both cod and krill, a common prey, with respect to their interactions with light stimuli in a lab setting and found krill to interact with green light sources but found no significant results for the behaviour of cod toward the same lights. Cod interact with passive fishing gear modified with artificial light (Bryhn et al., 2014) and the krill surrounding the gear. Some bycatch reduction studies have shown different behavioural responses of cod to active gears modified with green light (Grimaldo et al., 2018; Melli et al., 2018; Southworth et al., 2020). The behaviour of wild adult Atlantic cod to various wavelengths of light has not been assessed for handline fishing gear.

The economic and cultural significance of cod prioritizes research with the goal of enhancing sustainable gear options for the cod fishery. Handlines modified with a light attachment that is theoretically attractive to Atlantic cod, such that catch rate is increased, could benefit the fishery, and valuable basic knowledge about the species' behavioural traits could be gained. Research on modifications to handlines that target Atlantic cod's visual ecology might also promote a viable gear option with marketable benefits for small-scale inshore fishers and fill important knowledge gaps regarding the applicability of such modifications. Increasing handline catch rates and potentially catch size would be highly economical for handline fishers through a reduction in fuel use (fewer, shorter trips to catch quotas), reductions in bait use, and increased profitability and marketability for sustainably harvested catch.

A recent pilot study in Newfoundland, Canada, investigated the catch rates of handlines modified with green light-emitting diode (herein LED, emittance peak at 520 nm) attachments and obtained promising results that suggested a substantial increase in catch rates of handlines using green LED devices (Blackmore, 2019). An inshore commercial cod stewardship fishery is ongoing in Newfoundland and Labrador, wherein bottom-set gillnets are the primary gear owing to their catch efficiency (Rouxel and Montevecchi, 2018). Handlines are a common gear used in the off-time between setting and hauling gillnets to achieve quotas and are the sole gear type permitted for use in the recreational "food" fishery (Department of Fisheries and Oceans Canada DFO, 2021b: see also Arlinghaus and Cooke, 2009). In order for a paradigm shift to occur in the favoured gear type of the Newfoundland and Labrador cod fishery, a highly efficient, sustainable, and profitable gear type would be required to replace or supplement gillnets. Owing to their high-quality live catch, handlines are the gear of choice to promote widespread gear-switching, and to reduce gillnet fishing effort. The pilot study was performed with small samples in both the recreational and commercial fishery, with various gear types and fishing methods (Blackmore, 2019), thus the present study was designed to assess the same devices in a commercial, standardized setting, to test the effects of green LED attachments on handlines on catch rates, bycatch rates, and size of catch for commercial fishers.

2. Methods and materials

2.1. Study design and procedure

In this study, three commercial fishing vessel owners were contracted to fish with and without handline enhancements. Experimental light treatments were applied to vessels, as opposed to individual lines, where the light catch basin of a line using the LED could influence the catch rate of nearby control lines from the same vessel. This allowed assessment of the effectiveness of LED lights on parameters of fishing efficacy and simulated how the LEDs might be used in practice. For logistical reasons, all lines fishing aboard each vessel either used LED handline attachments or not for the entire trip, and light use was randomized across the season for each vessel. To account for day effect, when possible, multiple vessels fished on the same days. Fishing activities were recorded for 62 days, from 13-Sep-2020–6-Nov-2020 in Motion Bay, Newfoundland and Labrador, Canada (47.466397, −52.695966). Three vessels were selected to participate in the research study by random draw from the Petty Harbour Fishermen's Cooperative (PHFC): RB (three crew members, 10 ×3.5 m vessel), BC (three crew members, 10 ×3.5 m vessel) and DK (two crew members, 6.7 ×2.5 m vessel). The PHFC has banned gillnet fishing in their area, allowing us to test handline fishing applications with crews who could directly implement gear modifications.

