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Artificial lights improve the catchability of snow crab (*Chionoecetes opilio*) traps

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ABSTRACT

This study investigated the behaviour and commercial catchability of snow crab (*Chionoecetes opilio*) in response to different low-powered LED lights under laboratory and field conditions. We created a novel choice-experiment in a laboratory setting in which we investigated the behaviour of snow crab in response to coloured LED lights. The results showed that snow crab movement was dependent on light colour, with animals choosing to move toward blue and white lights, away from purple lights, and no detectable effect for green and red lights. We then conducted two field experiments to investigate the effect of the same LED lights on the catch rates of commercial traps during the 2016 snow crab fishery on the east coast of Newfoundland and Labrador. Results from the first field experiment showed that adding white and purple LED lights into baited traps significantly improved Catch Per Unit Effort (CPUE) by 77% and 47% respectively. Results from the second field experiment showed that unbaited traps equipped with only LED lights (no bait), could also catch snow crab in comparable amounts to traditional baited traps, with soak time and depth explaining some of the variation in CPUE. Taken together, these experiments suggest that fishing enterprises can improve their catching performance and profitability by adding LED lights to their traps, or by using LED lights as a bait replacement.

1. Introduction

The snow crab *(Chionoecetes opilio)* fishery in Newfoundland and Labrador (Canada) began in 1968 (Dawe et al., 2002). A Total Allowable Catch (TAC) and quota allocation management system was applied by the late 1980s (DFO, 2016a). Since 1973, regulating the minimum legal landing size to >95 mm carapace width (CW) and excluding the capture of females has provided an effective precautionary approach to fisheries management (Conan & Comeau, 1986; Dawe & Mullowney, 2016). By the early 1990s, snow crab had become a very important commercial fishery and a major economic contributor to Canada's most eastern province. Landings in 2015 were 47,310 metric tons accounting for CAD $258 million in landed value, representing more than 50% of landed value of finfish and shellfish combined in Newfoundland and Labrador (DFA, 2015, p. 34). However, the current snow crab resource has shown signs of population decline, leading to a reduction in the Total Allowable Catch (TAC) in recent years, including an overall quota level decrease of approximately 13% from 2015 to 2016 (DFO, 2016a). The fishing season typically starts in early April and is completed by the end of August (DFO., 2009). There were approximately 2600 fishing licenses (DFO, 2016a), sharing a TAC of 43,802 tonnes of snow crab in 2016 (DFO., 2016b). The small Japanese-style conical trap is the only legal gear type, with a minimum mesh bar length of 65 mm or minimum mesh size of 135 mm (DFO, 2016a).

Given the important contribution of snow crab to the economy of eastern Canada, a substantial number of studies have been conducted during the past few decades on its capture and selectivity. Underwater video of snow crab behaviour around baited traps has contributed much to the understanding of the capture process (see Chiasson et al., 1993; Vienneau, Paulin, & Moriyasu, 1993; Winger & Walsh, 2011). Several technical measures and operational methods have been evaluated over a number of studies to improve trap selectivity and performance, including variations in trap shape, mesh size, plastic barriers, escape mechanisms, biodegradable twine, bait choice, and soak time (e.g. Atkins, Hearn, & Dawe, 2002; Chiasson et al., 1993; Coulombe & Beaulieu, 1987;

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Grant & Hiscock, 2009; Hébert, Miron, Moriyasu, Vienneau, & DeGrâce, 2001; Vienneau et al., 1993; Winger & Walsh, 2007, 2011; Grant & Hiscock, 2009; Winger, Legge, Batten, & Bishop, 2015).

Using light as a stimulus to attract and accumulate fish has existed for thousands of years, ranging from simple torches to sophisticated artificial illumination systems using multiple vessels (Breen & Lerner, 2013), including application both overwater and underwater (e.g. An, 2013; Bryhn, Königson, Lunneryd, & Bergenius, 2014; Ortiz et al., 2016). Given the often dark and murky nature of the underwater environment, the introduction of light as a stimulus can have forthright and profound effects on the behaviour of aquatic animals (Breen & Lerner, 2013). Historically, purse seines, stick held lift nets, squid jigging, and drop nets were the major fishing methods using light (e.g. Breen & Lerner, 2013; Matsushita & Yamashita, 2012; Matsushita, Azuno, & Yamashita, 2012; Yamashita, Matsushita, & Azuno, 2012). However, the use of light has now spread to other fishing methods and greater depths, including: traps, pots, trawls, longlines and gillnets for improving the catchability of target species as well as reducing the bycatch of non-target species (e.g. Bryhn et al., 2014; Hannah, Lomeli, & Jones, 2015; Ortiz et al., 2016; Wang, Boles, Higgins, & Lohmann, 2007). Advances in fishing technology including the application of Light Emitting Diode (LED) lights, that last longer are more efficient and have better chromatic performance than other lights, (e.g. An, 2013; Breen & Lerner, 2013; Bryhn et al., 2014; Kroger, 2013; Matsushita & Yamashita, 2012; Matsushita et al., 2012; Nguyen & Tran, 2015; Yamashita et al., 2012), is an important contribution towards improving modern fisheries which face increasing demand, higher harvesting costs, and a responsibillity to ensure ecologically responsible methodologies.

To our knowledge, there has been no scientific investigation on the behaviour of snow crabs in response to coloured artificial lights and its relevance to fisheries applications. The only piece of incidental information came from a study by Murphy (2014, p. 140) during the development of baited traps for flatfish. The study accidentally discovered that unbaited traps equipped with an LED light captured occasional snow crab as bycatch. This was the first evidence that underwater LED lights might be an effective stimulus for capturing snow crab.

The purpose of this study was to investigate the behaviour and commercial catchability of snow crab in response to LED lights under laboratory and field conditions. In our laboratory experiment, we created a novel choice-experiment in a controlled tank environment (similar to Y-maze or T-maze experiments in fish, king crab, blue crab, green crab and mud crab) (e.g. Olsén, 1985; Ryback, 1969; Truong, 2008, p. 204; Zhou & Shirley, 1997). We gave individual snow crab the opportunity to choose to move toward or away from LED lights of different colour. We then conducted two field experiments to investigate the effect of LED lights on the catch rates of traps during the 2016 commercial snow crab fishery. In our first field experiment, we tested the effect of adding LED light to baited traps to evaluate the effects on Catch Per Unit Effort (CPUE). In our second field experiment, we tested the effect of adding LED lights to unbaited traps to determine the likelihood of catching snow crab with only light as the stimulus (i.e. no bait).

