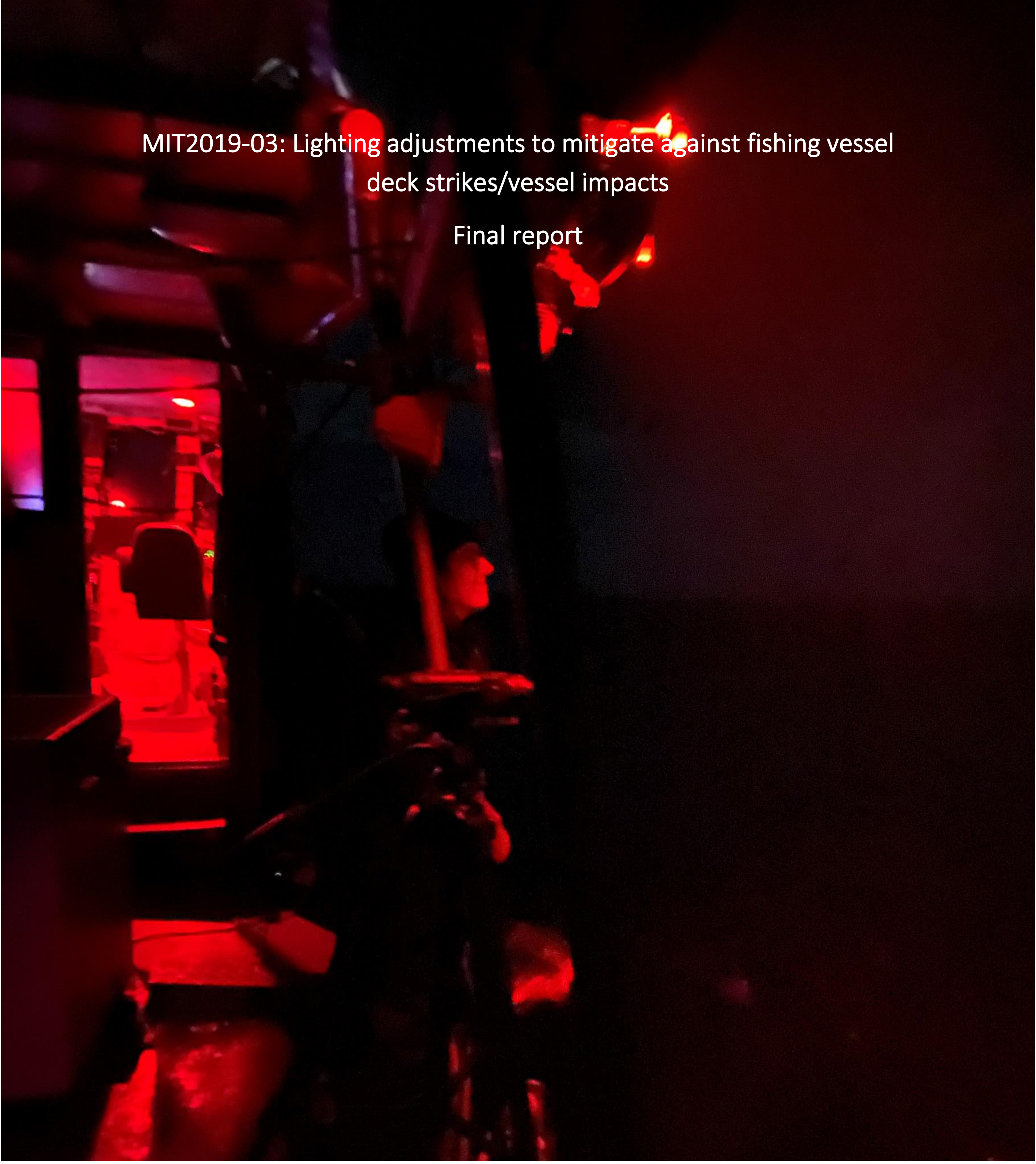

MIT2019-03: Lighting adjustments to mitigate against fishing vessel deck strikes/vessel impacts

Final report

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Cover image/Figure 1 - Red LED light treatment on board commercial long line fishing vessel Southern Cross. *Photo: Chris Gaskin*

Contents

Overall summary

Artificial light at night (ALAN) can negatively impact the behaviour of nocturnally active seabirds by causing disorientation, exhaustion, and injury or mortality from light-induced collisions. Procellariiformes (e.g., petrels, prions, shearwaters, diving petrels and storm petrels) are disproportionately attracted to ALAN compared to other seabird groups, fledglings on their maiden flight are most at risk. The Hauraki Gulf has one of the world's highest diversities of seabirds, including several threatened species. Many of the species in the region are vulnerable to light pollution. While most of these species breed on uninhabited offshore islands, the extensive shipping activity in this region puts seabirds at great risk of light-induced collisions with vessels as they pass or are anchored nearby. This includes fishing vessels working at night.

The first part of this study, undertaken on two seabird islands, tested which light intensities and colours were least attractive to seabirds through behavioural experiments where we shone lights into the sky and recorded seabird attraction. We also modelled the lights into the visual system of seabirds to identify how seabirds perceive lights differently. Our land-based experiments showed an equal statistical attraction to the light types we tested but provided anecdotal observations where more research and larger sample sizes are required. The number of seabirds trapped in the light beam differed by island and moon phase. The number of seabirds observed in thermal imagery differed by island and moon phase when comparing small LED lights only. Fifteen birds were grounded, most on Pokohinu Burgess Island during the flood LED treatment. Differences between islands likely reflected the local seabird diversity at each island.