Fishing occurred 4–5 days each week, depending on weather and crew schedules, or until the weekly license quota was reached (DFO, 2020a). All fishing was done from an anchored position on berth sites. Each crew fished in different locations within Motion Bay, at depths ranging from 30 to 100 m, with an average daily fishing time of 317 min. Log sheets were filled out on every trip by either on-board researchers (RJB, KW) or the skipper, and included data on the crew and recorder, date, light treatment, number of lines fishing, time spent fishing, total catch weight, and bycatch (number of individuals and species ID, with photos taken and sent to RJB if the recorder was unsure). On return to port and while fishers were filleting and processing their catch, the length and weight of a subsample of the catch (approximately 50 haphazardly selected individuals) was recorded. Lengths were measured as total length using a ribbon tape, in centimetres rounded to the nearest cm. Weights were measured using a Pesola spring scale in kilograms, rounded to the nearest 0.1 kg. The weight of Atlantic cod varies with length at a predictable allometric growth relationship (Árnason et al., 2009), and thus the results of weight measurements could be considered redundant for presentation alongside length, but we chose to include all analyses, with weight being the more relevant measurement to fishers. Researchers attended different vessels each day, fishing with the crew, overseeing the crews' fishing methods and participation in the study, as well as training the skippers to fill out log sheets. For applicability to the inshore commercial fishery, no variables were altered with regard to the fishing practices of the participant crews, such that data recorded on days without using lights represented a true control for "normal" fishing.

Experiments were performed with approval from the Memorial University of Newfoundland Animal Care Committee under Animal Use Protocol 20181915.

2.2. Fishing gear and devices

All three crews fished using the same gear: traditional handlines consisting of a 200 lb-test fishing line with an 8–10 oz lead weight and #12 hook, baited with capelin, mackerel, herring, or squid (configuration shown in Fig. 1a). Each crew member fished with 2 lines each, totaling 4 or 6 lines per vessel, unless a researcher was aboard the vessel

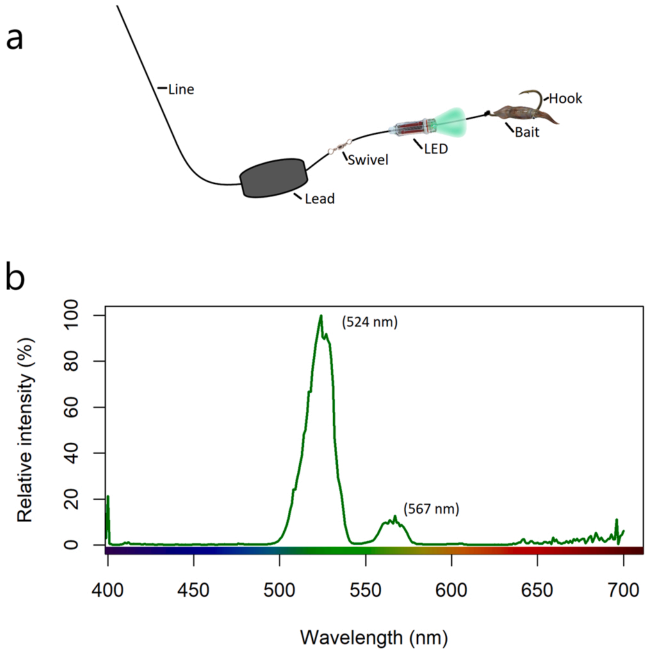

Fig. 1. (a) Experimental handline configuration showing the position of the LED attachment on the line, and (b) the light profile of the LED as measured by spectrophotometry, showing its peak relative intensity at 524 nm (maximum intensity set to 100%).

in which case 5 or 7 lines were deployed. The LEDs used were ProGlow UltraBright LEDs (FishTek Marine, Devon, U.K.), which were attached directly to the line between the hook and swivel and have an automatic submersion switch that emits green light peaking at 524 nm when in contact with water (emission profile shown in Fig. 1b). Throughout the experiment, one device stopped working and was replaced. The light emission profile for LED devices was measured before experimentation began using a Jaz® spectrophotometer (OceanInsight, Orlando, U.S.A.) fitted with a cosine-corrected optic fibre (CC-3-UV, Ocean Insight) in scope mode. Six LEDs were measured at full battery, positioned 1 m from the cosine corrector, with an integration time of 200 ms.