2. Materials and methods

2.1. LED lights

Lindgren-Pitman LED Electralume® fishing lights were used in both laboratory and field experiments, which had a forward voltage of 3.2 V, luminous intensity of 4.7 cd, forward current of 35 mA, and power dissipation of 124 mW. The lights had an operating temperature range of −30 to 85 °C, a maximum operating depth of 850 m (1270 psi), and a battery life of approximately 300–500 consecutive hours, depending on the type of AA battery used as a power source.

Five colours of lights were purchased and used in this study: blue, green, purple, red, and white. We evaluated the distribution of spectral wavelengths emitted from each light using a benchtop spectroflourometer. The steady-state luminescence spectra were acquired using a Photon Technologies International (PTI) Quanta-Master 6000 spectroflourometer, with wavelength selection provided by a Czerny-Turner f/3.4 grating monochromator. Luminescence was detected by a Hamamatsu R-928 five-stage photomultiplier tube (PMT) in photon-counting mode contained within a PTI Model 814 PMT housing, which in turn was enclosed in a Products for Research S600 PHOTOCOOL Peltier cooling device to minimize contributions from dark current spectral artifacts. Peak wavelengths were 464 nm for blue lights, 519 nm for green lights, 446 nm for purple lights, 632 nm for red lights, and 456 nm for white lights (Fig. 1).

2.2. Laboratory experiment

2.2.1. Snow crab

Snow crab were collected approximately 360 km southeast of Newfoundland from the Lilly and Carson Canyons in September 2015 by using baited traps deployed at an ocean depth of 150 m. The crabs were transported to holding facilities at the Northwest Atlantic Fisheries Centre, located in St. John's, Newfoundland, and held in circular holding tanks (1.25 m diameter, 0.8 m high) with water temperature controlled between 0.8 to 1.7 °C and salinity near 30‰. Crabs were fed chopped herring or squid *ad libitum* three times a week. All crabs used in the experiment were hard-shelled legal sized (CW was larger than 95 cm) males with good apparent health.

2.2.2. Experimental cage and pool tank

A small rectangular experimental cage was designed and built for holding an individual snow crab. It consisted of an aluminum frame, black plastic walls, and a mesh floor and ceiling. Dimensions of the cage were 60 cm long, 30 cm wide, and 30 cm high. The walls at both ends of the cage were hinged at the bottom and rigged to open simultaneously from a remote location.

The experiment was performed in a large covered pool tank with dimensions 4.9 m long, 2.7 m wide, and 0.8 m deep (see Fig. 2). The inner walls of the pool tank were dark blue in colour. During the experiment, the water temperature and salinity in the pool tank was kept stable at approximately 1 °C and 30‰ salinity. In addition, to avoid bias during the choice experiment, water flow to the tank was shut off, ambient light in the tank room was low, and there were no odor or food sources in the tank. In order to identify the position of the crab when leaving the experimental cage, we equally divided the bottom of the pool tank into 4 regions: right up (I), right down (II), left down (III), and left up (IV). The floor of the tank was equipped with Passive Integrated Transmitter (PIT) antennas for the purpose of alerting the researcher that the crab had left the experimental cage.

The light was suspended at the end of the pool tank in a manner that allowed direct visual line of sight upon opening the cage. To limit the amount of light emitted, we suspended the LED light in a vertically oriented 64 mm diameter black polyvinyl chloride (PVC) tube. The light aligned with a small 22 mm diameter hole that was 20 cm from the floor of the pool tank. This created a small focused light pattern with the source approximately 2.3 m from the cage.

2.2.3. Data collection

Choice experiments were conducted from January 28 to February 19, 2016. A total of 110 individual untrained naïve crab were examined. Each trial began by randomly selecting a light colour and light position (left or right end of the pool tank). A single crab was then randomly removed from a holding tank, temporarily tagged with a PIT tag, placed in the experimental cage, and then the cage was lowered into position in the middle of the pool tank. The total duration out of water was less than 1 min. The cover was then returned over the pool tank, removing all external stimuli. After waiting 15 min for acclimation, the cage was remotely triggered and the doors of the cage were opened. An audible alarm sounded when the crab exited the cage, at which time we recorded the time until exit and then removed the tank cover to determine the crab's direction (left or right, toward or away from the light) and position of the crab on the floor of the tank (I, II, III, or IV).

The first ten trials were conducted without LED lights to ensure crab movement was random upon opening the cage. In the absence of any experimental treatments (i.e. a dark tank), we wanted to confirm that crab showed no innate preference to move left or right, and ensuring there was no bias of the pool tank or the experimental cage. Experimental treatments were subsequently conducted using the five LED light colours of blue, green, purple, red, and white. Each light colour was randomly selected and replicated 10 times at each end of the pool tank (x2), for a total of 20 replicates per colour.

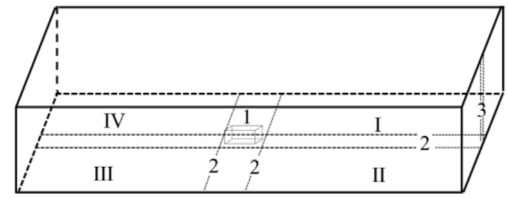

Fig. 2. A schematic of experimental tank. (1) is a small rectangular experimental cage; (2) is a PIT antennas; (3) is a light orientation black PVC tube, which was either located in the left or in the right side of the tank; (I, II, III, IV) is a temporary region to identify the position of the crab when leaving the experimental cage.

All traps were fished in long-lines with a distance of 36.6 m between individual traps. The three trap treatments were randomly positioned within these fleets and multiple fleets were deployed in close proximity. The lights were attached close to the bait jar in the centre of each trap. A total of 596 trap hauls (402 control traps, 76 purple light traps, 118 white light traps) were successfully carried out during six fishing trips. All legal-sized male crabs (>95 mm CW) were counted and the number recorded per trap haul was defined as the Catch Per Unit Effort (CPUE). In the event sub-legal males or females were captured they were immediately returned to the sea and not recorded. A random sample of crabs were removed from each treatment and the carapace width (CW) was measured to the nearest mm throughout the course of the experiment.

