# Artificial light improves size selection for northern shrimp (*Pandalus borealis*) in trawls

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## Abstract

Size selection in the northern shrimp (*Pandalus borealis*) trawl fisheries is a widely studied topic. While the focus has largely been on codend and grid selectivity, studies have shown the importance of other design changes and the application of artificial light to evoke behavioural responses. LED lights of three different colours; green (~470–580 nm), white (~425–750 nm) and red (~580–670 nm), were mounted in the belly section of a shrimp trawl to investigate their influence on the overall selectivity of the trawl. The study was conducted using a twin-trawl setup, one with light and the other without light. For catch-comparison analysis, a polynomial regression with random effects was applied. The number of valid hauls with green, white and red lights were eleven, eight, and nine, respectively. All lights tested significantly affected the length-dependent retention of shrimp. Green light had the greatest effect, red the least. Significant loss was observed for shrimp below 17.5 mm carapace length (CL) for green light, 19.5 mm CL for white and 20.8 mm CL for red light.

*Keywords:* Crustacean; demersal fishery; bycatch reduction; catch comparison; size selectivity.

# Introduction

Shrimp fisheries are important worldwide, and harvesting is mostly done using trawls (Gillet 2008). In general, shrimp fisheries are regarded as poorly selective and frequently associated with excessive bycatch of other species (Kelleher 2005; Gillet 2008). The northern shrimp (*Pandalus borealis*) fisheries are no exception. In many areas, the issue of fish bycatch has to a large extent been remedied by the introduction of sorting grids like the Nordmøre-grid (Isaksen et al. 1992; Garcia 2007). However, important issues remain regarding excessive catches of undersized shrimp, and bycatches of juveniles and small-sized teleost species.

The northern shrimp (*Pandalus borealis*) fishery in Skagerrak and the North Sea is not exempt from these problems. In this fishery, a 19-mm bar spacing Nordmøre-grid is mandatory to use, as well as a codend with a minimum mesh size of 35 mm. As most of the shrimp pass through the grid, the selectivity of undersized shrimp is based on the selective properties of the codend. Shrimp vessels operating in Skagerrak and the North Sea grade their shrimp catch onboard into three categories: undersized shrimp (<15 mm carapace length), industrial shrimp (≥15 and <20 mm carapace length), and boiled shrimp (≥ 20 mm carapace length). Although there is a landing obligation for all shrimp caught, including the undersized shrimp, the prices for boiled shrimp can be over 5 times higher than those for the industrial shrimp, which in turn implies risk for discards and high grading. Therefore, technical measures to reduce catches of the smallest shrimp are sought – both for economic and conservational reasons. In the Norwegian waters of Skagerrak and the North Sea, the minimum legal total length of shrimp is 6.5 cm (approximately 15 mm carapace length), and real-time closures are enforced in areas where numbers of undersized shrimp exceed 15% of the total catch (Anon. 2005).

Most of the research carried out in shrimp fisheries has focused on reducing the bycatch of juvenile fish, either by changing the grid section or altering codend configuration (e.g. Campos et al. 2002; Broadhurst et al. 2004; Grimaldo 2006; Larsen et al. 2018a). In addition, attempts have been made to reduce catches of undersized shrimp by for example, adding low-bar-spacing grids to the main sorting grid design (He and Balzano 2007; Larsen et al. 2018b) or modifying the meshes in the codend

(Thorsteinsson 1992). However, despite the positive contribution of these measures, the results reported show that they do not entirely solve the problem.

Studies have shown that shrimp selection can occur in the trawl body, long before the shrimp reach the aft part of the trawl gear (High et al. 1969; Thorsteinsson 1981; Polet 2000; Broadhurst et al. 2012), and that ambient light level affects penaeid shrimp selection (Broadhurst et al. 2015). Conolly (1992) reported that shortening the belly of the trawl and consequently increasing the mesh openings and angle of attack of the netting panels, significantly reduced the bycatch of juvenile fish in the Brazilian shrimp fishery. More recently, Ingólfsson and Jørgensen (2020) documented a significant reduction in the catches of undersized shrimp in the Norwegiannorthern shrimp fishery by using a short-belly trawl.

The use of light to reduce catches of unwanted species has gained interest in different fisheries in the last years (Nguyen and Winger 2018; Southworth et al. 2020). Shrimp have been believed to show limited behavioural response to the various trawl components during the capture phase (High et al. 1969; Wardle et al. 1993; Hannah and Jones 2003). Therefore, most studies carried out with light in shrimp trawl fisheries have focused on the reduction of fish bycatch rather than the potential for alterations in the exploitation pattern of shrimp. Studies have shown that it is possible to influence fish behaviour and reduce the bycatch of certain species by placing lights at different positions in a shrimp trawl (e.g. Hannah et al. 2015). Research with lights have been carried out in other areas like the Barents Sea northern shrimp fishery, although with more varying results (Larsen et al. 2017).

The vision and spectral sensitivity of northern shrimp that inhabit environments with low light intensities has not been much studied. Eaton and Boyd (1970) and Eaton (1972) concluded that the spectral sensitivity of northern shrimp peaked around 500 nm (510 nm for males with carapace lengths below 20 mm). More recently, Frank et al. (2012) investigated the spectral sensitivity of several deep-water crustaceans including two shrimp species, *Heterocarpus ensifer* and *Euganotonotus crassus*. Similar to the results of Eaton and Boyd (1970), their results also showed that the spectral sensitivity peaked at around 500 nm with a sensitive range of approximately 400-

600 nm. Six other crustacean species included in the study by Frank et al. (2012) also showed sensitivities in the same range. It is thus reasonable to assume that northern shrimp would be able to see light of different colours and would be particularly sensitive to green light.

