MIT2022-06 Light mitigation: Reducing vessel interactions with seabirds

Draft Final Report

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Executive Summary

Artificial light produced by vessels operating at night has been shown to influence behaviour and cause negative impacts to seabirds. Of particular concern, birds may be attracted to fishing vessels by light and become disorientated and confused, leading to collisions with the vessel (vessel strikes) and subsequently injury or death.

This work describes two sets of trials examining bird responses to a series of different light treatments of varying colour and intensity. Land-based trials at a fairy prion breeding colony used short duration treatment periods in three blocks per night over a two-hour period. At-sea trials in the Hauraki Gulf used the same lights and treatments, but with longer durations and two blocks per night.

Snapshot abundance and behaviour counts were made from video footage recorded using a thermal camera. For the colony-based data, generalised linear mixed-effects models were applied to the counts from treatment periods, taking into account the experimental design and the variation in bird numbers throughout the night. Behaviour counts showed greater differences between treatments than snapshot abundance counts. Brighter and whiter lights attracted significantly higher counts of birds than low intensity amber and red lights. Environmental variables incorporated in the model, including relative humidity, wind speed, wind direction, and moon phase and illumination described variation in both the snapshot or behaviour counts. Counts of birds were much lower at sea and appeared to be dominated by variation in the number of birds attending the vessel.

Results are consistent with those in the literature and support the recently introduced Mitigation Standards to reduce light-induced vessel strikes of seabirds with New Zealand commercial fishing vessels. Based on the findings in this study we make two recommendations for future work:

- The use of amber lights should be tested under fishing conditions to see if they are suitable for use on fishing vessels.
- Support vessels to implement the mitigation standards and minimise unnecessary use of light

Introduction

Most larger fishing vessels will spend multiple days at sea and often operate at night, requiring the use of artificial light. Longlining does not require bright light outside of the vessel during shooting operations, however hauling gear at night requires the area beside and in front of the hauling station to be illuminated. Trawlers need to illuminate the area around and behind the stern of the vessel during shooting and hauling operations, whereas gear maintenance, cleaning, and sorting fish require illumination of the deck area. At times when the vessel is steaming or crew are working below deck less light is necessary, however it is desirable from a safety point of view to constantly provide some form of illumination. Many vessels will use working lights, in addition to navigation lights, to increase visibility to other vessels, and to allow safe movement around the vessel, when at anchor or lying to. The use of lights to attract target species, for example in the pilchard purse seine and squid jig fisheries, is not currently common in New Zealand.

The effect of artificial light at night on wildlife in general, and seabirds in particular, is well documented in the literature and comprehensively summarised in an Australian Commonwealth (2020) publication "National light pollution guidelines for wildlife". This report stresses the importance of managing light spill, intensity, and colour to minimise impacts on vulnerable species, and recognises that seabirds are likely to perceive light differently to humans, with vision further into the ultraviolet frequencies.

Rodrigues et al. (2017) note that burrow-nesting procellariforms are most affected by grounding due to lights, especially fledglings. Studies at colonies with different lights emitting different spectra have shown the potential for warmer-coloured lights to reduce bird attraction, and that fledglings are more susceptible than adults (e.g., Rodriguez et al. 2017b).

Analysis of collisions of birds with commercial fishing vessels, recorded by observers as 'vessel strikes' is confounded by differing levels of observer coverage and effort in different fisheries, areas, and seasons as well as variations in overlap with different species. The degree of observation effort is not recorded and will likely depend on where the observer is working on the vessel, and their other tasking. However, it appears that species such as diving petrels (*Pelecanoides spp.*), storm petrels (family *Oceanitidae*), and prions (*Pachyptila spp.*) are over-represented in the data (Holmes, 2017). Instances of large numbers of birds striking vessels are rare and tend to have been correlated with areas adjacent to breeding colonies, fledgling periods, and poor weather condition such as low cloud, overcast, drizzly, misty, foggy conditions which created a 'halo' effect around vessel lights (DOC pers. comm.).

Mitigation Standards to reduce light-induced vessel strikes of seabirds with New Zealand commercial fishing vessels (DOC & MPI 2023) describe actions to minimise the number of birds killed or injured due to light-induced disorientation and attraction to vessels. These include:

- Lights not essential for operations and/or vessel/crew safety are eliminated.
- Activities requiring external lighting at night are avoided whenever possible.
- High-risk areas are avoided at high-risk times when using external lighting at night.
- All essential lights are shielded, angled, and/or positioned to only light areas required for operations and safety and minimise light spill.
- All essential lights use the lowest intensity as appropriate for operations and vessel/crew safety.
- Windows are blacked out wherever and whenever practical (e.g., while at anchor).
- All essential lights filter light spectra as appropriate for operations and vessel/crew safety.
- Minimise all deck lighting (including outward facing lights) that is not necessary for ship or crew safety, especially when the vessel is sheltering or anchored near seabird breeding colonies.

These standards are translated into vessel-specific plans which generally include generic wording promoting the minimum light levels required for safe operation and that particular care be taken around seabird colonies, especially in low visibility and during fledging periods.