2.3. Field Experiment No. 1

This experiment was conducted aboard an inshore fishing vessel (*F/V The Phoenix*, 10.7 m LOA) targeting snow crab, approximately 20 nautical miles southeast of Petty Harbour, Newfoundland and Labrador (Latitude between 47°14′10.56″N and 47°23′51.12″N, Longitude between 52°31′41.16″W and 52°16′50.58″W) from April 26 to May 23, 2016 (see Fig. 3). The depth at the sampling site ranged from 165 to 173 m. Small Japanese-style conical traps with a bottom diameter of 101.5 cm, top diameter of 55.5 cm, height of 44 cm, and mesh size of 135 mm were used, typical for this fishery (e.g. Hébert et al., 2001; Winger & Walsh, 2007, 2011; Grant and Hiscock, 2009; Winger et al., 2015; DFO, 2016a). Inspection of the traps was conducted prior to sea trials to ensure the traps were identical in all aspects. Three experimental treatments were investigated: (1) Control trap – baited trap with 453 g of mixed squid and herring in a perforated plastic jar; (2) Purple Light trap – baited similar to Control trap, with the addition of a purple LED light; (3) White Light trap – baited similar to Control trap, with the addition of a white LED light.

2.4. Field Experiment No. 2

This experiment was conducted aboard an offshore fishing vessel (*F/V Atlantic Champion*, 19.8 m LOA) targeting snow crab along the Newfoundland and Labrador continental shelf, between May and June 2016. Depth at the sampling site ranged from 80 to 300 m. The trap and bait types, as well as fishing technology used and the LED light attachment methods were similar to Field Experiment No.1. Six experimental treatments were investigated: (1) Baited trap – baited trap without light, and treatments 2–6 which consisted of traps equipped with an LED light and no bait. Five light colours were used in treatments 2–6: blue, green, purple, red, and white. These treatments did not include bait in order to compare their effectiveness against baited traps. Trap numbers 40, 70, and 71 were selected to attach LED lights for consistency. The legal-sized male crab were counted in baited trap numbers 25, 39, 41, 69, and 80 and all functioning LED light traps. A total of 208 trap hauls (131 baited traps and 77 LED light traps) were evaluated during the experiment.

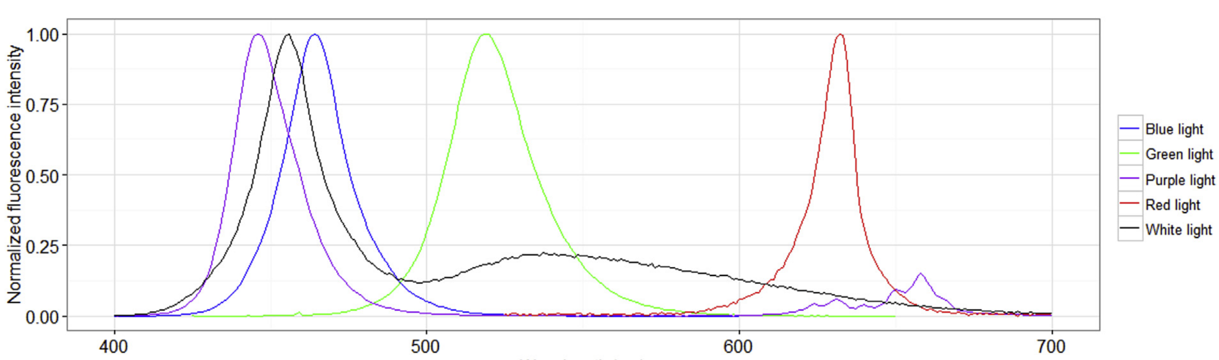

Fig. 1. Normalized fluorescence of Lindgren-Pitman LED Electralume lights. Peak wavelengths were 464 nm for blue lights, 519 nm for green lights, 446 nm for purple lights, 632 nm for red lights, and 456 nm for white lights. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.5. Statistical analysis

For the Laboratory Experiment, we used a chi-square (χ^2) test to confirm crab direction was random in the absence of any experimental treatment. A χ^2 test was also used to determine whether movement direction of a crab depended on LED light treatments. Crab direction was defined by a binary variable (i.e. toward or away from the LED light). A binomial logit link Generalized Linear Model on untransformed data was used to compare departure time (explanatory variable), crab size (explanatory variable), and direction (response variable). A Regression General Linear Model was used to determine the relationship between crab size and time leaving the experimental cage.

For Field Experiment No. 1, CPUE was analyzed using a Two-way ANOVA to assess the effects of the experimental treatments and fishing trips as factors affecting catch rate. A Two-way ANOVA was also used to compare mean size of snow crabs caught by the experimental treatments for different trips. Pairwise post hoc comparisons were conducted using Tukey's HSD. For the Two-way ANOVA we tested and found that assumptions were met with regard to homogeneity of variance, normal distribution of errors, independence of errors, and errors sum to zero. Kolmogorov-Smirnov two-sample test was used to compare the snow crab size frequency distributions between the treatment factors, as well as between fishing trips.

For Field Experiment No. 2, CPUE was compared between baited traps and illuminated traps using Non-parametric Wilcoxon Rank-Sum Test and also evaluated graphically. A Regression General Linear Model was used to determine the relationship between CPUE and soak time. An ANCOVA was used to compare the slopes of the CPUE - soak time relationships between illuminated traps and baited traps. Generalized linear models based on the Bayesian Model Average multiple regression were used to estimate the effects of light treatment, soak time, and depth on CPUE. The log-transformed catch rate (LnCPUE) is described as a linear combination of the explanatory variables and its error according to the equation:

$$\text{LnCPUE} = \beta_0 + \beta_T \text{T} + \beta_{ST} \text{ST} + \beta_D \text{D} + \varepsilon$$

where, β_0 is the intercept (constant); β_T, β_{ST} and β_D are the coefficients for the trap treatment, soak time, and depth, respectively. Similarly T, ST and D are the light treatment, soak time, and depth factors, respectively, while ε is error. The most parsimonious model was chosen based on the lowest BIC and highest posterior probability.