2.3. Statistical analysis

We tested the influence of LED handline attachments on Catch Rate (kg/hr/line), Bycatch Rate (organisms/hr/line), Catch Weight (kg), and Catch Length (cm). To determine the factors influencing the dependent variables we performed generalized linear mixed model (GLMM) analyses that included ‘Light treatment’ and ‘Fisher’ as fixed factors, and ‘Fishing date’ as a random factor. The Total Catch model was fitted using a negative binomial distribution, and Bycatch Rate data were normal and fitted using a Gaussian distribution model. Catch Length and Catch Weight data were log-transformed prior to analysis and subsequent models were fitted using a Gaussian distribution. Degrees of freedom were calculated from the GLMMs and residuals were checked for homogeneity and independence, then fitted to Q-Q plots to check normality. All model assumptions were evaluated using the DHARMa package and assigned a model distribution that best fit the residuals. Models were compared using AIC (Akaike, 1974), using the *anova* function in the car package (Fox and Weisberg, 2019). Cook’s distances were plotted to identify any outliers, and any values above a precalculated maximum acceptable value $(4/(n-k-1))$, where $n =$ sample size and $k =$ number of parameters in the model, were flagged. Analyses were performed with and without flagged outliers, and the outliers were kept in the presented data if the interpretation of the subsequent results remained unchanged. When applicable, post hoc Tukey’s contrasts tests were performed using the “multcomp” package in R (R Development Core Team, 2017). All statistical analyses were performed, and all plots were produced, using R statistical software (R Development Core Team, 2017).

2.4. Size selectivity analysis

Atlantic cod length data were analyzed using the unpaired method in the selfisher package (Brooks et al., 2022). Relative retention probability between both treatments was modelled as a function of length class (per cm). Logistic generalized linear models (GLMs) were used to fit the expected proportions of Atlantic cod caught with and without lights using a binomial error. Flexible models were fit by maximum likelihood of proportions retained, including low order polynomials (degree 0–4) and splines (3–5 degrees of freedom; using the *ns* function in the splines package (Bates et al., 2011)). The model was scaled up to incorporate the subsampling ratio. The best model was considered to have the lowest AIC (Akaike, 1974), using the function *AICtab* in the bbmle package (Bolker, 2017). If retention was 0.5 at a given length class, then there was no difference in catch between treatments at that particular length class. If retention was 0.75, then 75 % of Atlantic cod at the given length class was captured by fishers using lights and 25 % by fishers not using lights. Confidence intervals (CIs) for the model were generated with the *bootSel* function in selfisher, and 1000 bootstrap simulations were used to generate 95 % CIs that account for within and between trip variation (Millar, 1993). Retention was considered significantly different between treatments if 0.5 was not contained within the CIs.

3. Results

To determine the effect of LEDs on catch parameters, the experimental treatment was randomized across the season with lights used $n = 33$ days and control $n = 29$ days. Partitioned by crew: $n = 15$ lights, $n = 9$ control for BC; $n = 4$ lights, $n = 10$ control for DK; and $n = 14$ lights, $n = 10$ control for RB. Due to human error and insufficient data, some fishing days had to be discounted from the analyses. A complete description of the number of replicates for each variable tested is in Table 1.

Table 1 Summary of replicates performed for tests of catch efficacy variables in the Newfoundland inshore cod fishery.

3.1. Catch rate

The influence of lights and fisher on catch rate was investigated using a negative binomial GLMM and showed that the mean catch rate of lines using lights was 14.65 kg/hr/line, whereas the mean catch rate of lines without lights was 17.69 kg/hr/line ($p = 0.0839$; Fig. 2). The influence of fisher on catch rate was not statistically significant at our predetermined $\alpha = 5\%$ ($p = 0.0683$), however it was less than 10 %, so a post hoc Tukey’s contrasts test was performed to identify if harvesters had significant differences in catch rate. BC and DK had increased catch rates when using LEDs, whereas RB showed a decrease and was shown to be statistically significant ($p = 0.00479$) (Fig. 2). The results were qualitatively the same with and without a possible outlier ($x = 38.90$ kg/hr/line), which therefore remains in the analysis.