The recent shift from incandescent to LED lights has changed the spectra of light emitted. The most commonly available and cheapest LED lights tend to produce a 'high temperature' or white – blue light of around 5-6000 K which is near daylight from a human perspective. Coloured LEDs allow for the temperature of lights to be tuned to specific temperatures, albeit with an increase in price and typically a lower temperature, warmer, and more yellow light (R. Surrey, pers. comm.). LED lights also hold the advantage that they can be configured directionally and do not require the reflectors used to concentrate the output of incandescent lights.

The previous iteration of this project (Lukies et al. 2021) identified the need for further work examining the potential for use of different light types to reduce attraction of seabirds. Two land-based trials over a total of 12 nights and seven nights at sea trials on two boats were conducted. Three higher-power white light combinations were tested including LED, halogen and fluorescent lights, and lower-power white, red, and green LEDs were also included. The number of birds observed was significantly different between the Little Barrier (Hauturu) and the Mokohinau (Pokohinau) Islands land-based trials, but not between different lighting treatments.

Objectives

1. Characterise current light set-ups in use on fishing vessels.
2. Improve initial trials of different light set-ups both on land at seabird colonies and at sea on commercial fishing vessels.
3. Identify options for mitigating vessel strikes.

Methods

Proposed methods were presented at a Conservation Services Technical Working Group (CSP TWG) and refined following feedback, including not providing attractants such as berley or chum when conducting at-sea trials.

Lighting rig

Based on conversations with fishers and industry representatives, and experience at sea across the New Zealand fishing fleet, it was clear that there is a lot of variation in lighting types and tasks which require light both within and outside the vessel. Many, especially smaller, vessels are replacing incandescent lights with LED equivalents and adding small LED lights for specific tasks. Due, at least in part, to the Liaison Programme there is an awareness of the need for reducing lighting where possible and LED lights were noted by skippers as proving relatively cheap and easy lighting solutions for specific tasks. With the shift to LED lights, it was deemed prudent to source reasonably powerful marine grade LED lights similar to those used to light up areas around the boat, for example during recovery of fishing gear. Few options were available off-the-shelf however Hella NZ were helpful and were able to supply suitable ‘extreme environment’ rated LED work lights. Red LEDs were sourced separately from a company supplying apiarists, as they use red light to minimise disruption to bees when working on hives at night.

Hella Hypalume LED lights with twin light bars were used to provide amber and white light. The white light was rated at 28,000 lumens, and 240 V AC powered. The separate light bars were switched independently to provide full and half power settings for the white light. The amber light was rated at 19,000 lumens and powered with 24V DC. A shade covered one of the light bars to provide a half-power setting for the amber light. Six 24V DC Bee clam red LED lights, each rated at 800 lumens, were used to supply red light.

All lights were powered by a Honda eu20i petrol generator at least 10 m away from the lighting rig, which was left running throughout the experimental period.

Takapourewa | Stephens Island trials

Stephens Island is a remote island at the north of the Marlborough Sounds (Te Tau Ihu o Te Waka-a-Māui) in the Cook Strait (Raukawa Moana), with a land area of 1.5 square km and at its summit sits 283 m above sea level. A fairy prion (Tītī wainui, *Pachyptila turtur*) colony of more than a million pairs (Taylor, 2000), covers a large part of the island. Prions typically lay in November and the trials were conducted in December and January, pre-fledging, as monitored by DOC staff. This was important to avoid any fledglings forming part of the bird counts. Trials were conducted beside a track running on the eastern side of the island about 80 metres below the ridgeline (Figure 1).

Figure 1. Location of trials on Stephens Island. Red lines show approximate arc of light.

Lights were attached to a single pole one to three metres above ground level and positioned perpendicular to the earth's surface. The setup was orientated seawards, facing south-east, and the ground sloped downwards toward the sea at approximately 50 degrees (Figure 4b).

Trials were conducted by DOC staff, on days when time, availability, and weather allowed, during the period between 8th December 2022 and 18th January 2023. A total of seventeen nights were sampled between 2200 and 0000 hours, and each night was split into three treatment blocks. Each block contained six one-minute treatments, with each treatment separated by a five-minute dark interval (i.e., lights off). Treatments included a no light (dark) control, red light, high/low intensity white light, and a high/low intensity amber light. Treatments were run in a randomly assigned order (using a random number generator), for each block. In addition to recording bird abundance and behaviour using a thermal scope, researchers also used a recording sheet to annotate the number of birds grounded, the number of collisions with the lighting rig, the maximum number of birds visible with the naked eye, per treatment, cloud cover, moon visibility related to cloud cover, moon phase and any other relevant information.

At sea trials

A fibreglass 12 m charter fishing vessel was used for at sea work. The fishing vessel was clean with no bait or berley on board. Lights were rigged on a frame at the stern of the vessel, three metres above the water level. The lights were angled downwards approximately 30 degrees from horizontal to illuminate an area close to vessel, as was deemed typical during fishing operations. The thermal scope was attached to a gimbal 1.5 m below the lights and one metre forward of the stern (Figure 2).