Only data from successful trap hauls were used in the above analyses. Data was excluded in cases where the lights malfunctioned, traps appeared damaged, or the bait jar was missing. Analyses were carried out with *R*, version 3.2.3 for Windows. A confidence level of $P < 0.05$ was used for most analyses, except where multiple tests were conducted for post hoc comparisons, in

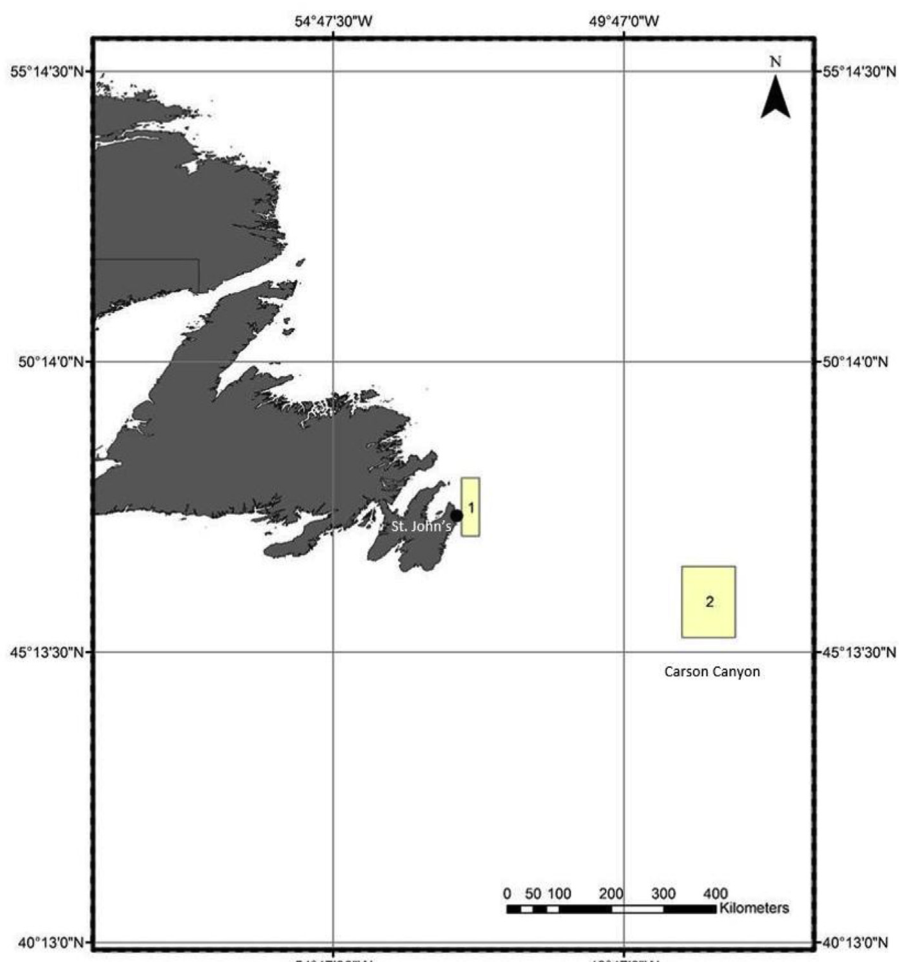

Fig. 3. Map of the at-sea study area. Boxes denote locations of Field Experiment No.1 and No. 2.

which case a Bonferroni correction was applied to the probability level to reduce the family-wise error rate (i.e. α 0.05 was divided by the number of tests to reduce the risk of making a type 1 error).

3. Results

3.1. Laboratory experiment

In the absence of a light treatment, our results showed that crab randomly moved out from the experimental cage, showing no preference for either the left or right exits ($\chi^2 = 0.4$, *P*-value = 0.527). No significant difference was found among the crab positions after exiting the experimental cage. Of the 110 snow crabs tested, 30, 22, 27, and 31 were distributed in the position I, II, III and IV, respectively ($\chi^2 = 1.782$, *P*-value = 0.619). There were 29 crabs that moved toward and 21 crab away from the LED light ($\chi^2 = 1.28$, *P*-value = 0.258) when placing LED lights in the left side of pool tank. Similarly, placing LED light in the right side of the tank, 28 crabs moved toward the LED light and 22 crabs toward no light side respectively ($\chi^2 = 0.72$, *P*-value = 0.396).

Movement toward light was statistically significant ($\chi^2 = 5$, *P*-value = 0.025) for blue and white LED lights, accounting for 75% of the observations, whereas purple light appeared to have a negative effect on crab behaviour, with 85% of crabs observed moving away from the purple light ($\chi^2 = 9.8$, *P*-value = 0.002). No significant difference in crab movement (toward or away) from LED lights was observed when using green or red lights ($\chi^2 = 1.8$, *P*-value = 0.180; $\chi^2 = 0.2$, *P*-value = 0.655, respectively). See Table 1 for a summary of results.

The departure time of crab from the experimental cage varied from 10 to 1782 s. Mean departure time was 179.13 s (±28.86 SE) with 65% of crab leaving the cage in less than 120 s. Only 13% of crabs stayed in the cage greater than 300 s. Crabs tended to leave the experimental cage very quickly in the white LED light treatment (mean = 99.85 s ± 18.62 SE), whereas crab took substantially longer in the red LED treatment (mean = 386.05 s ± 106.36 SE). The departure time of crab with blue, purple, and green LED lights was 154.3 s (±86.71 SE), 166.95 s (±47.13 SE), and 183.19 s (±69.19 SE), respectively. It took on average 100.95 s (±19.47 SE) for crab to exit the experimental cage when deployed with no light. Fig. 4 illustrates the time until crab moved out corresponding with different light colours.

No relationship between crab movement direction and departure time was detected using Logit Models for binary data (95% Confidence Interval of Odds ratio = 0.998÷1.001, Odds ratio = 0.999; *P*-value = 0.195). Similarly, a binomial Generalized Linear Model using a logic function showed that there was no relationship between crab movement direction and their size (95% Confidence Interval of Odds ratio = 0.961 ÷1.044, Odds ratio = 1.002; *P*-value = 0.939). However, our results showed that larger crabs left the experimental cage significantly faster than smaller individuals according to the equation: Departure Time = 895.566−6.476*CW.