3.2. Bycatch rate

The GLMM investigating the influence of lights on bycatch rate showed that the mean bycatch rate for lines with lights was 0.113 ± 0.088 organisms/hr/line, whereas the mean bycatch rate for lines without lights was 0.115 ± 0.086 organisms/hr/line ($p = 0.4577$; Fig. 3). Fisher had no significant effect on rate of bycatch between conditions ($p = 0.427$). Table 2 shows a complete list of bycatch occurrences. One outlier remains in the analysis; its removal quantitatively changed the mean bycatch rate for lines with lights but qualitatively changes nothing with regards to the statistical significance or

Table 1
Summary of the effects of catch efficacy variables in the Newfoundland inshore cod fishery.

Variable	Replicates of experimental treatment		Average value	Factor	χ^2	df	p
Catch Rate	Light	21	14.65 kg/hr/line	Lights	2.9874	1	0.0839
N = 46	Control	25	17.69 kg/hr/line	Fisher	7.1145	3	0.0683
Bycatch Rate	Light	22	0.141 ± 0.154 organisms/hr/line	Lights	0.5515	1	0.4577
N = 47	Control	25	0.115 ± 0.086 organisms/hr/line	Fisher	2.7791	3	0.4270
Catch Length	Light	478	56.05 ± 9.37 cm	Lights	0.0088	1	0.9254
N = 767	Control	289	55.93 ± 8.61 cm	Fisher	15.0122	3	0.0005 *
Catch Weight	Light	478	2.16 ± 0.38 kg	Lights	0.3243	1	0.5690
N = 767	Control	289	2.23 ± 0.58 kg	Fisher	6.1532	3	0.1044

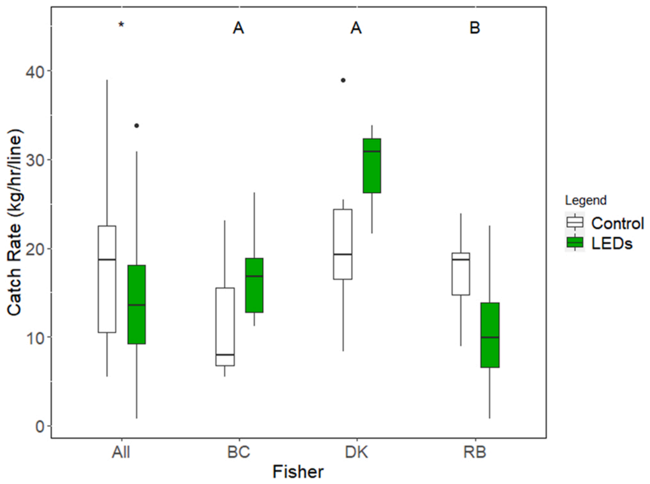

Fig. 2. The effect of green LED handline attachments on catch rates (kg/hr/line) of Petty Harbour inshore fishers (n = 25 days control, 21 days using LEDs). Results of the Tukey's contrast test for multiple comparisons of means are shown as annotated labels, where * denotes the significance of the overall results, A denotes non-significant individual results and B denotes statistically significant individual results (α = 5 %).

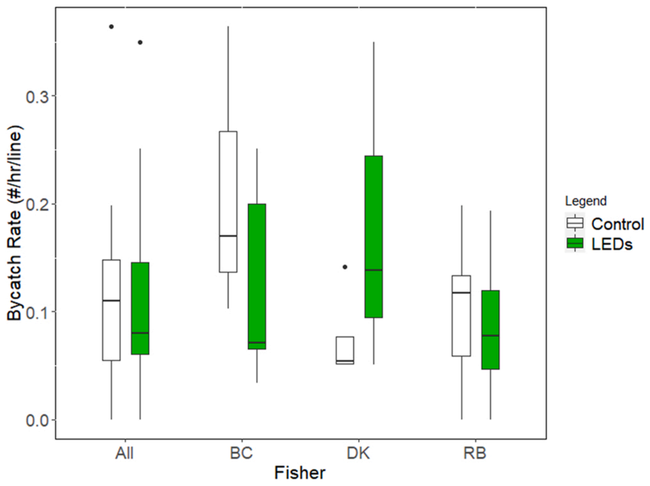

Fig. 3. The effect of LED handline attachments on bycatch rate for Petty Harbour inshore fishers (n = 25 days control, 22 days using LEDs).

interpretation of subsequent results, justifying its inclusion.