The second part of this study, undertaken on vessels either anchored near the Mokohinau Islands or drifting off the eastern Coromandel, tested which light intensities and colours were least attractive to seabirds through behavioural experiments where we shone lights horizontal to the vessel and recorded seabird attraction. Significantly more birds were observed in thermal imagery and from near the Mokohinau Islands than the eastern Coromandel, possibly due to the species present on each of the island groups or the time of year or vessel used during the experiments. Additionally, statistically significant numbers of birds were observed in thermal imagery and in boat-based observations closer to sunset and sunrise than during the middle of the night. Boat-based experiments showed an equal statistical attraction to the light types tested. The logistical challenges and resource constraints were key limitations resulting in small sample sizes.

Further research into the effects of ALAN in the Hauraki Gulf, and globally, is urgently required to address the increasing threat of ALAN to seabirds, especially for those species listed as threatened. The recommendations for future boat-based behavioural experiments should attempt to target specific seabird species that are vulnerable to ALAN, time experiments to incorporate a greater range of moon phases and weather, augment experiments to obtain more data for each treatment (and preferably without confounding variables, such as time of year and location), increase the number of each light type to be more consistent with the level of deck lighting used on fishing vessels, and invest in

automation of detection to reduce the labour involved in manually detecting birds in thermal videos.

Introduction

Seabird attraction to artificial light at night

Artificial light at night (ALAN) is intensifying globally as a result of human activities and is increasingly recognised as a threat to biodiversity (Kyba et al., 2017; Longcore & Rich, 2004). Most animals have circadian clocks governed by the night-day cycle and it is because of this that ALAN can disrupt behaviours such as foraging, migration, communication, rest and recovery (Hölker et al., 2010). Advances in technology have promoted a shift towards more energy-efficient lighting systems without first understanding how these artificial lights impact the nocturnal activities of animals (Longcore & Rich, 2004).

Light attraction and disorientation are well documented in nocturnally active seabirds and ALAN has been found to disproportionately affect some Procellariiformes including petrels, prions, shearwaters, diving petrels, and storm petrels, and especially fledglings on their maiden flight (Fontaine et al., 2011; Montevecchi, 2006; Rodriguez & Rodriguez, 2009). Many nocturnal seabirds have special adaptations that allow them to see in low light levels such as large tubular-shaped eyes, increased retinal rods, oil drops and rhodopsin (the pigment sensitive to light) (Bowmaker, 1991; Mitkus et al., 2016; Ndez-Juric, 2016). It is this visual system that is adapted to low light levels that make some nocturnal seabirds likely more sensitive to short-wavelength blue light (including white light) and less sensitive to long-wavelength red light (Tanaka, 2015).

The visible light spectrum, as determined by the human visual system, includes the wavelengths: red (700 nm), orange (630 nm), yellow (600 nm), green (550 nm), blue (470 nm), indigo (425 nm) and violet (400 nm). Unlike mammals, some birds are also able to detect ultraviolet wavelengths (UV, 300-400nm; Kelber, 2016), though this ability in individual seabird species remains questioned (Hart, 2004; Håstad et al., 2005).

The collective term ‘fallout’ is used for seabirds in both marine and terrestrial environments that crash land due to the disorientation, exhaustion, injury or mortality caused by light-induced collisions (Rodríguez et al., 2017b). Between 4% and 40% of collisions result in mortality due to the impact itself, predation, vehicle strike or because birds are unable to get airborne again and seek shelter where they may starve or dehydrate (Rodriguez et al., 2014; Telfer et al., 1987). It is because of these risks and high mortality rates that ALAN is becoming an increasing concern for seabirds, particularly the 31% listed as globally threatened (Dias et al., 2019; Rodríguez et al., 2019).

Seabirds of northern Aotearoa New Zealand

Aotearoa New Zealand is a seabird hotspot with 86 species breeding throughout the country (Forest & Bird, 2014), approximately one-quarter of the global population (~370 species). New Zealand also has the highest number of endemic and threatened seabirds with 36 species listed (Croxall et al., 2012). The northern New Zealand region and Te Moananui-ā-Toi/Tīkapa Moana/Hauraki Gulf, in particular, is a global centre of seabird diversity with breeding colonies of 27 species found primarily on offshore islands and rock stacks (Gaskin & Rayner, 2013). Protecting the seabirds of the Hauraki Gulf and Northland's offshore islands is therefore of local, national, and international value. Artificial light at night has been identified as a threat to seabirds in many locations around the world, including northern New Zealand (Barros et al., 2019; Dias et al., 2019; Glass & Ryan, 2013; Imber, 1975; Le Corre et al., 2002; Merkel & Johansen, 2011; Miles et al., 2010; Rodriguez et al., 2014; Rodriguez & Rodriguez, 2009; Whitehead et al., 2019). While seabird colonies on islands in the northern New Zealand region are often remote and may lack the intensity of light pollution present in cities, their locations frequently border shipping lanes where illuminated fishing vessels, cargo ships and cruise liners travel when visiting local ports and harbours (Whitehead et al., 2019). It is the lights of these vessels in areas utilised by seabirds that pose a risk to the many species found in the region, especially to those listed as threatened (Black, 2005; Merkel & Johansen, 2011).

Light-induced collisions in the Hauraki Gulf

There is considerable anecdotal and documented evidence for seabird-light collisions in northern New Zealand. During one recent light-induced collision event, 64 endemic Buller's shearwater (rako, *Ardenna bulleri*) and four threatened flesh-footed shearwater (toanui, *Ardenna carneipes*) collided with a cruise ship in the Hauraki Gulf (Morton, 2018). While many of these birds were released alive, 20 birds died because of incorrect restraint and release measures by crew members. This event, combined with deck strike data collected by fisheries observers, highlighted the need for research to minimise light-induced collisions in the Hauraki Gulf (Department of Conservation, 2019). Other reports of light-induced collisions in the region include birds colliding with the lighthouse on Burgess Island (Pokohinu, Mokohinau Islands) and being grounded by lights in Auckland City and various coastal towns (Sandager, 1890; Whitehead et al., 2019; C. Gaskin, pers comm).