Figure 2. Lights and camera mount at the stern of the vessel (left) and lighting rig in use (right),

Trials were conducted on three consecutive nights starting on 13th March 2023. Each night, two randomised treatment blocks were tested with the same six treatments as on Stephens Island. The first block typically started at 2030 hours and the second at 0230 hours. Within each block, treatments were tested for 20 minutes and separated by a 10-minute dark period. Prior to the first treatment footage was collected for a seven-minute dark period, unless the first treatment was the control. On the first night the first treatment block was completed whilst dodging slowly into the wind to the east of the Hen and Chickens Islands (Marotere) and then the second block was completed at anchor on the north side of the islands. On the second night tests were conducted whilst drifting between the Hen and Chickens and Little Barrier (Hauturu), to the north of the shipping channel, and on the third night testing was undertaken further north again dodging into the wind, following reports from game fishers of more bird activity (Figure 3). Speed over the ground during all treatments was less than a knot, and between treatments the vessel steamed back to the start position at approximately three knots.

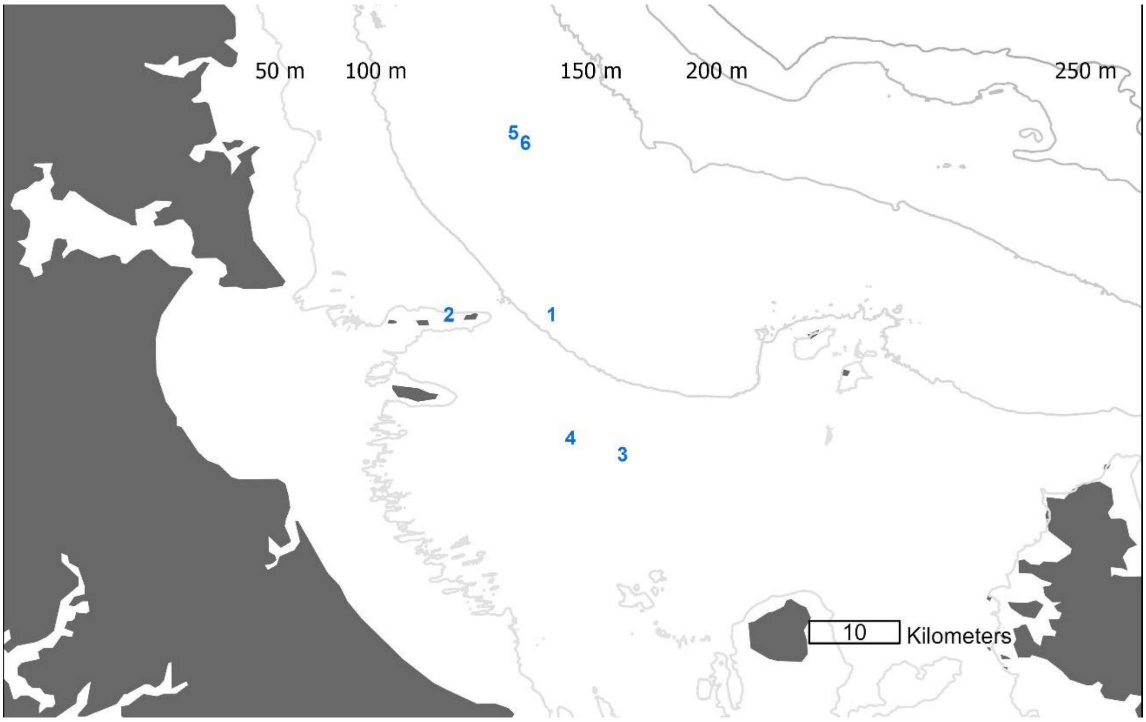

Figure 3. Location of at sea trials showing location of sequential treatment blocks. Two blocks were conducted per night.

Thermal camera

A Pulsar Helion XP38 thermal imaging camera was used to record bird abundance and attraction of the birds to different coloured lights and light intensities (Figura 4a.)

Stephens Island

The thermal imaging scope was set up on a tripod beside the lighting rig a metre above ground level, orientated horizontally and along the light beam and maintained in the same position throughout all experiments (Figure 4b) This was set to record continuously throughout the trial each night and produced consecutive seven-minute clips. The scope was set to auto calibrate for the first four nights and then used in manual mode thereafter. The image was cast to a separate screen using the stream vision app, to facilitate manual focussing and checking of time stamps and image quality. The pre-set rocks mode with a 2.7x digital zoom setting was used, cropping the full sensor image to 450 x 338 pixels with a field of view of 11.4 x 8.6 degrees (horizontal x vertical). The focus was set to a distance of approximately 100 m. The audio function on the camera was used to identify treatment periods, with the researcher verbally calling out the start/stop time.