The only wolffish bycatch throughout the study was *A. lupus*, which was caught 20 times (Table 2). Fourteen instances of *A. lupus* bycatch occurred when lights were not used (control), whereas six occurred when lights were used (experimental). This sample size precludes complex statistical modelling, but running a binomial test for the cumulative probability of the control lines catching 14 wolffish of the total 20 ($Pr{=}X \geq x$) returns a likelihood of $p = 0.057$ for that outcome. This signifies that this outcome is unlikely due to chance alone, and that the light condition of experimental lines may have influenced the catch of wolffish.

Table 2
List of all bycatch species encountered and the number of occurrences throughout the study (X denotes that encounters with this species were not quantified).

Species name	Occurrences
Shorthorn Sculpin – *Myoxocephalus scorpius*	149
Longhorn Sculpin – *Myoxocephalus octodecemspinosus*	5
Atlantic Wolffish – *Anarhichas lupus*	20
Winter Flounder – *Pseudopleuronectes americanus*	2
Blue Shark – *Prionace glauca*	1
Atlantic Lyre Crab – *Hyas araneus/alutaceus*	2
Northern Basket Star – *Gorgonocephalus arcticus*	5
Daisy Brittle Star – *Ophiopholis aculeata*	3
Spiny Sunstar – *Crossaster papposus*	1
Green Sea Urchin – *Strongylocentrotus droebachiensis*	1
Sea Strawberry – *Gersemia rubiformis*	2
Ascidia sp.	1
Irish Moss – *Chondrus crispus*	X
Various epibionts, such as isopods, copepods, etc	X

3.3. Catch length

To investigate the effects of lights on catch length of Atlantic Cod, a Gaussian GLMM was used and showed that overall, the average length of catch using lights was 55.93 ± 8.61 cm, whereas the average catch length without lights was 56.05 ± 9.37 cm ($p = 0.9254$, Fig. 4). The influence of fisher on catch length was statistically significant ($p < 0.001$).

A size selectivity analysis on the catch length data was performed

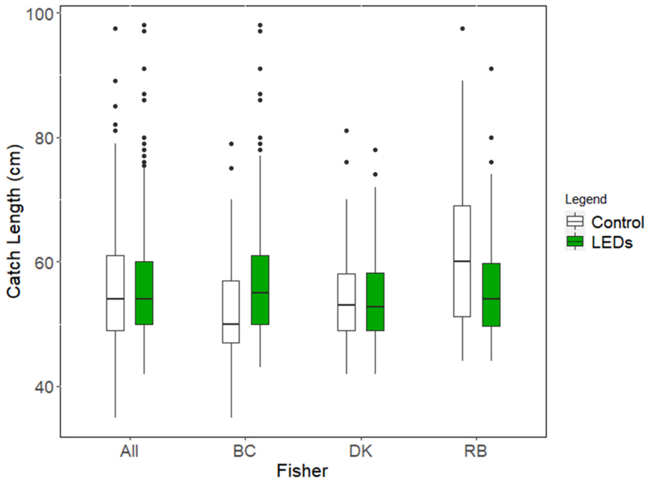

Fig. 4. The effect of LED handline attachments on catch length (cm) for Petty Harbour inshore fishers (n = 289 control, 478 LEDs).

using a spline model with three degrees of freedom. The analysis showed that confidence intervals at every length class included 0.5 proportion (Fig. 5), indicating no significant difference in size selectivity for handlines with or without green LEDs.