Types of lights used on vessels

The lighting types used on vessels have different wavelengths within the visible light spectrum. The intensity or brightness of the light, as well as the colour or wavelengths emitted, are likely to be important in seabird attraction (reviewed in Commonwealth of Australia, 2020). Since 2000, the most prevalent light types in use on land include light-emitting diode (LED), metal halide and high-pressure sodium (HPS) lights (Rodríguez et al., 2017a), whereas on vessels, LED, metal halide, halogen and fluorescent lights are the most common (Nguyen & Winger, 2019). Artificial lights on vessels are commonly used for crew safety, setting fishing gear at night, navigation or to attract nocturnal species of fish and squid (Black, 2005; Nguyen & Winger, 2019).

High-pressure sodium lights emit a higher wavelength light that is yellow or orange in colour, whereas LED lights emit more blue light of a lower wavelength (reviewed in Longcore et al., 2018) and metal halide emit a broad range of wavelengths (Rodríguez et al., 2017a). There is a shift toward the use of LED lights due to their energy-efficiency (reviewed in Commonwealth of Australia, 2020) but this may have a negative impact on nocturnally active species such as some seabirds due to their blue light sensitivity (reviewed in Commonwealth of Australia, 2020).

Project Aims

This study aimed to test which light intensities and colours are least attractive to seabirds, to facilitate understanding of how to minimise the impact of light-induced collisions with vessels in the Hauraki Gulf and elsewhere.

The study has four components:

1. Literature review
2. Light analysis and fishery industry survey
3. Land-based behavioural experiments
4. Boat-based behavioural experiments

Literature review - summarised

Key Findings

The species and age-class most vulnerable to artificial light at night

Most of the literature on seabird attraction to ALAN discusses petrels and shearwaters as the group of seabirds most impacted. It is during nocturnal migration, foraging or when returning to colonies that petrels and shearwaters are most at risk of artificial light attraction as their eyes are suited to seeing in low light levels (Commonwealth of Australia, 2020). Many of these species exhibit phototrophic feeding behaviour, where they forage at night on bioluminescent prey (Imber, 1975) and this foraging strategy is discussed as a potential reason for the high rate of light attraction in nocturnally foraging species.

Fledgling petrels and shearwaters are particularly vulnerable to land-based artificial lighting on their maiden flight and are the focus of much of the literature. Adult birds may have learned to avoid artificial light sources (Montevecchi, 2006) and differ to fledglings in that they are not attracted to light from a distance, with adult birds only becoming disorientated if flying directly past the source (Imber, 1975). As such, fledglings frequently contribute to greater than 90% of the birds grounded by artificial lights.

Of the two main hypotheses for why fledglings are more attracted to ALAN than adult birds, the literature seems to support either the bioluminescent prey hypothesis or the navigational hypothesis, with few studies supporting both. It was first suggested that fledgling petrels and shearwaters may be instinctively attracted to light at night as bioluminescent prey contribute to their diet, thus they may associate light with food (Imber, 1975; Le Corre et al., 2002; Montevecchi, 2006). Secondly, it is thought that fledglings possess an innate behaviour to navigate using the moon and stars, and that these navigational cues get confused with artificial lights (Reed et al., 1985; Rodriguez & Rodriguez, 2009; Telfer et al., 1987). The navigational cue hypothesis is supported by the lower fledgling grounding rates during the full moon as it is easier to distinguish between natural and artificial light sources (Rodríguez et al., 2017c; Rodriguez & Rodriguez, 2009).

Deck strike incidents with different fishing methods and fisheries

White lights on deck are commonly used for crew safety, setting fishing gear at night, navigation or to attract nocturnal species of fish and squid (Black, 2005; Nguyen & Winger, 2019). The amount of light used by vessels depends on the type of fishing method, target species and location. The types of lights used on fishing vessels have changed over time, with a shift from oil and acetylene lights in the early 1900's to the Light Emitting Diode (LED), metal halide, fluorescent and halogen lights currently in use (Nguyen & Winger, 2019).

Of the different fishing methods, trawling is most commonly mentioned in the literature regarding seabird attraction to ALAN on fishing vessels (Abraham et al., 2016; Black, 2005; Glass & Ryan, 2013; Merkel & Johansen, 2011). This may, however, be an artefact of increased observer coverage on trawl vessels, which appears to be true for inshore fisheries in New Zealand (Ramm, 2010).

Studies of deck-strike were comparatively scant in the literature despite the frequency in which they occurred during specific deck-strike observations (e.g. nightly in some cases) in addition to being described as 'common' in one study.

The impact of moon phase and weather condition on seabird fallout

Almost every study mentioned the moon phase, weather or both as factors determining seabird fallout events. Ambient light from a full moon may limit the intensity of artificial light and allow birds to see structures, thus reducing the rates of collisions (reviewed in Montevecchi, 2006; Reed et al., 1985). Alternatively, petrels visit their colonies less on moonlit nights compared to dark nights which would reduce the likelihood of encountering artificial light (Imber, 1975; Montevecchi, 2006) and thirdly, fledging may be inhibited by a bright moon.

Similar to the moon, the weather appears to play a key role in seabird grounding and deck-strike. Water droplets in the air refract light and increase the lit-up area which can attract a higher number of birds (Montevecchi, 2006; Telfer et al., 1987; Wiese et al., 2001). This pattern has been observed globally, with increased seabird fallout rates during cloudy, misty and overcast weather in New Zealand (Sandager, 1890), Hawaii (Telfer et al., 1987), Greenland (Merkel & Johansen, 2011), Wales (Guilford et al., 2019), Tristan archipelago and Gough Island (Ryan, 1991) and throughout the Southern Ocean (Black, 2005).