3.2. Field Experiment No. 1

Attaching artificial lights in the baited traps had a statistically significant positive effect on CPUE (Table 2). The Two-way ANOVA for treatment and trip factors indicated significant differences for trap treatment (*F*-value = 85.484, *P*-value < 0.001), fishing trips (*F*-value = 38.086, *P*-value < 0.001) as well as the interaction of these factors (*F*-value = 1.965, *P*-value = 0.035).

The CPUE observed for the different treatments are shown in Fig. 5 and Table 2. Traps equipped with white lights produced the highest catch rates, yielding a mean CPUE of 21.5 (±0.85 SE) crab/trap, followed by the purple light trap, yielding 17.8 (±1.13 SE) crab/trap, and finally the control trap, with only 12.1 (±0.38 SE) crab/trap. This corresponds to a 77% and 47% increase in the mean CPUE when adding white and purple lights to baited traps. Post-hoc comparisons revealed a significant difference between the white light traps and control traps (*t*-value = 9.361; *P*-value < 0.001) as well as a significant difference between the purple light traps and control traps (*t*-value = 5.679; *P*-value < 0.001), and also the white light traps and purple light traps (*t*-value = 3.681; *P*-value = 0.002) (Table 2).

Comparison of the mean and median CPUE across different fishing trips and light treatments is shown in Fig. 6 and Table 3. With the exception of Trip 5, the median CPUE tended to decrease in the control and purple light traps, whereas it was generally more variable in the white light traps. The mean CPUE in the first two trips and the last two trips (i.e. trip 1 and 2; trip 5 and 6) were higher than the middle two trips (trip 3 and 4) for all experimental treatments. Post-hoc comparisons are shown in Table 3. The CPUE using white light traps were statistically higher than control traps for all trips. Purple light traps were statistically higher than control traps for trips 2, 3, 4, and 6, but not different in trips 1 and 5. White light traps were statistically higher than purple traps for trips 3 and 4, but not different in trips 1, 2, 5, and 6 (Table 3).

The size frequency distribution of legal male crab captured in the different trap treatments are shown in Fig. 7. Mean CW of crab caught by control traps ($n = 171$), purple light traps ($n = 235$), and white light traps ($n = 219$) were 104.8 mm (±0.60 SE), 107.68 mm (±0.55 SE), and 105.4 mm (±0.48 SE), respectively. Results of the Two-way ANOVA revealed that the mean crab size varied significantly between the trap treatments (*F*-value = 9.137, *P*-value < 0.001). Subsequent pairwise comparisons of crab size distribution indicated a significant difference between purple light traps and control traps (Kolmogorov-Smirnov test: D = 0.176, *P*-value = 0.006), as well as purple light traps and white light traps (Kolmogorov-Smirnov test: D = 0.155, *P*-value = 0.008), but no statistical difference between white light traps and control traps (Kolmogorov-Smirnov test: D = 0.120, *P*-value = 0.125). Although a statistical difference in the size of crab was detected across fishing trips (Two-way ANOVA, *F*-value = 12.883, *P*-value < 0.001), no obvious trend was apparent over time as the season progressed. Fig. 8 shows the mean CW for crab caught during each fishing trip, with values ranging from a low of 104.03 mm (±0.72 SE) to 109.09 mm (±0.81 SE) during field experiment No.1.

3.3. Field Experiment No. 2

The CPUE observed for the different experimental treatments (baited and 5 light colours without bait) are shown in Fig. 9. Mean CPUE ranged from 9.8 to 13.1 crabs/trap haul (Table 4). No statistical differences in CPUE among the baited traps and illuminated traps (without bait) were detected using Non-parametric Wilcoxon Rank-Sum Test (Table 4). The degree of variance was highest among green light traps (SE = 3.41) and lowest among the baited traps (SE = 0.69).

Although there are four appropriate models to describe CPUE, the most parsimonious model included only parameters for soak time and the depth (based on lowest BIC and highest posterior probability) (Table 5). The probability of the regression coefficient being different from zero for the trap treatment factor was very low, only 12.0%, compared to 58.5% and 100.0% for the depth and soak time factors, respectively (Table 6). A negative coefficient for depth (D) indicates lower CPUE was observed with increasing depth (fishing depth varied between 80 and 300 m). The positive coefficient for soak time (ST) indicates higher CPUE was observed with increasing soak time which ranged from 27 to 195 h.

Table 1
Summary of snow crab responses to the LED lights during the laboratory experiment.

Treatment	Sample size	Towards the light	Away from the light	χ^2	*P*-value
Blue light	20	15	5	5	0.025
Green light	20	13	7	1.8	0.180
Purple light	20	3	17	9.8	0.002
Red light	20	11	9	0.2	0.655
White light	20	15	5	5	0.025

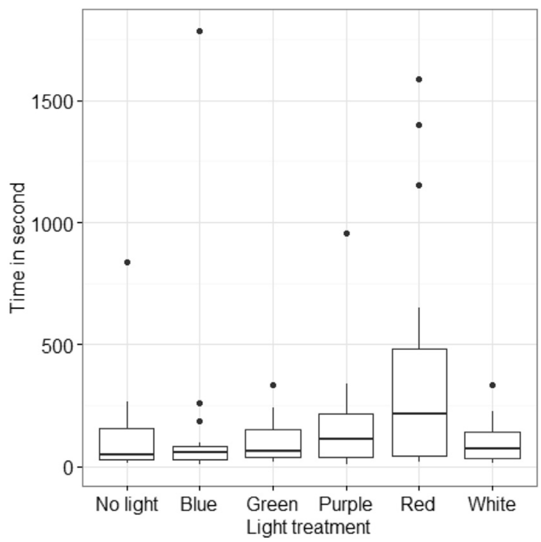

Fig. 4. The time until crab moved out of the experimental cage by different light treatments.

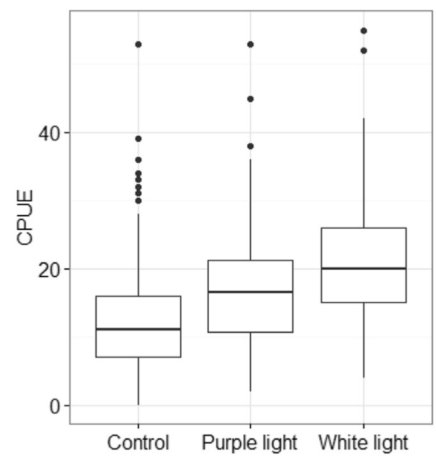

Fig. 5. Boxplots of CPUE of snow crab for the different trap treatments evaluated in Field Experiment No.1.