An animal's sensory systems is vital for its survival. Vision plays a role in e.g. orientation, food search and predator avoidance (Cronin and Douglas 2014). Therefore, when attempting to exploit animals' senses to achieve size- and species selection in fisheries, care should be taken not to harm the sensory systems of the specimens that avoid capture. The long-term damaging effect of bright light on the crustacean eye depends on the ambient light intensity and the adaptational state to which the animals had been adjusted (Gaten 1988). The degree of light-induced crustacean photoreceptor damage depends on a number of variables, but once manifested, damage tends to be progressive and irreversible (Meyer-Rochow 2001). When exposed to white light with an intensity of 0.47 $Wm^{-2}$ for 10 min, some damage of the retinula cells of the deep-water-living crustacean *Cirolana borealis* were observed, but the cells had recovered after 12 h. At greater intensities (4.9 to > 70 $Wm^{-2}$), the damages were greater and recovery poor (Nilsson and Lindström 1983). Studies on dark-adapted *Nephrops norvegicus* show that 15 sec exposure to dim daylight of 5.5 $Wm^{-2}$ intensity can cause substantial damage (Shelton et al. 1985). After 5 min exposure, the destruction was almost total. In the absence of direct studies on light-induced damage on the eyes of northern shrimp, results from studies on other crustaceans indicate that light intensity should, for precautionary reasons, be kept at low levels and preferably for short periods.

Recent sea trials carried out in Skagerrak by the Norwegian Institute of Marine Research (IMR, unpublished), showed that the size distribution of shrimp varied between eight standard hauls and three hauls where red (635 nm peak) lights were used to film in the belly section of the trawl. These observations led to the hypothesis that lights could be used to stimulate escape behaviour of shrimp through trawl meshes. The aim of the present study was thus to investigate whether lights of different colours, including the red light in the aforenamed trials by IMR, could be used to stimulate escape behaviour of northern shrimp in the belly section of a trawl.

## Material and Methods

### *Vessel, gear and data collection*

To test the effect of light on the size selectivity of shrimp, comparative sea trials were conducted off the coast of Norway (in Skagerrak) onboard the commercial shrimp trawler 'Tempo' (27.4 m length overall and 745 kW main engine) between the 17th of November and the 6th of December 2017.

Two trawls, both identical to the four-panel short belly trawl used by Ingólfsson and Jørgensen (2020), were towed simultaneously. The reason for using short trawls was to ensure mesh openness and facilitate shrimp size selection with the light stimuli. The upper and side panels of the 59.5 m long trawl bellies were built of netting with meshes that decreased from 200 mm nominal mesh length in front to 50 mm in the rearmost panels (8 m 200 mm, 12 m 120 mm, 12 m 60 mm and 27.5 m 50 mm). The bottom panels and codends had a mesh size of 40 mm. A pair of Thyborøn trawl doors (2500 kg and 16 m$^2$ each) and a 3000 kg centre weight were linked to the trawls by 53 m long bridles. In each of the trawls, a Nordmøre grid (1 × 1.75 m, 19 mm bar spacing) was installed in front of the codend. To investigate the potential effect of light on the shrimp catches, a single LED dive light (Brinyte DIV01V, 21 cm long, 3.0–4.6 cm wide, 0.27 kg weight in seawater) with a 120° beam angle, was mounted 6 m in front of the 8 m long grid section in the test trawl (Fig. 1). The distance from the torch to the bottom panel is determined by the number of meshes, the mesh openings and the shape of the belly transect. Assuming 30% lateral mesh opening and a circular shape of the transect, the vertical distance would be 3.4 m. The control trawl had no light. Lights of three different colours were used during the trials, green (520 nm peak), red (635 nm peak) and white (~430 – 750 nm) (Fig. 2, intensities shown after 3 h of operation). The spectral radiances (mWm$^{-2}$ nm) for the lights were measured for over 12h at 8°C. The intensity for the red light at 635 nm after 30 min (about the time from when the light was turned on until fishing started) was 18.0 mWm$^{-2}$, and fell to 7.7 after 3 h and 2.8 after 6 h. From 6 to 12 h, the intensity dropped linearly to 1.2 mWm$^{-2}$. The maximum intensity for the green light at 520 nm after 0.5 h was 7.2 mWm$^{-2}$ and dropped to 5.0 after 3 h and 4.0 after 6 h. From 6 to 12 h, the intensity fell linearly to 2.9 mWm$^{-2}$. The intensity for the white light at 606 nm after 30 min was 3.9 mWm$^{-2}$ and fell to 2.5 and 1.8 after 3 and 6 h respectively. From 6 to 12 h, the intensity dropped linearly from 1.8 to 1.3 mWm$^{-2}$. The total radiations for all wavelengths after 0.5, 3, 6 and 12 h were 457, 182, 65, and 29 mWm$^{-2}$ for red, 664, 399, 283, and 200 mWm$^{-2}$ for white and 307, 212, 169, and 124 mWm$^{-2}$ for green light, respectively.

During the field experiments, one colour was tested at a time and the lights were alternated between the trawls (Table 1). The lights were fastened on both the trawls by means of frames made of PE plastic tubes and pointed forward towards the trawl opening (Fig. 3). They were cut with an inclination of ~15 degrees so that the light tilted downwards. In front of the lights, five cm stripes of silvery duct tape were adhered to increase light reflection. The light frames were kept on both the trawls to ensure they had the same position throughout the experiments and that the only difference between the different configurations was the light of the torches.

In each haul, the shrimp catches from the two codends were kept separated and weighed to the nearest kg after grating. Shrimp samples for length measurements were taken from each codend catch, aiming for samples sizes of ~500 specimens in every case. Digital calipers with an accuracy of 0.01 mm were used to measure carapace lengths. All measured lengths were rounded to the nearest 0.5 mm prior to analysis.