Types of artificial light

The lighting types used by humans utilise different wavelengths within the visible light spectrum and it is the wavelength of light, rather than colour, that is the most important factor in seabird attraction (reviewed in Commonwealth of Australia, 2020). Since 2000, the most prevalent light types in use in the terrestrial environment include LED, metal halide and high-pressure sodium lights (Rodríguez et al., 2017a), whereas on vessels, LED, metal halide, halogen and fluorescent lights are the most common (Nguyen & Winger, 2019). High-pressure sodium lights emit a higher wavelength light that is yellow or orange in colour, whereas LED lights emit more blue light of a lower wavelength (reviewed in Longcore et al., 2018) and metal halide emit a broad range of wavelengths (Rodríguez et al., 2017a). There is a shift toward the use of LED lights due to their energy-efficiency (reviewed in Commonwealth of Australia, 2020) but this may have a negative impact on nocturnally active species such as some seabirds due to their blue light sensitivity.

Studies of seabird attraction to different light types and colours

To reduce light-induced collisions in the future, we must increase our understanding of the types, colour and spectra of light that are attractive to seabirds. As it stands, only one study has tested seabird attraction to different types of lights. Rodríguez et al. (2017a) illuminated a sports field alternately with three common outdoor lighting systems during the short-tailed shearwater fledging period on Phillip Island, Australia. Forty-seven percent of fledglings were grounded during the metal halide light treatment, followed by 29% for LED lights and 24% for high pressure sodium lights. The authors went on to discuss how the orange light and narrower emission spectrum of high-pressure sodium lights were likely less attractive to the shearwaters due to their nocturnal visual system compared to metal halide and LED lights that produce more blue light and have a wider spectrum. A different result was observed in Kaikōura however, as most Hutton’s shearwater fallout was concentrated around high pressure sodium lights (150 watts) (Deppe et al., 2017). High wattage metal halide 150W and LED 252mA lights also attracted shearwaters in lower numbers (Deppe et al., 2017).

Changing the spectral reflectance of lights has also influenced the number of grounded birds in previous studies. Tropical shearwaters (*Puffinus bailloni*) on Réunion Island found red and yellow lights less appealing than green and blue lights in a study of different light colours by Salamolard et al. (2007). Similarly, using red filters on power station floodlights reduced light-induced avian mortality by up to 80% (reviewed in Wiese et al., 2001) and the replacement of white lights with green lamps on offshore oil rigs reduced collisions by nocturnally migrating songbirds (Poot et al., 2008). An opportunistic lighting experiment tested the collision rate of Manx shearwaters with a building in Wales when lights were turned on or off over the course of one night (Guilford et al., 2019). Collision rates were 25 times higher when light was present than in its absence. Identifying the types, colour and spectra of light that are less attractive to seabirds while still being sufficient for human safety will be crucial in decreasing deck-strike and grounding events in future (Troy et al., 2013).

Conclusion

As artificial light increases globally the need to understand how this impacts biodiversity becomes even more pressing. Little is known about the visual system of many species of petrels and shearwaters or how ALAN impacts on their nocturnal activities such as foraging, migration or returning to the colony. This review has highlighted the need for more studies on seabird physiology and anatomy which would provide important conservation information for seabirds. Additionally, a greater knowledge of the light types, colours and wavelengths that seabirds are attracted could help reduce light-induced injury and mortality in future. With 86 species found breeding in New Zealand and almost half of those threatened, we have an international obligation to reduce seabird injury and mortality from deck-strike in our territorial waters.

See full report - https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-conservation-services/reports/final-reports/mit2019-03-lighting-adjustments-to-mitigate-against-deck-strikes-final-literature-review-and-methodology.pdf

Light analysis and fishery industry survey - summarised

Specific aims

- Analyse deck strike data from Hauraki Gulf for patterns in fishery types, species impacted. Survey fisheries for operational lighting types and deployment methods.
- Characterise the wavelengths and intensity of lights used on boats and model how these are perceived by seabirds.

Methods

Fishing vessel survey

A survey was sent to fishing vessels that operate throughout New Zealand waters to determine which types of lighting they used.

Lighting characteristics and how they are perceived by seabirds

We measured light types that were used by fishing vessels in New Zealand identified by the survey using a spectrophotometer. Spectrophotometers measure biologically relevant light in the bird detectable range of 300 to 700nm and are recommended for wildlife-ALAN studies (Commonwealth of Australia, 2020). Visual modelling was based on the spectral sensitivities of wedge-tailed shearwaters (Hart, 2004), which is UV sensitive (UVS; ie. has photoreceptors tuned to UV rather than violet wavelengths; Holveck et al., 2017). This is the best available choice for our study because it is the sole procellariform for which visual spectral sensitivities have been calculated, and is burrow-nester, like the study species in our field experiments.

Results and discussion

Seven fishing companies responded to the survey with lighting information for fourteen vessels that were a mix of trawlers, longliners and one purse seine. Five different light types were identified: eleven vessels used LED's, seven used fluorescents, five used halogen and mercury and sodium lights were used by one vessel each. Halogen and fluorescent lights were always turned on whereas LED's were turned on as required. We acquired six different lights for testing based on the fishing vessel lighting survey: two different white LED's, fluorescent, halogen, in addition to green and red LED's to test whether different colours or wavelengths were attractive to seabirds.