Table 2
Mean CPUE of snow crab for the different trap treatments in Field Experiment No.1, including their pairwise post hoc comparison using Tukey's HSD. SE is standard error of the mean and CI is confident interval.

Trap category	Number of traps	CPUE	SE	Change of CPUE of purple and white light trap compared to control trap (%)
Control	402	12.1	0.38	
Purple light	76	17.8	1.13	+47.0
White light	118	21.5	0.85	+77.4

Treatment comparison	*t-value*	95% CI	*P*-value
White light versus Control	9.36	7.59 to 11.13	<0.001*
Purple light versus Control	5.68	3.57 to 7.79	<0.001*
White light versus Purple light	3.68	1.20 to 6.17	0.002*

*Significantly different at Bonferroni's adjusted alpha level (*P*-value < 0.0167).

Further description of the relationship between average CPUE and soak time bins is illustrated in Fig. 10. The linear regression model for the illuminated traps is $\text{CPUE}_{\text{illuminated trap}} = 6.72 + 0.07^*(\text{soak time})$, while this model for the baited traps is $\text{CPUE}_{\text{baited trap}} = 7.5 + 0.04^*(\text{soak time})$. All parameters are statistically significant (*P*-value < 0.001). The slope of regression line was significantly different from zero (*P*-value < 0.001) using ANCOVA. The positive slopes indicate CPUE increased for both illuminated traps and baited traps with increasing soak time. Analysis of covariance indicated the slopes of the CPUE versus soak time relationships for illuminated traps differed significantly from the baited traps (*P*-value < 0.001). These results suggest that longer soak times disproportionally benefit illuminated traps compared to baited traps.

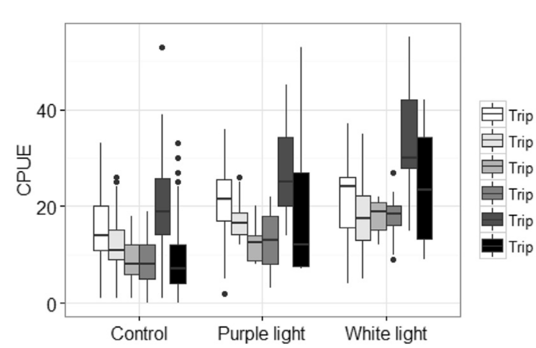

Fig. 6. Boxplots of CPUE of snow crab for the different trap treatments by fishing trip, evaluated in Field Experiment No. 1.

Table 3
Mean CPUE of snow crab for the different trap treatments in each fishing trip in Field Experiment No.1, including their pairwise post hoc comparison using Tukey's HSD. (NS) indicates no significant difference. (+) indicates significant difference detected. SE is standard error of the mean.

Treatment	CPUE (±SE)					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Control	14.9 ± 0.82	12.2 ± 0.66	8.7 ± 0.59	8.5 ± 0.45	20.6 ± 1.44	9.9 ± 1.14
Purple light	20.4 ± 3.37	17.5 ± 1.23	12.5 ± 1.18	13.2 ± 1.20	27.3 ± 2.77	19.8 ± 4.51
White light	22.3 ± 1.31	18.0 ± 1.51	17.9 ± 1.09	17.9 ± 0.93	34.5 ± 3.60	24.5 ± 3.77
Average total	17.2 ± 0.75	14.1 ± 0.60	10.6 ± 0.61	10.7 ± 0.50	24.0 ± 1.40	13.5 ± 1.35
Treatment comparison						
White light versus Control	+	+	+	+	+	+
Purple light versus Control	NS	+	+	+	NS	+
White light versus Purple light	NS	NS	+	+	NS	NS

[+]Significantly different at Bonferroni's adjusted alpha level (*P*-value <0.0167).

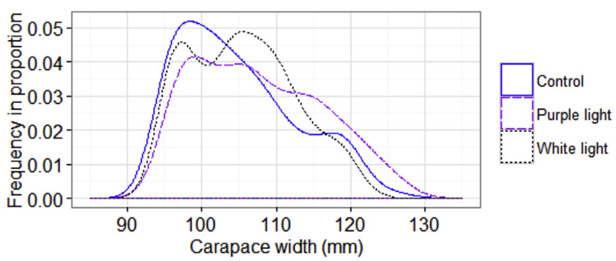

Fig. 7. Size frequency distribution of carapace width of legal male crab captured in the different trap treatments in Field Experiment No. 1.

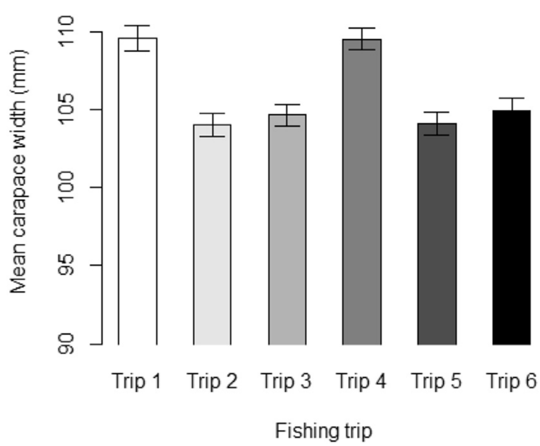

Fig. 8. Mean CW of snow crab captured during each of the six fishing trips during Field Experiment No.1.

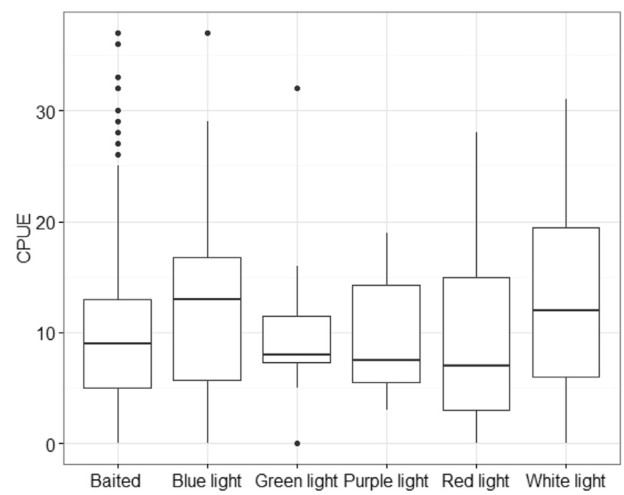

Fig. 9. Boxplots of CPUE of snow crab for the different trap treatments evaluated in Field Experiment No.2.