No in-situ measurements of the ambient light intensity at the fishing depths were made during the experiment. However, measurements of light intensity were recorded during a hydrographic transect in the Skagerrak on 5 Dec 2018 with the RV G.M. Dannevig. These measurements were made with a Seabird PAR instrument, but the sensor did not allow for data resolution deeper than approximately 90 m. Therefore, to estimate the light level at fishing depths of 170–350 m, we used the observed light intensity at 75 m and the extinction coefficient provided by Clark and Wertheim (1956) for shelf water deeper than 90 m (k= 0.039). Measurements used for the calculations were recorded at position 58° 08.05’ N and 9° 10.90’ E at 10:24 UTC. The calculated light intensity ranged from $5.3\times10^{-4}$ Wm$^{-2}$ at 170 m depth to $4.8\times10^{-6}$ Wm$^{-2}$ at 350 m.

*Data analyses*

The relative length-dependent efficiency of the test trawl compared to the control trawl, wasestimated applying a polynomial logistic regression, based on the methods of Holst and Revill (2009). Alternatively, a generalized additive mixed model could be applied, or bootstrapping methods to account for the between haul variances. The choice of a parametric random effect model, however, allows for a simple way of testing formally the effects of explanatory variables (carapace length and light colour in our case).

A generalized linear mixed effect model (GLMM) with logistic link was applied. For investigating the effect of different light colours on length-dependent relative catch retention, using two identical trawls, the full model with a *k*-order polynomial is:

$$\text{logit}(\pi) \approx \text{o} + \alpha_1 \Lambda + \alpha_2 \Lambda l + \beta_0 + b + \beta_1 l + \cdots + \beta_k l^k \qquad (1)$$

Here $\pi$ is the probability of shrimp of length $l$ being retained in the test trawl, giving that it was caught in one of the trawls. o = $\log(q_t/q_c)$ is an offset, with $q_t$ and $q_c$ denoting the sampling proportions from the test and control catches, respectively. The $\alpha$*’s* and $\beta$*’s* are the model parameters. The $b$ is the random effect at haul level, assumed to have mean of zero and be normally distributed, accounting for between-haul variation. $\Lambda$ is the mean wavelength, weighted with light intensity I ($\Lambda = \Sigma\, \lambda\, I / \Sigma I$). The calculated means were 522, 588 and 632 nm for green, white and red light, respectively. A forward selection procedure was followed, with and without $\alpha_1$ and $\alpha_2$ in equation 1, incrementing the polynomial order one at a time up to k = 4, selecting the model with the lowest AIC (-2 × maximized log-likelihood + 2 × number of parameters), counting the random effect as one parameter. The models were tested with and without lower order polynomials.

Presented significance of terms are from deviance goodness-of-fit tests. Length-dependent relative catch ratio $r$ with the test trawl with light, given that both trawls catch equally, is derived from the relative catch $\pi$:

$$r = \pi/(1-\pi) \qquad (2)$$

The relative catch ratio is more intuitive to comprehend as it describes proportional catch loss (or increase), and therefore added as separate plots (Fig. 4, middle panel). The confidence intervals are calculated as for ordinary regression models, treating the random effect as a nuisance parameter; $\text{logit}(\pi) \pm 1.96 \times \text{SE}(\text{logit}(\pi))$ (Hosmer and Lemeshow 2000; Zuur 2012). Standardized residuals were checked for normality and homogeneity. Models were then checked for over/under-dispersion. The function *gam* in the mgcv package in R was used for the analysis (Wood 2017; R Core Team 2020).

## Results

The small frames were easy to handle, and the plastic clamps facilitated quick insertion and removal of the lights. In all cases, the lights were on and with bright illumination at the end of the tows. A total of 29,714 shrimp were measured from 28 valid hauls, 11 with green (seven starboard, four port), eight with white (four starboard, four port) and nine with red light (six starboard, three port). White and red lights were used alternately the first eight days, before the green light was added to the series. Average haul duration was 10.4 h and fishing depths varied from 170 to 315 m. Shrimp catches in individual hauls ranged from 121 to 662 kg per trawl (Table 1). Towing speed was ~0.8 $\text{ms}^{-1}$ (1.6 knots).

Best fit of the regression model was obtained for a second order polynomial model with significant effects of carapace length and light colour (Table 2):

$$\text{logit}(\pi) \sim \beta_0 + \alpha_1 \Lambda + a_2\, l\, \Lambda + \beta_1\, l + \beta_2\, l^2 + b_0$$

The dispersion parameter $D$ for the presented model was estimated at 1.4, i.e. some overdispersion present. The residual inspection, however, did not reveal any indications of model mismatch. The data were thus fitted with a quasibinomial link to account for the overdispersion.

The modelled relative catch retention and catch ratio (Fig. 4, Table 3) showed increasing catch loss with decreasing shrimp size when light was used for all the light sources tested, but the pattern differed significantly between the three light sources ($X^2 = 12.1$, dof = 2, $p = 0.002$). The red light caused the least reduction, and significant loss was observed for shrimp sizes below 17.5 mm carapace length. For white light, the catch loss was significant for shrimp below 19.5 mm carapace length. Green light yielded the greatest reduction with significant loss for shrimp below 20.8 mm carapace length. These upper size limits for catch loss of shrimp were read from the estimated upper confidence limits in Fig. 4 (upper panel). For all the three comparative fishing experiments, the smallest shrimps had carapace lengths of 10 mm (Fig. 4, lower panel).

## Discussion

This study demonstrated that artificial light installed at the rear end of the trawl's belly increased the escape of small shrimp compared to an identical trawl without light. The relative escape increased with decreasing shrimp length and differed significantly between light colours.