When modelled from a seabird visual perspective, the flood LED was more similar in hue to the halogen light than the white LED and the fluorescent light. This was surprising as from a human perspective the flood LED produced a whiter light more similar to the white LED and fluorescent lights than the halogen light which was more yellow. The flood LED was the brightest with the highest peak in the red spectrum, followed by the halogen and red LED lights. The visual modelling shows the red LED light is perceived by seabirds as bright, whereas from a human perspective the red LED was dimmer than both the green and white LED lights. A seabird could likely easily distinguish between all the other lights, especially those with the highest just noticeable difference (JND) values, e.g. LED red, LED white and fluorescent lights.

Conclusion and recommendations

The lights tested were suitable for use in the land-based behavioural experiments as they reflected the type of lights used by fishing vessels in the region. Additionally, all six lights differed in colour and/or hue from a seabird perspective, therefore the experiments could produce some significant results in terms of seabird light attraction.

See full report - https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-conservation-services/reports/draft-reports/mit2019-03-lighting-adjustments-to-mitigate-against-deck-strikes-draft-report-yr1.pdf

Land-based behavioural experiments - summarised

Specific aims

- Carry out land-based behavioural experiments to test seabird responses to artificial lights and alternative options such as different colours/filters.

Methods

The behavioural experiment was carried out on two islands in the Hauraki Gulf: Pokohinu/ Burgess Island, Mokohinau Islands (35.9167° S, 175.1167° E) in December 2019 (5 nights) and Te Hauturu-o-Toi/Little Barrier Island (36.1946° S, 175.0753° E) in January 2020 (7 nights). These islands were chosen due to their remote locations, and multiple species of breeding seabirds. Lights were attached to a horizontal wooden beam positioned approximately 1m above the ground facing skyward. These were connected by an extension cord to a petrol-powered generator 30m away. A 20m x 20m plot was marked around the lighting set up as a boundary for the ground-based observations.

A random lighting schedule was cycled where the light type tested varied in placement from sunset each night to control for times of greater seabird activity. Starting half an hour after sunset, each light was projected skyward for 10 minutes followed by an interval of 10 minutes of darkness to avoid potential attractiveness effects of the previous light treatment. The behavioural experiments continued through the night depending on weather conditions and seabird activity levels. Because nocturnal seabirds are social and attracted to vocalisations, light experiments were carried out in silence except for unavoidable generator noise.

Results and discussion

This study aimed to test which colours and intensities of lights are least attractive to seabirds to minimise the impact of light-induced collisions in the Hauraki Gulf, a region of high seabird diversity. Modelling the seabird visual system showed how differently seabirds view artificial light which is crucial when aiming to reduce light-induced collisions near seabird islands in the region. There were some differences observed in seabird behaviour dependent on the moon phase and island and the potential reasons are discussed below.

This study faced several limitations which were later addressed in the sea-based behavioural experiments. These limitations were:

- We could not tell what was happening outside of our study plot and whether a “distant light effect” was attracting birds from afar.
- The ground-based observations were more indicative of our human-visual system thus this was not the most robust measure of light attractiveness to seabirds, the reason for using thermal imagery in this study.
- However, the thermal imaging also had its limitations, in that the field of vision was not as wide as that of the observers.
- Also, different lenses on the thermal scope meant some of the earlier thermal imagery was incomparable. This was corrected later in the study, and for the boat-based behavioural experiments.

The differences in the lights’ hue and brightness were not reflected in significant differences in seabird attractiveness to the light types. Ground-based observations saw considerably fewer seabirds during the red LED treatment.

Difference between islands

The observed difference in birds trapped in the light beam and observed through thermal imagery (small LED’s only) between islands may have been due to the different species on each of the islands. A wider variety of seabird species were seen and heard on Burgess Island than on Hauturu where almost all birds observed were Cook’s petrels (tītī, *Pterodroma cookii*). Of the fifteen bird groundings observed, thirteen birds grounded on Burgess Island were of multiple species.

Common diving petrels (kuaka, *Pelecanoides urinatrix*) are probably the species in the region most impacted by ALAN and frequently appear in deck strike records (e.g. Abraham & Richard, 2019; Glass & Ryan, 2013; Holmes, 2017). This species is common on Burgess Island and fledge in November-December. The experiment was carried out in late December and missed peak-fledging for common diving petrels. Had the experiment occurred several weeks earlier we would likely have observed more common diving petrel fledglings attracted to the lights on their maiden flight.

Most of the birds observed on Hauturu were Cook's petrels. Chicks of this species fledge in March-April, therefore, the individuals we observed would have been adult birds. Juvenile Cook's petrels are frequently grounded by lights in Auckland city and its northern suburbs (Gaskin & Rayner, 2013; Whitehead et al., 2019). Given the prevalence of Cook's petrel grounding in anecdotal evidence, it was surprising how few birds were trapped by the light beam during this study. This was probably due to the abundance of adult birds which, in general, may have learned to avoid artificial light sources (Montevecchi, 2006) and lack of juveniles present during the experiment.

Difference between moon phase

More birds were trapped in the light beam and observed in thermal imagery (small LED's only) during the third quarter moon phase than during the new moon. This is in contrast to other studies where greater fallout occurred during the new moon for Newell's shearwaters (*Puffinus newelli*), Leach's storm-petrels (*Oceanodroma leucorhoa*), Manx shearwaters (*Puffinus puffinus*), Hutton's shearwater (Kaikōura tītī*, Puffinus huttoni*) and Cory's shearwaters (*Calonectris borealis*) (Deppe et al., 2017; Miles et al., 2010; Reed et al., 1985; Rodriguez & Rodriguez, 2009; Telfer et al., 1987).