4. Discussion

In this study we found that LED lights affect snow crab behaviour. Different wavelengths of light (i.e. colours) produced different behavioural responses in both laboratory and field conditions. Field experiments indicated that the catch rate of baited traps significantly increased with the addition of LED lights (Field Experiment No.1), and that substantial numbers of crab entered traps when only LED lights were used as the stimulus (Field Experiment No.2).

The laboratory experiment indicated that, like many aquatic species (e.g. herring, anchovies, mackerel, tuna, squid, cod, large-head hairtail, scad and other pelagic species) (Marchesan, Spoto, Verginella, & Ferrero, 2005; Matsushita & Yamashita, 2012; Matsushita et al., 2012; Nguyen & Tran, 2015; Yamashita et al., 2012; Yami, 1976) snow crab could be lured using artificial light colours. In our study, crab responded differently to different LED light colours, and there was evidence to suggest that behaviour was dependent on crab size. Crab moved towards blue light and white light, were not affected by red or green light, and moved away from purple light. The lack of response to red light in our study is consistent with previous studies which have suggested crustaceans do not respond to that part of the visual spectrum (e.g. Butler, Tiggelaar, & Shields, 2014; Truong, 2008, p. 204; Zhou & Shirley, 1997). The results of our laboratory experiment were consistent with Marchesan et al. (2005) who suggested that fish responded differently when exposed to different light colours. Evidence suggests that the observed response could be related to eye structure and physiology. For example, Matsui, Takayama, and Sakurai (2016) noted that the pupillary and reticular response in Japanese flying squid was very sensitive under low-powered blue, green, and white LED lights, but much less sensitive and exhibited a weaker response to red LED light. While much is known about vision in decapod crustaceans (e.g. Porter & Cronin, 2006, pp. 183–195), to our knowledge there is limited knowledge of the structure and function of the crab eye as it relates to their behaviour, suggesting a potential avenue for future research.

The capture efficiency of crab traps is known to depend on animal density, fishing season, type of bait, level of satiation, trap size and shape, size and position of entrances, soak time, and oceanographic conditions (e.g. Hébert et al., 2001; Winger & Walsh, 2007, 2011; Grant & Hiscock, 2009). Field Experiment No.1 indicated that the addition of white LED light significantly increased of the catch of crabs, accounting for a 77% increase in CPUE compared to the

Table 4
Mean CPUE of snow crab for the different trap treatments in Field Experiment No.2. p-values describe statistical difference uncertainty according to Non-parametric Wilcoxon Rank-Sum Test. SE is standard error of the mean.

Trap category	Number of traps	CPUE	SE	Change of CPUE of LED light traps compared to baited trap (%)	*W*-value from Non-parametric Wilcoxon Rank-Sum Test	*P*-value of difference
Baited	131	10.7	0.69			
Blue light	12	13.6	3.13	26.6	665	0.380
Green light	8	10.9	3.41	1.3	547	0.839
Purple light	8	9.8	2.2	−9.2	542.5	0.871
Red light	13	10.2	2.49	−4.7	915	0.660
White light	36	13.1	1.39	21.9	1946	0.109

Table 5
Bayesian Model Average multiple regression describing CPUE for the Field Experiment No.2. (T) is treatment; (ST) is soak time; (D) is depth.

Model	Equation	R^2	BIC	Posterior probability
1	CPUE = 7.25 + 0.05*ST	0.121	−21.38	0.364
2	CPUE = 13.17 − 0.06*D + 0.06*ST	0.146	−22.08	0.516
3	CPUE = 6.51 + 0.32*T + 0.05*ST	0.127	−17.46	0.051
4	CPUE = 12.40 + 0.30*T − 0.06*D + 0.06*ST	0.151	−18.05	0.069

Table 6
Estimated coefficients.

Parameter	Regression coefficient probability being different from zero (%)	Expected value	Standard deviation
Intercept	100.0	10.62	3.59
Treatment (T)	12.0	0.04	0.14
Depth (D)	58.5	−0.03	0.03
Soak Time (ST)	100.0	0.06	0.01

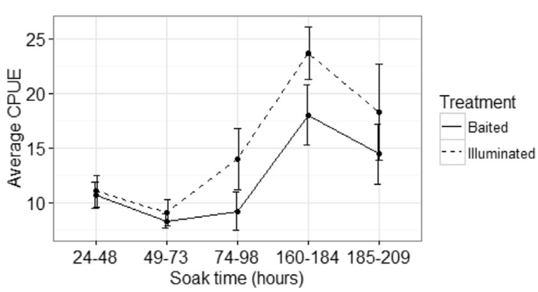

Fig. 10. Average CPUE in relatives to soak time bins for Field Experiment No.2. Vertical bars are standard errors.

control trap (Table 2). Similarly, our Field Experiment No.2 demonstrated that crab were strongly attracted by blue, green, and white LED lights. These results are consistent with our laboratory experiment in which crabs moved toward the blue and white lights. They are also consistent with Murphy (2014, p. 140) who documented crab entering unbaited flatfish traps equipped with only a green LED light (no bait). Bryhn et al. (2014) found that attaching a green LED light inside a baited pot increased the mean catch weight of legal sized Atlantic cod by 80%. An (2013) noted that catch rates of squid were highest using blue and white lights and lowest using red lights. Similarly, Lee (2013) found that chub mackerel responded positively to blue, yellow, and white LED light, while no effect was observed with using red LED light.

Some of our results are however, inconsistent across our experiments. While our laboratory experiment suggested crab move away from purple light, both field experiments suggest crab are not hindered whatsoever from entering traps with purple lights. These observations highlight the fact that the underlying functional explanations for crab behaviour toward LED light are still unclear. Many questions remain unanswered about detection thresholds and motivations in crab. For example, in some cases, animals appear attracted to prey which are attracted by the light (e.g. An, 2013; Bryhn et al., 2014; Marchesan et al., 2005; Yami, 1976). It could also be possible that in a dark and barren environment, the light accentuates the presence of shelter or structure. Evidence has shown that crab will enter unbaited traps in the absence of any stimulus or bait (e.g. Murphy, 2014, p. 140), suggesting the species may simply be “trap-happy” to some extent. Another hypothesis is that light enables crab to detect the trap entrance and/or conspecifics inside the trap. It remains unclear how crabs see and perceive light and we do not fully understand their behavioural responses toward light stimuli.