The side and top panels were constructed of larger meshes (200 mm in front decreasing to 50 in the aft belly) than the bottom panel (40 mm), and if selection took place through the former panels, a loss of large shrimp (>20 mm CL) would have been expected. This was not the case. The escape of shrimp was most likely through the bottom panel of the trawl. Catch loss has been associated with increased mesh size in the bottom panel of a shortened shrimp trawl (Ingólfsson and Jørgensen 2020). The size of the escaped shrimp conforms with that of the aforementioned study, using 40 mm mesh sizes. Observations on the vertical distribution of northern shrimp have shown that the biomass is densest close to the seabed, although they perform some vertical migration (Barr 1970). Using a demersal trawl with a headline height of 6–7 m, Delouche et al. (2006) caught about 90% of the biomass closer than 4 m from the bottom. Similarly, Larsen et al. (1993) caught more than 50% of the shrimp biomass closer than 2 m from the bottom with an 8 m tall sampling frame. The trawls in our experiment had headline heights of about 19 m and at the position of the light, the bottom panel is 7– 9 m off the seabed. It is therefore reasonable to assume that most shrimp were passing along the oblique bottom panel when they reached the area where the light was mounted. The lights can be interpreted by the shrimp as an unknown danger, triggering an anti-predatory response (Domenici, 2002). Two alternative behavioural responses to the light stimuli can explain the observed escape; either the light immobilized the shrimp, or an active escape response was evoked. During underwater filming in front of a trawl, applying artificial white light, northern shrimp remained passive and were run over by the trawl (E. Hreinsson, Marine and Freshwater Research Institute, Iceland, personal communication). On the other hand, in close proximity to an approaching green laser beam, shrimp avoided the beam by jumping (Op. cit). Assuming the response is to remain passive, the shrimp can be considered as drifting particles of different sizes, and the approaching inclined panel with open meshes acts as a filtering device. Without the light stimuli, the shrimp may to a larger extent move actively to avoid the bottom panel. If the light triggers an active escape response to the light, the shrimp will likely seek towards the seabed or away from the light, bringing them into contact with the bottom panel where the smaller specimens can escape. Whether the response is an instance of negative phototaxis or a more general threat avoidance response cannot be discerned given the experimental setup (see Melli at al. 2018).

Size selection was obtained with all the three light colours tested. Across the range of size groups for which catch loss was observed, the green light resulted in the strongest escape response, and red the weakest. Crustaceans are known to have strongest spectral sensitivity towards green light ~500 nm (Frank and Widder 1999; Johnson et al. 2002). Males of northern shrimp with carapace lengths below 20 mm have a mean spectral sensitivity peak of 510 nm (Eaton 1972). The spectral sensitivity above 520 nm is not known. For *Pandalus montagui* and *Nephrops norvegicus*, crustaceans often caught along with northern shrimp, spectral sensitivity at 600 nm is 10– 15% of the maximum sensitivity observed at 519 nm (Johnson et al. 2002). The same spectral range and sensitivity is likely to apply for northern shrimp. This could explain the response towards the red light applied in our study, which emits light with wavelengths in the orange field down to ~590 nm.

For the visible spectrum, light absorption increases with wavelength, and at 600 nm absorption per m is about 11-fold that at 500 nm, resulting in light of shorter wavelengths travelling significantly farther in water than light of longer wavelengths (Pope and Fry 1997). To put things into perspective; with the same intensities of red (600 nm wavelength) and green (500 nm) light, the animal is likely to observe green light as 100 times more intense than the red at a distance of 1 m from the light source. In addition, due to the differences in absorption, the relative difference increases 11-fold for every additional one metre distance. Therefore, while the total radiation for the different lights varied between light colours and over time (0.46–0.03 $Wm^{-2}$ for red, 0.66–0.20 for white and 0.31 – 0.12 for green from 0.5 to 12 h use), the between-colour variations in light intensity are likely insignificant as regards the perceived visibility to the shrimp. Also, while a less marked escape reaction was observed towards the red light than those of shorter wavelengths, it is noteworthy that with the relatively low light intensities within the animal's presumed spectral sensitivity range (up to ~600 nm), and lesser area coverage due to greater absorption of the longer wavelengths, the response towards the red light was still significant. Therefore, by applying green lights, the light intensity can probably be significantly reduced and still cause the behavioural response.

Due to the possibility of damaging the eye cells of deep living organisms (Nilsson and Lindström, 1983; Shelton et al. 1985; Meyer-Rochow, 2001), light levels and exposure time need consideration. While the light intensities in this study of <0.5 $Wm^{-2}$ were in great contrast to the darkness in the deep, they are unlikely to cause permanent damage to the shrimp eyes. In addition, their placement in the top panel, distanced from shrimp passing along the lower part of trawl, render eye damages unlikely. However, while placing a light of similar intensity in the codend itself could yield comparable results, such a location could cause permanent eye damages to shrimps that escape after being exposed to proximity of the light for extended period of time.

The employed LED dive torches used batteries as a power source, and for long hauls, battery lifetime becomes an issue. Further, when choosing wavelengths, the maximum spectral sensitivity of the species and light absorption need consideration. Having chosen wavelengths with high spectral sensitivity for the shrimp, light intensity can be reduced to extend battery life or alternative torches with longer battery life explored. In the present study, all the lights appeared to shine with bright lights at the end of all tows. Still the laboratory measurements showed that the spectral intensity of red, white and green light after 12 h of operation had been reduced to 6.5, 30.3 and 38.7%, respectively, of the spectral intensities after 0.5 h of operation, Thus, the torches with green light both provide the light with maximum spectral sensitivity to shrimp and maintain the highest proportion of the initial spectral intensity after 12 h of operation. Compared to the lowest spectral intensity of 0.03 $Wm^{-2}$ after 12 h of operation (the red torch), the ambient light intensity at the fishing depth was estimated at $5.3\times10^{-4}$ $Wm^{-2}$ at 170 m depth to $4.8\times10^{-6}$ $Wm^{-2}$ at 350 m. All the torches should therefore yield marked contrast to the ambient light level at the fishing depths, as suggested by a behavioural response of shrimp to all the light sources tested.