3.4. Catch weight

The GLMM investigating the influence of lights on catch weight showed that the mean catch weight for lines using lights was 2.16 ± 0.38 kg, whereas the mean catch weight of lines without lights was 2.23 ± 0.58 kg ($p = 0.569$; Fig. 6). The influence of fisher on catch weight was not statistically significant ($p = 0.1044$).

4. Discussion

Our results showed no significant difference in the catch rate, bycatch rate, or average weight or length of catch between days fished with or without green LED handline attachments (Figs. 2–4 and 6, respectively). This information is important to rural commercial fisheries, as the harmful effects of gillnets such as frequent bycatch and poor-quality catch are well-known and frustrating to small-scale harvesters (Rouxel and Montevecchi, 2018). A gear enhancement that could increase the CPUE of sustainable gear alternatives would be useful to many rural commercial fishers seeking more sustainable fishing methods. Non-significant results like these indicate that the investment in this particular gear attachment, which is available in marine supplies stores locally for ~$7.50, may not be worthwhile for those using handlines or those considering switching gears. These results contrast with those of a pilot study which showed that catch rates of individual lines using green LEDs effectively doubled when compared to handlines that fished simultaneously without lights (Blackmore, 2019). By using a more rigid study design with a much larger sample size, we are confident that the null effect reported in this study are reflective of the lack of effect that these LEDs have on catch parameters.

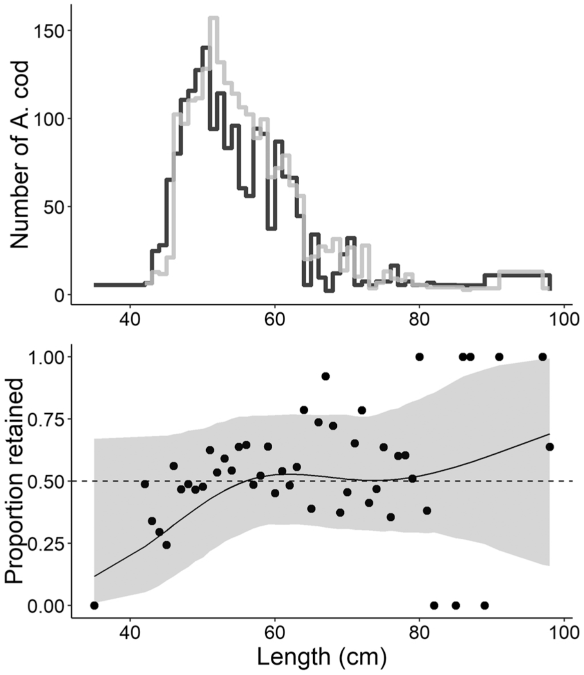

Fig. 5. Size selectivity analysis of modified handlines. At each length class, the frequency of individuals caught is shown in black for control and grey for experimental treatments. Retention probability for the experimental treatment is calculated from 0 to 1 such that 1.00 indicates a 100 % probability of catch by LED-modified handlines, 0.00 indicates a 0 % probability of catch by LED-modified handlines (100 % probability of catch by unmodified gear), and 50 % indicates an equal probability of catch for both gears, at a given catch length-class. Confidence intervals are shown by the shaded area, with the trendline as a solid black line-of-best-fit.

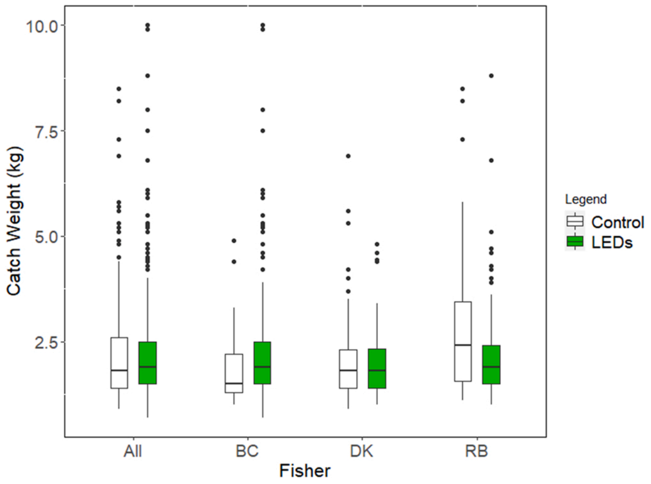

Fig. 6. The effect of LED handline attachments on catch weight (kg) for Petty Harbour inshore fishers (n = 289 control, 478 LEDs).