Seabirds observed for all light treatments

We predicted the greatest attraction would be to more intense lights, especially if they involved UV wavelengths. However, from the analyses done so far this was not the case, as no difference in the number of birds seen in thermal imaging, ground observations or trapped were observed considering the differences in brightness and colour contrast of the different lights from a seabird perspective. The only other experimental study that tested seabird attraction to different types of lights generated statistically significant differences among the lights tested. They found that 47% of short-tailed shearwater fledglings were grounded during the metal halide light treatment, followed by 29% for LED lights and 24% for HPS lights on Phillip Island, Australia (Rodríguez et al., 2017a). The authors went on to discuss how the orange light and narrower emission spectrum of HPS lights were likely less attractive to the shearwaters due to their nocturnal visual system compared to metal halide and LED lights that produce more blue light and have a wider spectrum. High Pressure Sodium lights would be most similar in hue to the red LED in this study whereas metal halide is probably more like the flood LED or halogen light.

Of the fifteen bird groundings observed in our study, three birds grounded during both the flood LED and LED white treatments, followed by one each for halogen and fluorescent. No birds were observed grounding during the red or green LED treatments.

Seabirds observed for LED's (white, red, green)
Due to the global shift toward energy-efficient LED lights, we wanted to test whether the colours red or green were less attractive to seabirds than the standard white light. The lights tested were the same light except for different colour filters. Using LED's where blue light (400-490nm) is filtered out, as with the red and green LED's in this study, is discussed as a key mitigation measure for light-induced collisions in nocturnal seabirds (Commonwealth of Australia, 2020; Longcore et al., 2018; Rodríguez et al., 2017a), in addition to shielding lights.

However, from the analyses done so far, we found no difference in the number of birds seen in thermal imaging, ground observations or trapped in the light beam, likely due to our small sample sizes. Although not statistically significant with our sample size, we observed less attraction to some of the lights than others. This is significant enough to warrant further research and is incorporated in the current research by PhD candidate Ariel Heswall (University of Auckland), who is carrying out further behavioural experiments on land using these same lighting treatments to augment our sample size here and incorporate some of the most at-risk birds (e.g. common diving petrels).

Conclusion

The results of the land-based behavioural experiments provided insight into the visual system of a nocturnal burrow-nesting seabird like those in the Hauraki Gulf which helped us to understand which lights seabirds view as intense. Our experiments showed an equal statistical attraction to the light types tested but provided anecdotal observations where more research and larger sample sizes are required. The land-based behavioural experiments also helped to refine the methodology for the boat-based behavioural experiments near seabird islands and further land-based behavioural experiments.

See full report - https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-conservation-services/reports/draft-reports/mit2019-03-lighting-adjustments-to-mitigate-against-deck-strikes-draft-report-yr1.pdf

Boat-based behavioural experiments

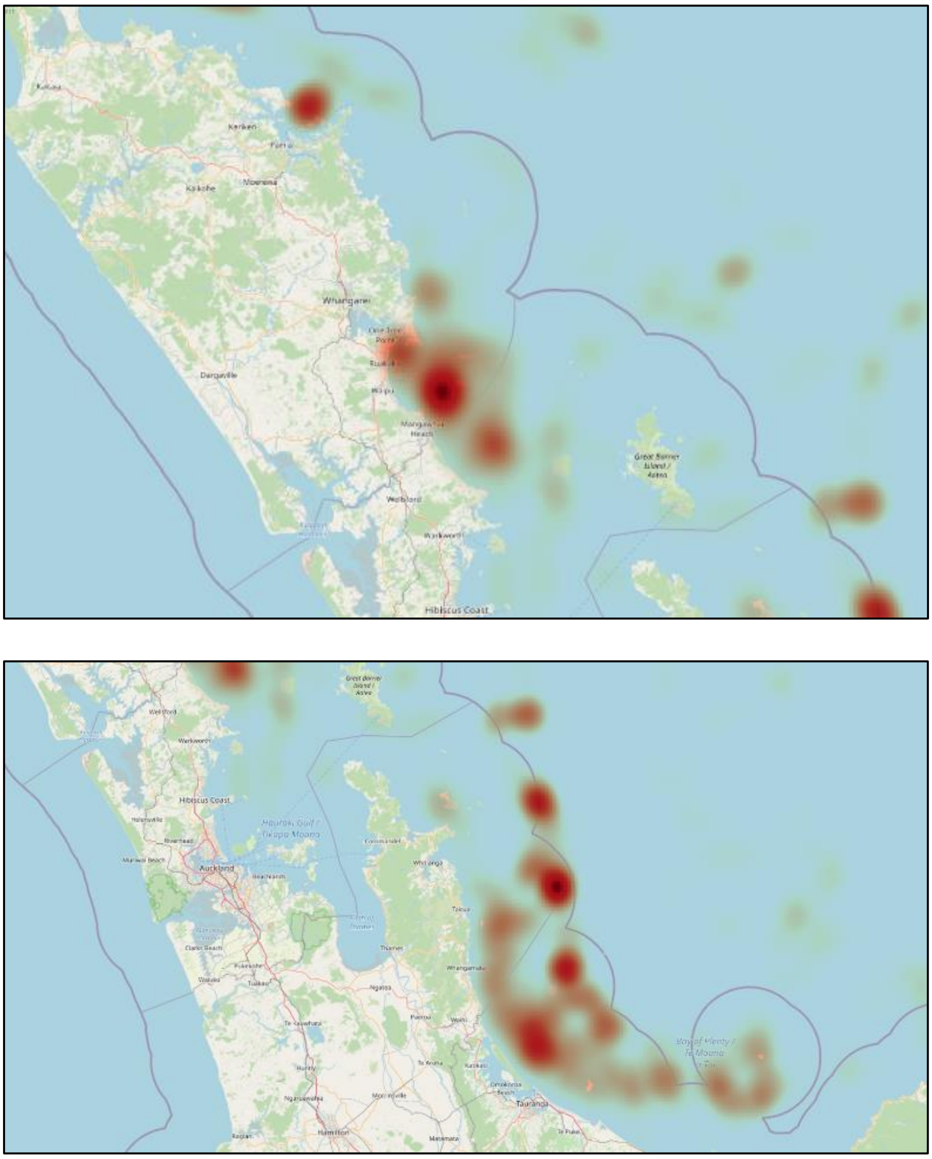
Specific aims

- To test the effects of artificial lighting on seabird behaviour at sea based on the refined methodology from the land-based behavioural experiments
- To test the effectiveness of using a fishing vessel as a platform for the boat-based behavioural experiments