In some cases, LED lights can attract animals, while in other cases deter them. For instance, Hannah et al. (2015) installed green LED lights along the fishing line of a bottom trawl, which significantly reduced non-targeted bycatch of several finfish species with no effect on target species of ocean shrimp (Pandalus jordani). Ortiz et al. (2016) demonstrated that bycatch of green turtle (Chelonia mydas) decreased by 63.9% when attaching green LED light to gillnets. Wang et al. (2007) showed that juvenile loggerhead turtles (*Caretta caretta*) significantly moved toward blue, green, yellow and orange LED lightsticks.

With regard to crab size and their behaviour, Field Experiment No.1 showed that the purple light traps caught larger crabs than both the control traps and white light traps. In contrast, our laboratory experiment detected no relationship between crab size and movement direction (i.e. toward or away from the LED light), however larger crabs exhibited a faster exit time from the cage than smaller crabs. A significant difference in crab size was found between trips, but it varied around 104 and 109 mm with no evidence that crab size changed throughout the commercial fishing season (i.e. across fishing trips). We speculate that very large male crab could behave differently than smaller crab in response to various stimuli.

Field Experiment No.2 provides evidence to suggest baited traps will have a higher CPUE than non-baited illuminated traps when soak times were short, while traps with lights performed better as soak times increased. The regression coefficent for the illuminated trap was twice that for baited trap (0.07 versus 0.04), while the intercept of the baited trap model is larger than the illuminated trap (7.5 versus 6.72). We speculate that bait plays a pivotal role in the first few days of soaking, but as the odor depletes, illuminated traps begin to perform better as they continue to attract crab irrespective of bait. The catch of illuminated traps may therefore be better when long soak times are employed. In addition, results from Field Experiment No.2 suggest that the LED lights (either blue, white, or green) may work as a suitable replacement to traditional bait. Fishing enterprises could theoretically reduce bait costs through LED light substitution, or enhance existing catch rates of baited traps by simply adding an LED light. The financial trade-off depends on many factors, not least of which includes the cost of bait, lights, fuel, and crews wages. The findings warrant an economic analysis of the risks and benefits on how best to operationalize these findings. Longer soak times would also promote more sorting on the bottom and potentially improve size selectivity.

The mean number of crab per trap for all three treatments combined during Field Experiment No.1 was 14.7 (±0.37 SE) (12.1 ± 0.38 for control trap, 17.8 ± 1.13 for purple light trap and 21.5 ± 0.85 for white light trap), and 11.3 (±0.57 SE) for all six treatments combined during Field Experiment No.2. This equates to a mean weight of 7.35 kg per trap for Field Experiment No.1 and 5.65 kg per trap for the Field Experiment No.2. These catch rates are lower than those documented by DFO (2016a), who reported 5–10 kg per trap in the Northeast and over 25 kg per trap in the Southeast of Newfoundland, between 2013 and 2015. This implies that the crab resource could be in a period of decline, or the experiments were conducted in areas of low crab density. Comparing the CPUE between Field Experiment No.1 and Field Experiment No.2, it appears the crab density in the offshore study area may have been lower than the inshore study area. These results suggest that LED lights could substitute bait when crab density is low.

Our laboratory experiment showed that crabs reacted relatively quickly in response to LED light. Observing 110 individual crabs (i.e. 100 unique crabs tested with lights and 10 unique crabs tested with no light), 87.3% of the individuals moved out the experimental cage within the first 5 min after opening the doors. The response duration of crab was also different depending on the light colours. These results agreed with Matsui et al. (2016) who found that the pupillary response in Japanese flying squid varied for different colours, but appeared after 1 min when the illumination provided for all colours of blue, green, red and white.

The proportion of crab that actually enter a trap when approached is an important contributing factor in the capture efficiency of a crab trap. Bryhn et al. (2014) found that the visual stimuli of a green light inside a cod pot created a positive effect on near-field and ingress behaviour of cod entering the pot. Therefore, the increased CPUE in the lighted trap may be attributed to an increase in the proportion of crabs that actually enter a trap when approached. More detailed studies, such as the use of under water camera research is recommended to better understand and further improve the effectiveness of using lights as a supplemental stimuli in the crab fishery.

Although no evidence exists to suggest low-powered underwater light harms or disturbs ecosystem function, there is potential for negative trade-offs in situations where underwater fishing lights are operated in non-natural situations (e.g. deep sea or nighttime). For example, the use of above-water fishing lights have been shown to affect fish foraging and schooling behaviour, spatial distribution, predation risk, migration, and reproduction (Nightingale, Longcore, & Simenstad, 2006). The density of predators has also been reported to increase when artificial lights were used (Becker, Whitfield, Cowley, & Järnegren, 2013), feeding of predators increased with prey density in high light intensity experiments, whereas under dark conditions increased prey levels failed to elicit a similar increased feeding response (Thompson, 2013). These effects have the potential to create unnatural top–-down regulation of fish populations (Becker et al., 2013). Further research into whether low-powered underwater lights affect ecosystem, fish stock, as well as the vulnerability of threatened species (e.g. wolfish) and marine mammals is therefore recommended.

In conclusion, this study found that LED lights affect snow crab behaviour. The laboratory experiment demonstrated that white and blue LED lights attracted crab better than green LED lights, while the purple LED light deterred them. Red LED light colour did not affect crab movement direction. Field Experiment No.1 showed that white and purple light could attract crab, but the white light increased CPUE more than purple light. Field Experiment No.2 suggested that blue, green and white LED light could substitute traditional sources of bait when the CPUE is low and soak times are long. Taken together, these experiments suggest that fishing enterprises can improve their catching performance by adding LED lights to their baited traps, or by using LED lights as a bait replacement. Economic benefits are yet unclear, but widespread use of lights could potentially reduce operating cost by spending less days on the water, reducing fuel consumption, reducing labor effort while fishing, and reducing bait expenses.

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