Targeting the visual ecology of Atlantic cod, we designed our study using green LED handline attachments as a tool for enhancing handline CPUE. The use of light in bycatch research has focused on artificial light devices to deter the species of concern from fishing gear (Ortiz et al., 2016; Field et al., 2019; Darquea et al., 2020), or to a portion of the gear that has been modified to release incidentally-caught individuals (Larsen et al., 2018; Grimaldo et al., 2018; Melli et al., 2018; Southworth et al., 2020). This method of bycatch reduction has been quite successful for some species in some fisheries, but variable and often with harmful side-effects such as diminished target-catch yields in others (Montevecchi et al., 2022). Instead of trying to balance a reduction in non-target catch while attempting to maintain or augment target catch, we opted to rethink the use of light in our study. By choosing to modify traditional handline gear with low bycatch potential, we were able to target a species' visual system while monitoring the LED's effect on bycatch frequency. Our study design incorporated the fishing practices of commercial fishers who fish exclusively with handlines to ensure that the methods were consistent with practices already in place. A major strength in this design and working with this group of harvesters was that the results were not hindered by the design in terms of their applicability and could be immediately implemented and relevant to the demographic who might incorporate the results of our study into their daily fishing practices. In short, the control for this study was no different than the standard fishing practices of the commercial harvesters with whom we worked. The LED attachment was the only altered variable during normal fishing activities, and any resulting differences in CPUE will inform harvester's decision on gear choices in the future.

We recognize inherent limitations in our experimental design. Foremost, the 2020 fishing season in Motion Bay was widely regarded as one of the most anomalous fishing seasons by members of the Petty Harbour Fishermen's Cooperative. This was based on many reports by local harvesters returning to port with low catch, sometimes fishing for 6 + hours and returning with only a few fish as compared to the hundreds of pounds of catch that would normally be expected. Fisheries and Oceans Canada (DFO) reported the lowest total catch of Atlantic cod for inshore vessels across Newfoundland and Labrador in 2020 compared to the previous five years (Department of Fisheries and Oceans Canada DFO, 2021c). This situation was beyond our control when designing our study, as the variability of fish available in the region can fluctuate widely due to a myriad of factors. Fishing location and depth was meant to be consistent within fisher, but slight variations in fishing effort at each berth caused fishing depth to change drastically, an oversight by the participating crews that was not relayed to researchers until after data collection had been completed. We acknowledge this as a flaw of our study and opted to not include fishing depth as a factor in our analyses. Daily variation in factors such as water current in the fishing location, and sea surface temperature affect the local dispersal of cod, particularly throughout the water column (Freitas et al., 2015; Staveley et al., 2019). Other environmental factors like prey dispersal and availability across the season are also likely drivers of the dispersal of Atlantic cod in the area (Tamdrari et al., 2012). Other factors, including overfishing and climate change would drastically impact the stock size for inshore cod across years. These factors likely affected the results and their interpretation by producing considerable variation in the data. Nevertheless, our results mirror findings from cod behavioural studies using light (Utne-Palm et al., 2018).