Methods

Location

The boat-based behavioural experiments were carried out at three locations in the Hauraki Gulf: the Mokohinau Islands (35.9240° S, 175.1257° E) for in October and November 2020 (three nights) and the east coast of the Coromandel Peninsula (Mercury Islands: 36.6124° S, 175.8595° E, Aldermen Islands: 36.9671° S, 175.9849° E) in May 2021 (two nights). These locations were chosen due to their distance from on-shore light sources, multiple species of breeding seabirds and the presence of night-fishing activity nearby (Figs. 2 & 3).



Figures 2 & 3. Night fishing hotspots for the Hauraki Gulf. *Data provided by Ministry of Fisheries.*

Figure 4. Locations for the boat-based behavioural experiments for October and November 2020, Mokohinau Islands. The vessel was anchored during these experiments. *Inset*: red circles highlighting the position of the Mokohinau Islands (upper circle) and the eastern Coromandel (lower circle) in the wider Hauraki Gulf.

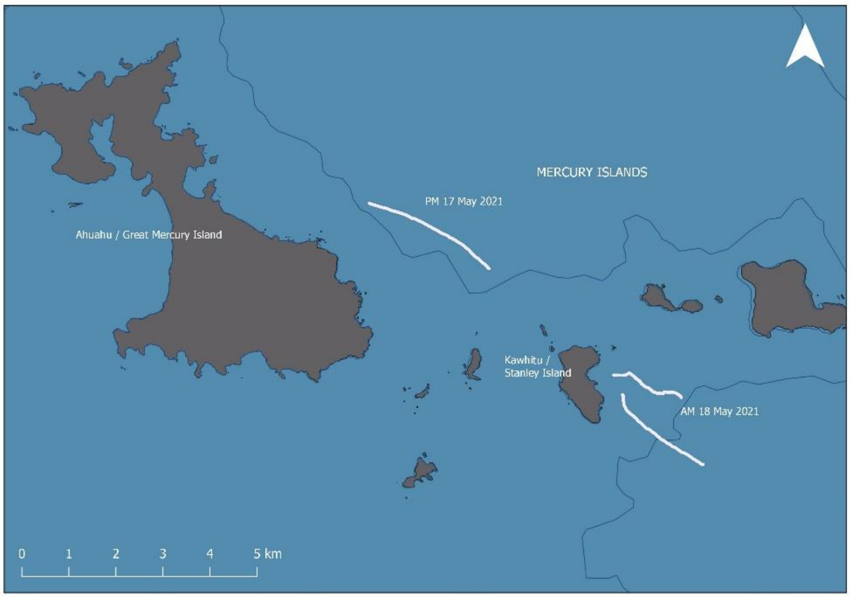


Figure 5. Locations for the boat-based behavioural experiments for the 17th/18th May 2021, Mercury Islands, east Coromandel. The vessel was drifting during these experiments.

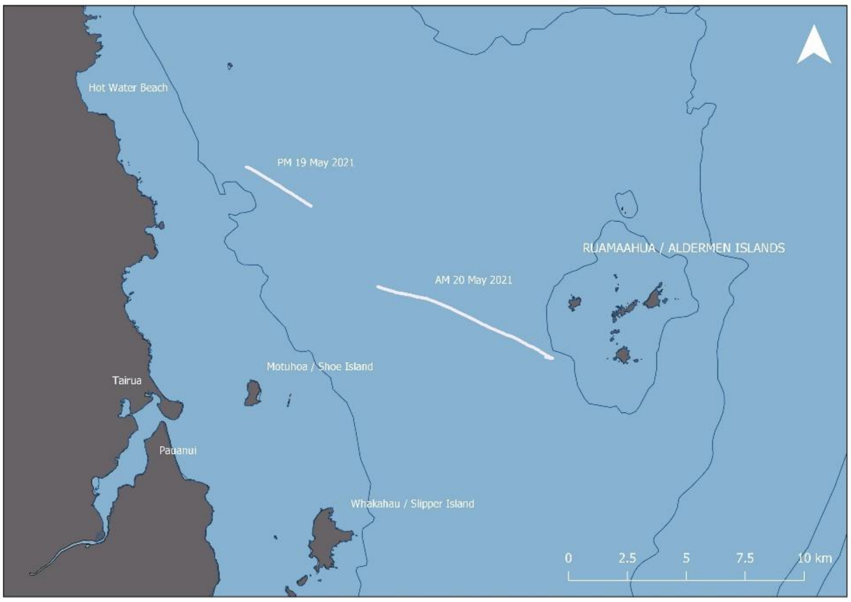


Figure 6. Locations for the boat-based behavioural experiments for the 18th/19th May 2021, Aldermen Islands, east Coromandel. The vessel was drifting during these experiments.

Vessels

Two different vessels were used as platforms for the at-sea experiments, the Whāngarei-based charter boat *El Pescador* (October/November 2020) (Fig. 7) and Whitianga-based longline fishing vessel *Southern Cross* (May 2021) (Figs. 8 & 9). We changed the vessel platform after the first round of boat-based behavioural experiments in Oct/Nov 2020 because *El Pescador* was not large enough to cope with the conditions required for the experiments while maintaining researcher and vessel safety (dark and windy nights offshore).