The two identical light frames were kept on both trawls throughout the experiments. This was done to eliminate a possible effect of the light frames themselves on shrimp behaviour. The frames were mounted on the outside of the trawl, with the narrower part pointing forward to minimize drag. The torches were mounted sheltered inside the plastic frames, and we consider it unlikely that the absence/presence of the small, lightweight (0.27 kg weight in seawater) torch housing itself influenced displacement of water inside the rear end of the trawl’s belly.

Earlier studies have shown that different types of lights can alter shrimp behaviour (Nguyen and Winger, 2018). For bottom trawls specifically, LED lights placed along the fishing line in a trawl resulted in a reduction of the bycatch of several fish species without loss of the target species, *Pandalus jordani* (Hannah et al. 2015). A commercial northern shrimp trawler, fishing in the Barents Sea, tested the same type of LED lights placed alternately along the fishing lines and headlines of three trawls simultaneously. The results showed no reduction in bycatch but a large loss of shrimp (R. Larsen, The Arctic University of Norway, personal communication). The latter study suggest that the lights should be distanced from the trawl opening to avoid loss of northern shrimp beneath or above the trawl. In our study, the decision to position the lights in the top panel rather than in the bottom panel was based on earlier observations using light in combination with underwater cameras. In 2017, we conducted a study, comparing a regular trawl to a short one. In three out of 11 hauls, a camera with the same red light as tested in this study was placed in the same position, 32 m behind the fishing line. No observations of shrimp movement or behaviour could be made, but the selectivity results from these hauls with light deviated significantly, with less catch retention of small shrimp, compared to the remaining eight hauls (unpublished). If the lights elicit active escape response, placing lights at the bottom panel or in the codend itself are possible alternatives, but mud clouds generated by the ground gear rise from the bottom in a short time, reducing visibility. Attempts to film codends on muddy shrimp grounds become in many cases unsuccessful (pers. obs.; Dellapenna et al. 2006). However, placing the lights in the upper panel, distanced from the trawl opening, should keep the light above the cloud. In addition, it is a position in the rear end of the trawl funnel, where the passage is reasonably narrow (3.4 m; Fig. 2) so that the lights should be visible to most passing shrimp.

To effectively use light to size-select northern shrimp, both the escape opportunities for the animal and the light source characteristics and placement need consideration. The meshes need to be open and of a mesh size suitable for releasing small, unwanted specimen, while retaining the larger commercial-sized shrimp. Shortening of the trawl belly results in more open meshes in this section of the trawl, which in turn can enhance escape (Broadhurst et al. 2012; Ingólfsson and Jørgensen 2020). Compared to the standard commercial trawl design, this trawl has a shorter body with steeper cutting rate and its bottom panel therefore slants at a higher angle. This shorter body presumably results in more open meshes in the bottom panel of the experimental trawl, while the steeper panel increases the contact probability of shrimp with the panel as the shrimps move through the belly towards the codend. Consequently, one would expect the lights to have a more pronounced effect on size selectivity in this trawl than in the standard trawl. Thus, in combination with choice of mesh size, the behavioural response due to the presence of light resulted in size selection that can be used to reduce catch retention of undersized shrimp.

The results show that application of a simple and cost-effective solution like light can improve size selectivity in the northern shrimp fishery. By using lights that meet the spectral sensitivity of the shrimp and combining the light avoidance response of northern shrimp with the appropriate mesh size in the trawl, release of undersized shrimp can be significantly improved. For the application of lights to be considered by fisheries managers, a standardised solution needs to be available for observers to control. A permitted light source should preferably emit constant light intensity over a period corresponding to the maximum haul duration of commercial vessels. Also, a solution for sufficient mesh openings in the proximity of the light needs to be specified. As this is technically attainable, we consider the application of lights for reducing catches of undersized shrimp to be a real option.

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**Figure legends**

Fig. 1. Trawl and placement of lights. Two identical trawls were towed simultaneously, light colour varied and the lights were interchanged between the trawls. Assuming 30% lateral mesh opening and circular shape of the transect, the vertical distance from the light to the bottom panel is 3.4 m.

Fig. 2. Measured spectral radiance of the torches used in the experiment. The green light has a peak at 520 nm (green *curve,* $\Lambda$ = 522 nm), the white light (orange curve) two peaks at 458 and 606 nm, respectively ($\Lambda$ = 588 nm). The red light (red curve) has a peak at 635 nm ($\Lambda$ = 632 nm). The figure shows measured spectral radiance after 3 h use (peak intensities at 7.7, 5.0 and 2.5 for red, green and white, respectively). Colour definition followed specification 8 in https://physics.info/color/.

Fig 3. The plastic frames that were mounted on each trawl. Plastic clamps were used to facilitate easy changing of torch lights. Five cm wide stripes of silvery duct tape were adhered in front of the torches to increase light reflection. The lights are 21 cm long and 3.0-4.6 cm in diameter.

Fig. 4. Top panel: Observed (open circles) and modeled (solid line) relative catch retention. Mid panel: Relative catch ratio (*r,* equation 2) for the experimental trawl as function of shrimp size (carapace length). All measured shrimp is included in the analyses, yet the catch retention curves and confidence limits are restricted to lengths found in at least half the hauls. The coloured areas illustrate pointwise 95% confidence limits for the modeled curves. The broken horizontal lines on the top and middle plots indicate equal catches in the test and control trawls. Where the confidence limits are below the broken lines, catch loss is significant ($p<0.05$). Bottom panel: Size distributions of catches in control and experimental trawls with red, white and green lights respectively. The dotted vertical lines indicate the limits for undersized shrimp (below 15 mm carapace length (CL)) and the most valuable cooked shrimp (above 20 mm CL). Shrimp below 20 mm CL is landed raw for peeling. The y-axis for the size distribution is on a square-root scale.

## Table legends

Table 1. Haul sequence, setting time (UTC), tow duration, arrangement of lights, shrimp catches and sampling rates for each haul.