Though quantifiably lower than many other gear types, handlines nonetheless produce bycatch of non-targeted groundfish species. The effects of light modifications to gear for enhancing the catch of target species likely also produce similar effects in non-target species. Of concern in the Atlantic cod fishery is the Atlantic wolffish (*Anarhichas lupus)*, an endangered species in the Eastern Atlantic (Helsinki Commission (HELCOM), 2013). In Canada, all four *Anarhichas* species are possible bycatch in groundfish fisheries and are listed as Species of Concern by the Species at Risk Act (SARA, Committee on the Status of Endangered Wildlife in Canada COSEWIC, 2012). In our trials, only *A. lupus* was caught incidentally, and it was the second-most frequently caught bycatch species throughout the study (Table 2). Interestingly, wolffish were caught 14 times by control handlines, and less than half as often (n=6) by handlines using green LEDs. This sample size is quite low but suggests a potential use of LEDs for reducing bycatch of this species of concern and warrants further research on the deterrence capability of LEDs with regards to wolffish behaviour. Since the target catch parameters of lines with and without green LED attachments were effectively unaltered, the use of LEDs as a bycatch reduction technology for wolffish is intriguing. A handline fishery would allow for bycaught wolffish to be returned to the ocean alive and hopefully sustaining minimal injury (as mandated in the Canadian Fisheries Act; Department of Fisheries and Oceans Canada DFO, 2021a). Wolffish bycatch in a gillnet is likely to be moribund or dead, therefore the possibility of deterrence using LEDs carries conservation implications with respect to various gear types. The visual sensitivities of adult Atlantic wolffish may differ from that of Atlantic cod, due to their sedentary lifestyle and feeding habits, and thus minute differences in sensitivity could be important in assessing the potential effectiveness of LEDs on deterring wolffish from fishing gears that target Atlantic cod.

We were unable to record the occurrence of undersized (< 40 cm total-length) cod catch due to limitations with data collection and logistical constraints, but this should be included as non-target catch and considered bycatch. The spectral sensitivity and genotypic expression of photopigments changes ontogenetically throughout the lifespan of Atlantic cod (Valen et al., 2014), therefore it is important to record undersized catch in studies testing visual gear modifications in the future. An effect of LEDs on the catch of undersized cod would be important information to small-scale harvesters, as current fishery regulations prohibit the retention of undersized groundfish catch. Discarding catch wastes time, effort, and bait, and encourages large apex predators such as Atlantic bluefin tuna (*Thunnus thynnus*), sharks, and seabirds to congregate in areas of high fishing activity (Montevecchi, 2022). Groundfish are not a common natural prey item of pelagic predators such as tuna (National Oceanic and Atmospheric Administration NOAA, 2021), thus their predation of cod via fishery discards introduces a potential novel threat to the fish stock. More importantly however, large predators pose a dangerous risk to fishers if they become entangled or caught by the gear. The effect of LED attachments on handline fishing effort with respect to catch weight also informs fishery management, as the most sustainable fishing practice for exerting pressure on a threatened stock like Atlantic cod is to target the mid-range ages and sizes of biomass (Myers et al., 1997; Darby, 2019). Undersized catches are often outside this target age and size, and do not form part of the super spawning stock biomass (SSSB). New technology capable of improving size-selectivity to the centre of biomass of target catch, while decreasing rate of catch of non-target juveniles, has conservation implications for the target species, particularly on a large scale with regards to international fisheries discards policies.

In conclusion, though statistically non-significant, the findings of this study are important for cod fisheries and research. Continuation of this research across multiple years would help account for the variation in fish availability within commercial seasons, which is the greatest limitation to the current study. The study is informative with respect to how visual ecology can be used as a tool in fishing practices and research. We encourage the continued study of visual modifications to fishing gears, especially methods that consider the sensory ecology of the target species. Future research into the sensory ecology of Atlantic cod and their behaviour will inform and shape the choice of devices deployed both in industrial and fisheries research applications. Researchers who work with gear technology in small-scale fisheries need to consider the applicability of their research to the fishery during the design phase of the study (Blackmore et al., 2021). Testing gear designs before application to industry and focusing on gear likely to be incorporated into fishing practices will benefit researchers and fishers alike.

CRediT authorship contribution statement

Robert J. Blackmore: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Funding acquisition. **Paul D. Winger:** Writing – review & editing, Project administration, Funding acquisition. **Pierre-Paul Bitton:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition. **Shannon Bayse:** Validation, Formal analysis, Visualization. **Kira Whittaker:** Investigation. **William A. Montevecchi:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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