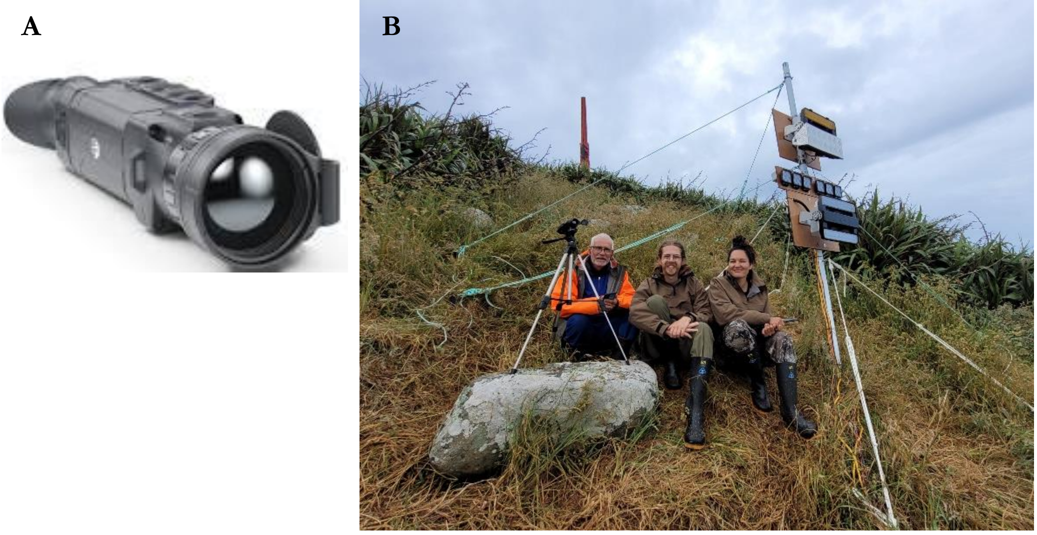

Figure 4. (a) Image of the Pulsar Helion XP38 thermal imaging camera and (b) relative position of tripod to the lighting rig

At sea

Following failure of the hard drive in the scope a new identical unit was supplied by DOC for at-sea trials. Footage used the minimum 1.9x (optical) zoom to give 640 x 480 resolution with a field of view of 16.3 x 12.3 degrees, and the forest mode was employed. Footage was not recorded between treatments to save hard drive space, and the focus was adjusted prior to the start of each treatment, and during treatments if deemed necessary. Footage was not cast to a screen, due to intermittent connection problems common to the scope.

Video review

Footage was reviewed by a single reviewer. Consecutive video clips which were stitched together for each night's footage, without rendering, using avi-demux software.

Stephens Island

Combined clips were reviewed twice, initially at two thirds speed, to count the number of birds visible at 10, 20, 30, 40, and 50 seconds into each treatment. The second review of each treatment minute at half speed, the number of birds observed to deviate from a straight flight path and turn towards the centre of the light beam, and the number of times a bird flew towards the camera was counted. This process was repeated for dark periods one minute before each treatment. Counting birds flying towards the camera aimed to capture movement in the light beam towards the light, and counting birds turning in the frame included those that were confused, disorientated, and trapped by the light. This was chosen as it was thought to be a more appropriate proxy of vessel strike risk than abundance.

At sea

Counts were made of the number of times a bird entered the video frame, by treatment and block. Review speed was 1.5 times.

Environmental variables

Data collected from a weather station located at the lighthouse approximately one kilometre from the study site on Stephens Island was sourced from the Meteorological Service of New Zealand. Records included wind speed, wind direction, relative humidity and precipitation.

At sea, the vessel heading and environmental variables including wind speed and direction, swell height and direction, and vessel heading and drift were recorded manually.

Data analysis

Statistical analysis was carried out in R (R Core Team (2021). To evaluate differences in the number of birds observed between treatments, generalised linear mixed effects models were used within the glmmTMB package (Brooks *et al.* 2017). The response variables were snapshot bird counts (number of birds observed in the field of view, repeated five times within each treatment period) and behaviour counts (the number of birds observed to turn in the video frame or move towards the camera). Poisson, generalised Poisson, and negative binomial distributions were tested to see which best fitted the models, and based on Akaike information criterion the Poisson distribution was selected for the general counts and the negative binomial for the behaviour model.

A random effect of treatment blocks nested within nights was included to account for differences in the number of birds between nights and segments of each night. Only for the snapshot counts, multiple measurements per treatment were included by adding treatment to this nested random effect.

Fixed effects included treatment (five treatment light colours and a dark control), as well as relative humidity, cloud cover, windspeed, and the time of night. The extent of eastward and northward wind direction was included as a fixed effect as the sine and cosine of the wind direction, respectively. A proxy of moon phase was also included, by using moon illumination (based on date and location, from https://www.timeanddate.com/moon/phases/@2182351). This measure represents the closeness to full moon (but does not distinguish between waxing and waning moon). Moon brightness was included as this same measure of moon illumination if the moon was visible, and zero if not (behind the hills, horizon, or clouds). To account for a variation in numbers of birds through the night in the model an offset of the mean count during one-minute dark periods prior to the treatment was included, or if the mean was zero a count of one was used.

For the at sea data, a negative binomial generalised linear mixed effect model was used to take into account the nested structure of the data (number of birds observed to turn into the video frame or move towards the camera, up to 20 times per treatment) to calculate the mean treatment counts.

The DHARMa package (Hartig 2022) was used to check model diagnostics, including distribution assumptions, heteroscedasticity, and outliers. Differences between treatments were assessed using the emmeans package (Lenth 2023).

Results

Stephens Island

Video footage quality varied but was reasonably consistent within nights and blocks. At times birds were hard to distinguish against the background and at other times were only visible in part of the video frame. Repeatedly viewing short sequences of video before and after snapshot counts allowed for more accurate counts.