Table 2. AIC results, showing the linear components of the logistic models tested for relative length dependent catch efficiency due to the presence of artificial lights. Polynomial models with carapace length ($l$) up to fourth order were tested, with wavelength ($\Lambda$) as explanatory variable for intercept and slope (carapace length). The difference in AIC between the second and third order models (model id 6 and 9) is only 0.2 and the more parsimonious second order model thus chosen.

Table 3. Results from the quasibinomial, polynomial generalized linear mixed effect models (GLMM) for the effect of light wavelengths ($\Lambda$) on length dependent shrimp catch retention (see equation 1).

## Tables

Table 1.

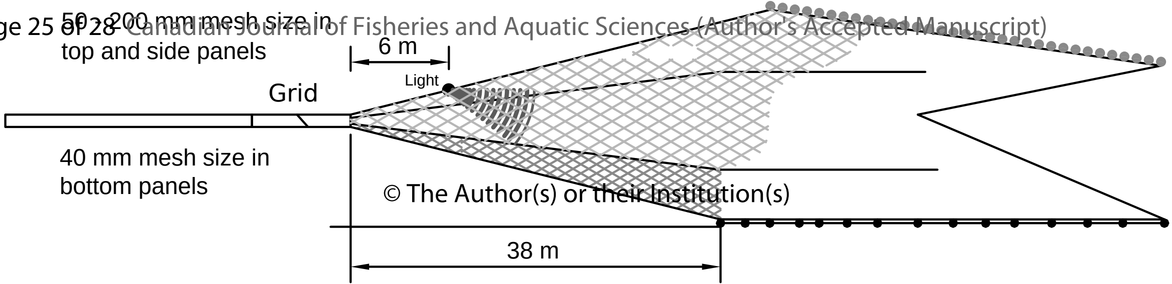
| | Tow start | | Catch (kg) | | | | | Sampling rates | |
|---|---|---|---|---|---|---|---|---|---|
| Haul no | Date (dd.mm) | Time (hh:mm) | With light | Without light | Light (colour) | Light (port, starboard) | Tow time (h) | With light | Without light |
| 1 | 17.11 | 00:47 | 570 | 662 | Red | Starboard | 13.9 | 0.005122 | 0.003557 |
| 2 | 17.11 | 18:13 | 338 | 469 | White | Starboard | 14.1 | 0.008689 | 0.005795 |
| 3 | 18.11 | 09:51 | 314 | 350 | Red | Port | 7.3 | 0.008401 | 0.007931 |
| 4 | 18.11 | 18:12 | 344 | 502 | White | Port | 5.8 | 0.008839 | 0.005746 |
| 5 | 20.11 | 03:00 | 172 | 156 | Red | Starboard | 8.0 | 0.019221 | 0.015481 |
| 6 | 20.11 | 12:08 | 415 | 391 | White | Starboard | 9.7 | 0.007386 | 0.006354 |
| 7 | 21.11 | 01:24 | 320 | 262 | Red | Port | 8.8 | 0.008214 | 0.010786 |
| 8 | 21.11 | 11:09 | 344 | 307 | White | Port | 8.9 | 0.009493 | 0.008230 |
| 9 | 21.11 | 20:58 | 543 | 545 | White | Starboard | 13.5 | 0.005804 | 0.006011 |
| 10 | 24.11 | 06:53 | 194 | 178 | Red | Starboard | 9.6 | 0.013335 | 0.016303 |
| 11 | 24.11 | 18:41 | 309 | 304 | White | Port | 13.0 | 0.009921 | 0.010966 |
| 12 | 25.11 | 09:31 | 231 | 296 | Green | Starboard | 7.4 | 0.012548 | 0.009269 |
| 13 | 25.11 | 18:03 | 364 | 355 | Green | Port | 6.0 | 0.008402 | 0.007766 |
| 14 | 27.11 | 04:40 | 290 | 323 | Green | Starboard | 7.4 | 0.010626 | 0.006375 |
| 15 | 27.11 | 13:14 | 264 | 220 | Red | Starboard | 11.8 | 0.011635 | 0.014052 |
| 16 | 28.11 | 03:34 | 201 | 204 | Green | Starboard | 11.5 | 0.014747 | 0.015570 |
| 17 | 28.11 | 16:04 | 269 | 260 | Red | Port | 11.9 | 0.009665 | 0.010253 |
| 18 | 29.11 | 04:43 | 264 | 282 | Green | Port | 13.3 | 0.010594 | 0.011320 |
| 19 | 30.11 | 09:35 | 133 | 150 | Red | Starboard | 11.9 | 0.010499 | 0.009363 |
| 20 | 30.11 | 23:18 | 161 | 168 | Green | Starboard | 12.7 | 0.021517 | 0.020062 |
| 21 | 01.12 | 13:23 | 161 | 271 | Green | Port | 10.6 | 0.025841 | 0.013635 |
| 22 | 02.12 | 01:02 | 269 | 254 | Red | Starboard | 10.0 | 0.012793 | 0.013145 |
| 23 | 02.12 | 12:15 | 336 | 458 | Green | Starboard | 11.8 | 0.009356 | 0.006782 |
| 24 | 03.12 | 23:08 | 137 | 153 | Green | Starboard | 12.8 | 0.016737 | 0.018203 |
| 25 | 4.12 | 13:12 | 300 | 272 | White | Starboard | 11.9 | 0.011874 | 0.011329 |
| 26 | 5.12 | 09:14 | 256 | 358 | Green | Port | 9.7 | 0.010242 | 0.007301 |
| 27 | 5.12 | 20:06 | 121 | 231 | White | Port | 10.1 | 0.026291 | 0.011656 |
| 28 | 6.12 | 07:27 | 286 | 318 | Green | Starboard | 12.3 | 0.014208 | 0.012389 |

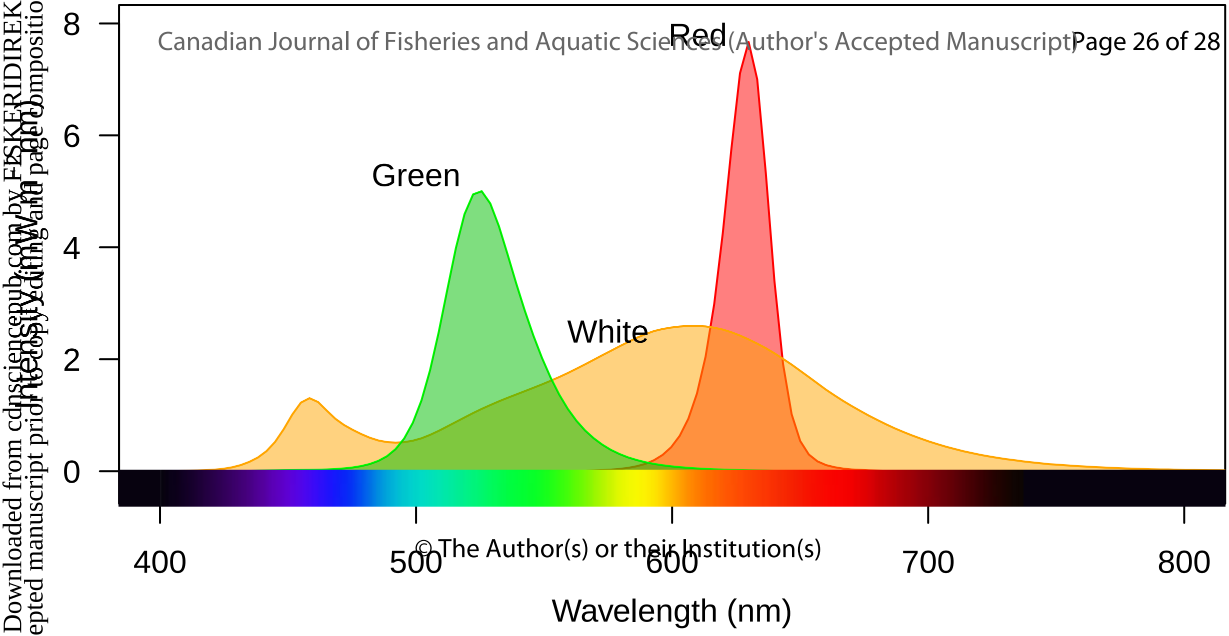
Table 2.

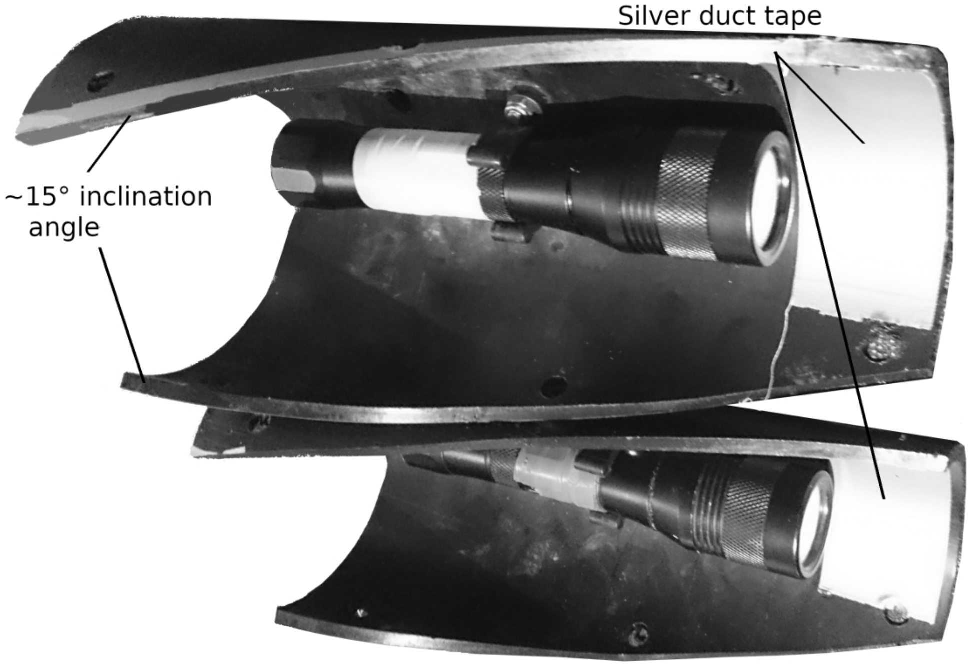
| *Model id* | *Model* | AIC |
|---|---|---|
| *0* | $\beta_0 + b$ | 3594.7 |
| *1* | $\beta_0 + b + \beta_1 l$ | 3412.3 |
| *2* | $\beta_0 + b + \beta_1 l + \alpha_1 \Lambda$ | 3408.2 |
| *3* | $\beta_0 + b + \beta_1 l + \alpha_1 \Lambda + a_2 l \Lambda$ | 3405.4 |
| *4* | $\beta_0 + b + \beta_1 l + \beta_2 l^2$ | 3403.9 |
| *5* | $\beta_0 + b + \beta_1 l + \beta_2 l^2 + \alpha_1 \Lambda$ | 3400.0 |
| *6* | $\beta_0 + b + \beta_1 l + \beta_2 l^2 + \alpha_1 \Lambda + a_2 l \Lambda$ | 3395.4 |
| *7* | $\beta_0 + b + \beta_1 l + \beta_2 l^2 + \beta_3 l^3$ | 3403.6 |
| *8* | $\beta_0 + b + \beta_1 l + \beta_2 l^2 + \beta_3 l^3 + \alpha_1 \Lambda$ | 3399.7 |
| *9* | $\beta_0 + b + \beta_1 l + \beta_2 l^2 + \beta_3 l^3 + \alpha_1 \Lambda + a_2 l \Lambda$ | 3395.2 |
| *10* | $\beta_0 + b + \beta_1 l + \beta_2 l^2 + \beta_3 l^3 + \beta_4 l^4$ | 3405.6 |
| *11* | $\beta_0 + b + \beta_1 l + \beta_2 l^2 + \beta_3 l^3 + \beta_4 l^4 + \alpha_1 \Lambda$ | 3401.6 |
| *12* | $\beta_0 + b + \beta_1 l + \beta_2 l^2 + \beta_3 l^3 + \beta_4 l^4 + \alpha_1 \Lambda + a_2 l \Lambda$ | 3397.2 |