Snapshot counts of birds in the video frame were highest in early December, with typically less than 20 individuals in the frame, and dropped off in mid to late December to generally less than ten individuals and further to less than five individuals in January. Considerable variation was apparent between treatments, blocks, and nights. Numbers of birds counted in the dark and treatment periods were generally similar, except at higher abundances.

Model results showed significant differences between some treatments, with higher counts in the more intense and whiter treatments (Figure 5).

For the environmental variables less northerly wind, days closer to full moon, less moon brightness, and later times all correlated with an increase in counts (Table 1). All environmental variables contributed to explaining the variation in the observed data (as determined by the Akaike information criterion).

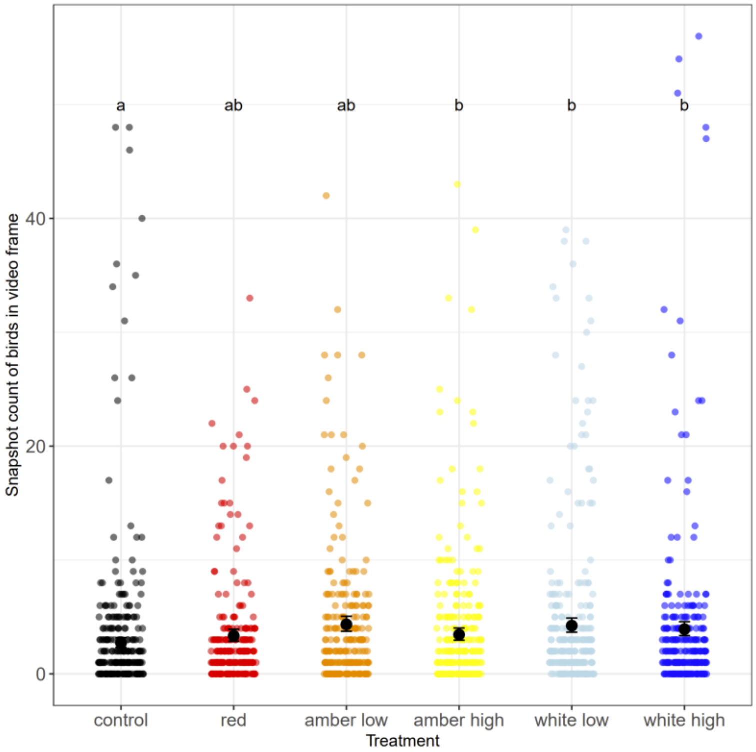

Figure 5. Plot showing raw snapshot counts with means and 95% confidence interval error bars. Significant differences between treatments derived from post-hoc tests are indicated by letters above each treatment (if two treatments have different letters this indicates that the treatments are significantly different; if they share a letter this indicates they are not significantly different).

Table 1. Results from the snapshot counts model showing effect chi-square value, estimated coefficients and standard error (log scale) and p-value for the variables included in the model.

Snapshot counts model

	Chi square	estimate	standard error	p-value
light treatment	26.07			< 0.0001
control		-4.598	1.482	
red		-4.388	1.479	
amber_low		-4.128	1.478	
amber_high		-4.359	1.480	
white_low		-4.154	1.477	
white_high		-4.230	1.478	
relative humidity	3.45	0.006	0.003	0.06
wind speed	0.38	0.002	0.003	0.54
wind eastwards	3.03	-0.091	0.052	0.08
wind northwards	17.11	-0.374	0.090	< 0.0001
cloud cover	1.17	0.001	0.001	0.28
moon phase	11.22	0.004	0.001	< 0.001
moon brightness	37.60	-0.010	0.002	< 0.0001
time	6.11	0.155	0.063	0.01

Behaviour counts, normalised using data from the dark periods prior to each treatment, showed clear differences between light treatments (Figure 6). The number of birds changing their behaviour did not differ between the dark control and red light, and all other treatments resulted significantly in higher bird counts. In general, whiter and brighter treatments resulted in higher counts (Figure 6).

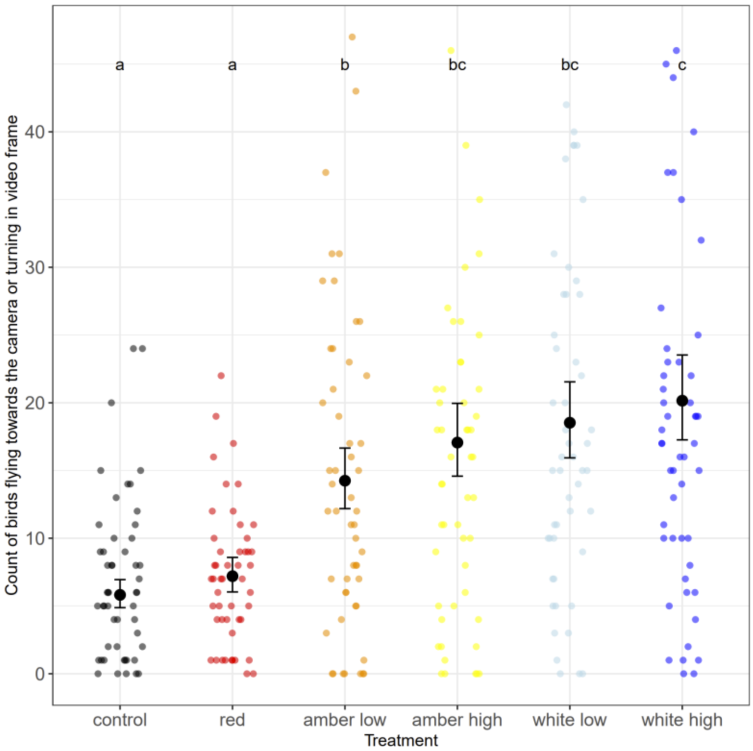

Figure 6. Plot showing raw behaviour counts with model estimated means and 95% confidence interval error bars. Significant differences between treatments derived from post-hoc tests are indicated by letters above each treatment.

Later at night, higher humidity, and lower wind speeds resulted in more birds flying towards the camera or turning in video frame (Table 2). All environmental variables improved the model fit, as determined by the Akaike information criterion.

Table 2. Results from the behaviour counts model showing chi-square value, estimated coefficients and standard error (log scale) and p-value for the variables included in the model.

Behaviour counts model	**Chi square**	**estimate**	**standard error**	**p-value**
treatment	199.26			< 0.0001
control		-6.65	1.73	
red		-6.44	1.73	
amber_low		-5.76	1.73	
amber_high		-5.58	1.73	
white_low		-5.50	1.73	
white_high		-5.41	1.73	
relative humidity	21.26	0.02	0.004	< 0.0001
wind speed	4.07	-0.01	0.004	0.04
wind eastwards	0.15	0.03	0.07	0.70
wind northwards	0.11	-0.04	0.11	0.74
cloud cover	2.76	0.002	0.001	0.10
moon phase	1.70	-0.002	0.001	0.19
moon illumination	12.58	-0.006	0.002	<0.001
time	9.90	0.23	0.07	0.002

Seven collisions occurred with the lighting rig; one during an amber high treatment, three during amber low treatments, two during a white low treatment and one during a red treatment. A total of 34 birds were grounded during treatments with higher numbers grounded in brighter and whiter treatments (Figure 7). No birds were observed to have lasting injuries.

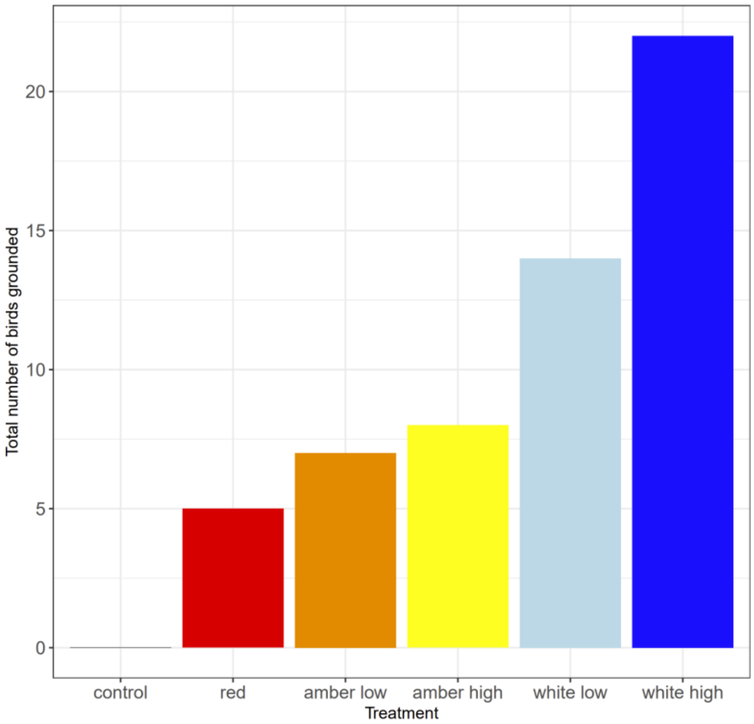

Figure 7. Total number of birds grounded per treatment

At sea

Video footage was clearer than that from Stephens Island, due to higher resolution, better definition between birds and the background, more in-focus images, and no areas where the image was saturated. This allowed for counts to be made at higher playback speed. The use of a gimbal provided a consistent field of view vertically, with the horizon static in the frame. The gimbal did not cope with horizontal displacement so well and the image swung through one to two degrees due to vessel roll and yaw. The frame also drifted horizontally occasionally, requiring manual resetting. Overall, use of the gimbal was considered worthwhile, providing a reasonably consistent view astern, which simplified video review.

Weather conditions were good with little or no swell and less than 15 knots of wind. Low numbers of birds were observed on the first night, either at sea or at anchor close to the islands. Slightly more birds were observed on the second and third nights but still less than 10 individuals were visible at any one time. Black petrels (Tāiko, *Procellaria parkinsoni*) and flesh-footed shearwaters (Toanui, *Ardenna carneipes*) appeared to be comfortable in the light beam and were observed to follow the vessel and to forage in the light, mostly at the edge of the lit area. They also spent time sitting on the water, both within and outside the lit area, more so during periods with lower wind speeds. Cook's petrels (Tītī, *Pterodroma cookiii*) and storm petrels spent more time on the wing and exhibited more erratic flight paths including sharp turns and hovering in the light beam. Prions also appeared to be more sensitive to light than either black petrels or flesh-footed shearwaters and were observed flying in long sweeping arcs, at times turning to stay within the lit area.