Table 3.

| Parameter | Explanatory variable | Estimate | SE | p |
|---|---|---|---|---|
| $\beta_0$ | Intercept | -8.765 | 1.947 | <0.001 |
| $\beta_1$ | Length | 0.501 | 0.128 | <0.001 |
| $\beta_2$ | Length$^2$ | -0.0066 | 0.0023 | <0.005 |
| $\alpha_1$ | Wavelength | 0.00803 | 0.0028 | <0.005 |
| $\alpha_2$ | Wavelength × Length | -0.0029 | 0.0001 | <0.05 |
| $\sigma_0$ | Random effect (Intercept) | 0.222 |  | <0.001 |


50 - 200 mm mesh size in
top and side panels
6 m
Light
Grid
40 mm mesh size in
bottom panels
38 m


8
6
4
2
0
Red
Green
White
Intensity (mW/m² nm)
400
500
600
700
800
Wavelength (nm)



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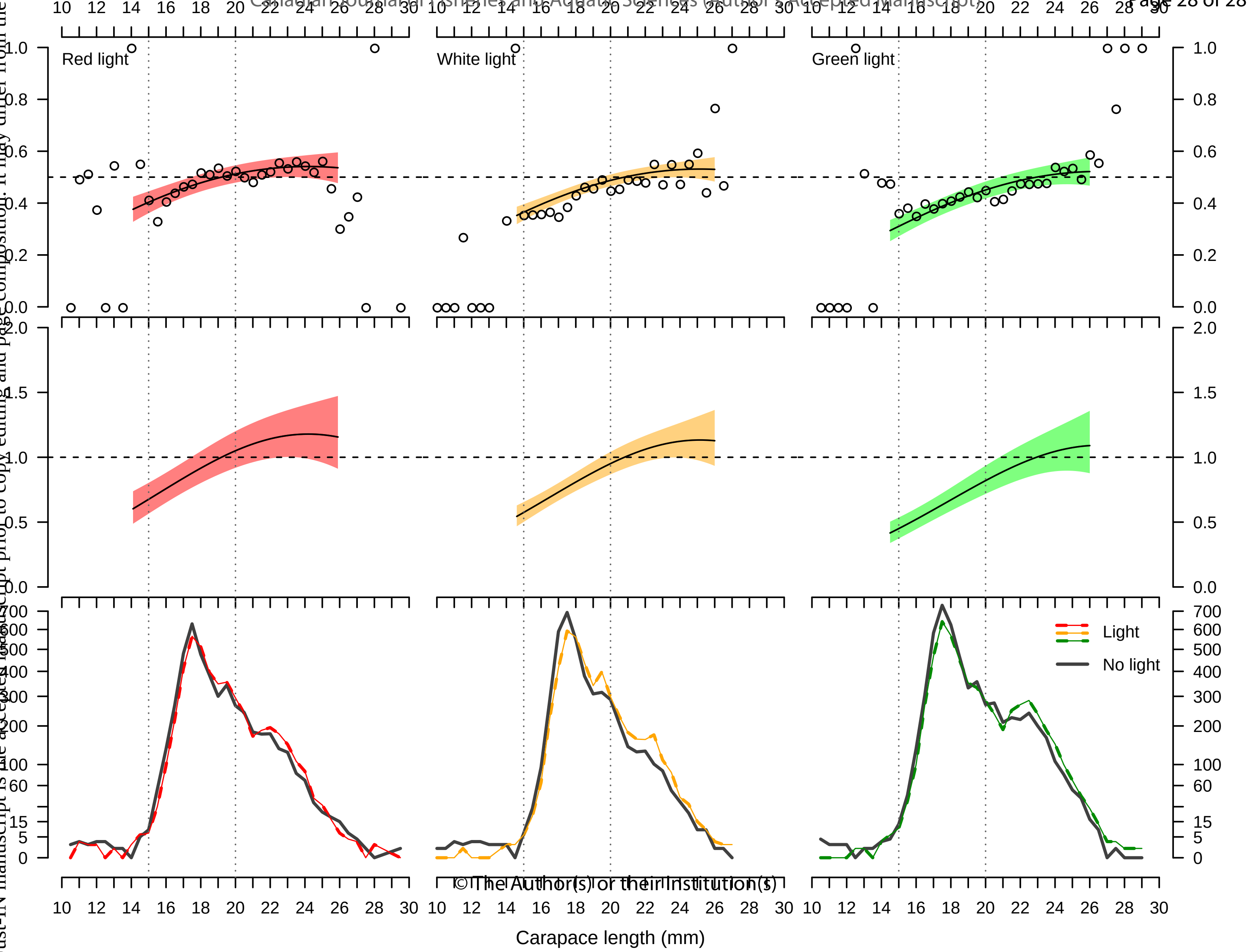
Red light
White light
Green light
Relative catch retention
Catch ratio
Frequency
0.0
0.2
0.4
0.6
0.8
1.0
0.5
1.5
2.0
0
5
15
60
100
200
300
400
500
600
700
10
12
14
16
18
20
22
24
26
28
30
Light
No light
Carapace length (mm)