No collisions with the lights or the vessel occurred, though one bird narrowly missed colliding with the white light. Counts of birds entering the video frame were variable between treatments, blocks and days, with no consistent pattern apparent (Figure 8). The small number of birds per treatment and small number of replicate treatments did not allow for a thorough analysis.

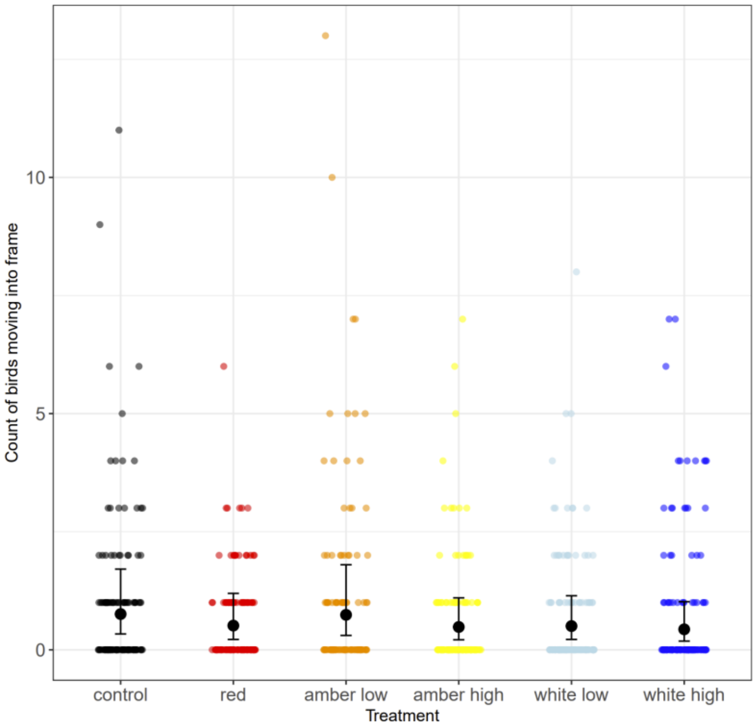

Figure 8. Per minute counts of birds moving into the video frame, by treatment, for the at sea data. Black dots indicate treatment mean (taking into account the distribution and nested structure of the data) and error bars are 95% confidence intervals.

Discussion

Model results for the land-based trials showed significantly higher snapshot counts of birds in the high amber, low white, and high white treatments compared to the control. The mean behaviour counts showed increasing numbers of birds turning in the light beam and/or flying towards the camera with increasingly whiter and brighter lights. The red and control treatments were not significantly different to each other but were significantly different to all other treatments. Low amber lights showed significantly lower counts than high white lights. Counts of grounded birds showed a similar pattern with increasing numbers with brighter and whiter lights, albeit with a small sample size.

Snapshot counts of birds were less informative than classifying and counting bird behaviour (Figures 5 and 6). This appeared to be due to generally similar snapshot counts before and after the lights were turned on. However, at higher abundances, the difference between snapshot counts in the dark period prior to the treatment and during the treatment were more apparent. Consequently, a wider field of view and associated increase in numbers may have provided more information. Making counts of behaviour had the advantage of incorporating bird abundance and potentially acted as a better proxy for vessel strike risk. However, it was more subjective than snapshot counts of individuals, so was more prone to observer bias, and therefore less repeatable. It should be noted that the video was only reviewed by one reviewer, and different behaviour counts could be expected from a second reviewer.

Model results from the snapshot count data indicated an increase in counts with a less northerly wind direction and time of night. The increase in snapshot counts with a less northerly wind direction may be due to the birds preferentially approaching the island downwind.

For the behaviour data, the increase in counts with lower wind speed may be related to the increased precision with which birds can manoeuvre in lower windspeeds, with less gliding and more flapping flight.

The increase in counts with relative humidity may be attributable to greater illumination of water particles in the air increasing the visibility and/or confusing nature of the light. High humidity, cloudy and foggy conditions, and poor visibility are often associated with vessel strikes (Merkel and Johansen, 2011, pers. obs. DG.).

Despite accounting for changes in number of birds using the offset derived from the dark periods prior to each treatment, later times in the night produced significantly higher snapshot and behaviour counts. So, while overall number of birds returning to their burrows decreases after a peak some hours after sunset, relatively more birds were attracted later at night. This could be attributable to a higher proportion of non-breeders active at later times of night, and non-breeders being more attracted to light. This is supported by non-breeders being selectively targeted for banding using spotlights in long-term studies of light-sensitive seabird species (Fischer et al. 2022).

The inclusion of moon illumination and phase into the model improved model fit. This is unsurprising in that lunar cycle commonly drives behavioural patterns (e.g., Bastos *et. al*, 2022). Moon phase seemed to be much more important for how many birds are around in general (snapshot count) than for behaviour counts. When the visible moon in the sky was brighter this also resulted in more birds in snapshot count, but this trend was opposite in the behaviour metric: brighter moon resulted in fewer birds flying directly into the frame. Our model included an index of the fullness of the moon, and the impact of more detailed moon phases (including waxing vs waning) could be further investigated.

Low numbers of birds attracted to the vicinity of the vessel limited the usefulness of the at-sea dataset. Although reasonably high counts were made in some blocks, sometimes the same birds were counted several times as they flew in and out of the video frame. This is not a problem per se but did mean that detecting differences between treatments was reliant on very small numbers of birds, with variable activity levels through the night. Steaming back to the same start position between treatments seemed to provide a reasonable break and a 'reset' of the number of birds behind the boat. Whilst advantageous in that it maximised the independence of treatments and required any birds in the area to 'find' the boat again once the new treatment started, it did increase differences in bird abundance in the area around the vessel between treatments. At sea observations indicated that bird activity may, at times, be concentrated towards the edges of the lit area as opposed to the centre, further supporting the need for a camera with a wider field of view.

Review of the at-sea footage was simpler and quicker due to the smaller number of birds and better video definition. The wider field of view, higher resolution, different camera, different settings, regular focus checks, and different conditions all could have contributed to higher quality footage and faster review. The use of a gimbal and orientating the lights and camera aft minimised, but did not eliminate, the problems associated with recording video from a moving platform. A larger vessel would have been more stable, but also more expensive.

Overall, the use of the thermal imaging scope was successful, and the optics and sensor were more than adequate for detecting birds out to several hundred metres. However, the scope used in the current study was designed for spotting game and had a very restricted field of view. For future work it would be worth investing in a wider-angle camera at the cost of some definition, however the trade-off would have to be considered carefully. A fully gyro-stabilised camera should also be considered.

The duration of treatments was appropriate and produced useable data. A cautious approach was taken on Stephens Island with short 'light on' periods due to the large numbers of birds. Finishing data collection prior to chicks fledging likely reduced collisions and mass groundings as well as bird counts. Longer treatment periods were necessary at sea, and 20 minutes provided two distinct blocks per night. With limited sea time, running more repeats of fewer treatments may have provided more useful data, but a small number of birds would likely still have resulted in a lack of statistical inference.

The land-based trials were slightly different from those undertaken by Lukies et al. (2022). Brighter lights were used and angled horizontally rather than up into the sky. More nights, a larger colony, and different species may have contributed to significant differences between treatments, despite shorter treatment intervals. The use of a behaviour metric as opposed to abundance counts also showed greater differences between treatments.

Overall, the results presented here support those in the literature, namely that reducing intensity and controlling the colour of lights can minimise grounding and the attraction and disorientation of birds (see review by Lukies et al. 2022). In this case lower intensity and 'warmer' lights appear to be beneficial. The Mitigation Standards to reduce light-induced vessel strikes of seabirds with New Zealand commercial fishing vessels (DOC & MPI 2023) are supported by these results. The use of red light, which was indistinguishable from the control treatment, should be considered where appropriate, especially in higher-risk areas. For example, if light is required for crew to move around the vessel at night when at anchor close to colonies then a set of red LEDs would be a worthwhile investment.

Whilst focussed on the fishing fleet, it should be noted that other vessels operate at night with varying lighting requirements, and the recommendations and mitigation standards are equally applicable to those fleets.

Recommendations

Although not necessarily a common occurrence for any one vessel, vessel strikes do injure and kill seabirds. Occasional kills across a fleet, and very occasional mass events, have the potential to add up to serious consequences for (especially small) populations. Some interactions could be avoided, and the risk of interactions minimised, by better management of light. The Mitigation Standards to reduce light-induced vessel strikes of seabirds with New Zealand commercial fishing vessels (DOC & MPI 2023) provide a solid framework for improving the status quo, and efforts should be made to facilitate changes on vessels in line with the standards.

Light audits should be undertaken to establish what level of lighting is required for different areas of the vessel during different operations, and a vessel specific light management plan drawn up to minimise unnecessary use of light. Light 'spill' should be measured and minimised by careful consideration of light placement, and the use of shades and non-reflective surfaces. Vessel light management plans should include the location of breeding colonies and timing of fledging periods within the vessel's area of operation to identify areas and times of year where it is desirable to run a 'dark ship', especially under conditions of poor visibility.

Warmer 'off the shelf' amber lights such as those used in this project should be tested under fishing conditions to see if they are suitable for use on fishing vessels, particularly when illuminating areas outside the vessel, for example when hauling longlines or shooting and hauling trawls.

Further at-sea trials would benefit from more repeats, a more appropriate camera, and simpler treatment schedules in order to increase the likelihood of detecting differences between treatments. Similarly, the slow release of fish oil could provide a consistent attractant without specific feeding opportunities, to increase abundance around the vessel.

Further colony-based trials would provide biological information on different species.

Contributions

Method development DG, KM, GT, JF, AR; Rig design and build DG, Stephens Island rig assembly and supervision of research assistants KM, Stephens Island video capture KM, KD, HB, MLL, MLL, at sea data capture DG, video review DG; data analysis EC, reporting DG, review KM, EC, JF.

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