Lights and lighting set up

To maintain consistency with the earlier land-based behavioural experiments, the same lights were used for the boat-based behavioural experiments, with the exception that only one new white LED flood light was tested rather than two (see Table 1). This new LED flood light was more comparable to those used by fishing vessels. The other lights tested were red LED, green LED, halogen and fluorescent.

Each vessel operated a white LED anchor light during the experiments to comply with maritime rules. The lights were attached to a wooden beam and secured to the vessel approximately 2m above the deck. The lights were angled slightly below horizontal facing seaward as this was considered more comparable to the direction of lighting on board fishing vessels than the vertical lighting direction used on land.

Table 1. Lights used in the land-based and boat-based experiments and their intensities in lumens.

Light type	Land-based experiments	Boat-based experiments
Flood LED	10800lm	5040 lumens
White LED	1000lm	-
Green LED	450lm	450lm
Red LED	350lm	350lm
Halogen	9900lm	9900lm
Fluorescent	1768lm	1768lm

The lighting set up was secured to the side of vessel with the best visibility and minimal external structures that could cause injury to birds disoriented by the lights. The *El Pescador* (Fig. 7), was anchored throughout the experiments, therefore, the lights were directed toward the stern which gave the best viewing of birds approaching. On the *Southern Cross* (Fig. 8), which was drifting throughout the experiments, the lights were directed out from the starboard side as the vessel would settle beam-on to the wind (Fig. 10). This also provided greater visibility for birds approaching the vessel. The light array was connected by an extension cord to a petrol-powered generator <5 m away. An open bucket of Kilwell Tuna Oil was placed on the stern of the *El Pescador* to smell more like a fishing vessel. This was not needed on the *Southern Cross* because the vessel was actively used for fishing.

Figure 7. The *El Pescador* charter boat used during the lighting experiments near the Mokohinau Islands in October and November 2020. The photo shows the lighting set up, generator placement and canopy covers used to prevent birds from getting injured when striking the vessel.

Figure 8. Light array on the starboard side of the *Southern Cross* used in May 2021. Tripod for thermal imaging scope cable-tied to the rail of the boat.

Figure 9. *Southern Cross* at the wharf in Whitianga. *Photos: Chris Gaskin*

Figure 10. Light array (LED flood illuminated) and thermal scope in action on board the *Southern Cross*, off the Mercury Islands. Winds gusting 40 kns were not forecast. *Photo: Chris Gaskin*

A random lighting schedule was cycled where the light type tested varied in placement from sunset each night to control for times of greater seabird activity. The randomised treatment schedule was done prior to nights on the boats using a random number generator. Starting one hour after sunset, each light was projected seaward for 10 minutes followed by an interval of 10 minutes of darkness to avoid potential attractiveness effects of the previous light treatment. The experiment continued through the night depending on weather conditions and seabird activity levels. On *El Pescador*, the experiments were carried out from dusk until seabird activity ceased, usually around 1-2am. On the *Southern Cross*, the experiments were carried out from dusk for one cycle of the lights (approximately 2hrs) then again from 2am until dawn (~6am) as this is the period when fishing vessels are active in setting their equipment and are likely to attract birds departing from the islands.

Deck observations

Observers were positioned on the deck beneath the lights. Researchers recorded behaviour related to attraction, including:

- the number of birds attracted to the area (within ~20 m of beam),
- the number of birds trapped in the light beam,
- the number of birds landing on the water (within ~20 m of beam),
- and the number of birds striking/landing on the vessel.

Thermal imaging

Seabird activity was recorded using two Pulsar Helion Thermal Imaging Scopes with a Pulsar Thermal Lens F28/1.2 (Yukon Advanced Optics Worldwide, Vilnius, Lithuania) at 2.5x magnification. The scope was positioned within 1m of the lighting set up and recorded activity along the light beam. Recordings were filed with the light type, time of night, and location and provided a reference for the behavioural response to light types. Each bird observed in the thermal recordings was counted and recorded during each treatment, including control periods.

Statistical analysis

Vessel-based attraction experiments were analysed using general linear mixed models (R version 1.3.959, R Core Team, 2019). Analyses tested the significance of birds observed by researchers on the boat and the light treatment presented and several temporal and environmental variables (location, time of experiment, moon phase, date, lumens of light treatment, time of moon rise, time from sunset/sunrise (using 2am as the cutoff between each), cloud cover, and vessel). We also tested the number of birds that were observed in recorded videos using a thermal imaging scope to account for the difficulty in observing birds at night using the same variables. Thermal imaging was especially important in determining the numbers of birds present during control treatments when we could not visually observe the birds. In addition to just looking at the number of birds present, we also tested to see if certain attractive behaviours were linked to treatment. Although we used two different vessels during this experiment, we pooled the data that was collected and used vessel as a variable within our model.

Commercial fishing vessel operation – long-line

In addition to running the behavioural experiments, we asked the crew of the *Southern Cross* to set and haul a line so we could observe their operation and use of lights on board while fishing. The line was set at 10:30pm, i.e., following the evening behavioural experiments on the 20 May (Fig. 11), so to not confound the experiment results. This was instructive in that we could observe the whole operation of baited hooks, tracers, lines, and floats, as well as the use of tori lines during a night set. The *Southern Cross* with its stabilizer made for a relatively comfortable platform on which to work, even in rough conditions and winds up to 40kns.

Figure 11. Crew setting line over stern. *Photo: Chris Gaskin*

Results

Location

When using the number of birds active during trials based on the thermal imaging videos we found significance based on location with Mokohinau Islands having more birds (P = 0.03, Fig. 13). Interestingly, the patterns of birds seen in each location was consistent between observations from the thermal imaging videos (Fig. 13a) and from the boat (Fig. 13b).

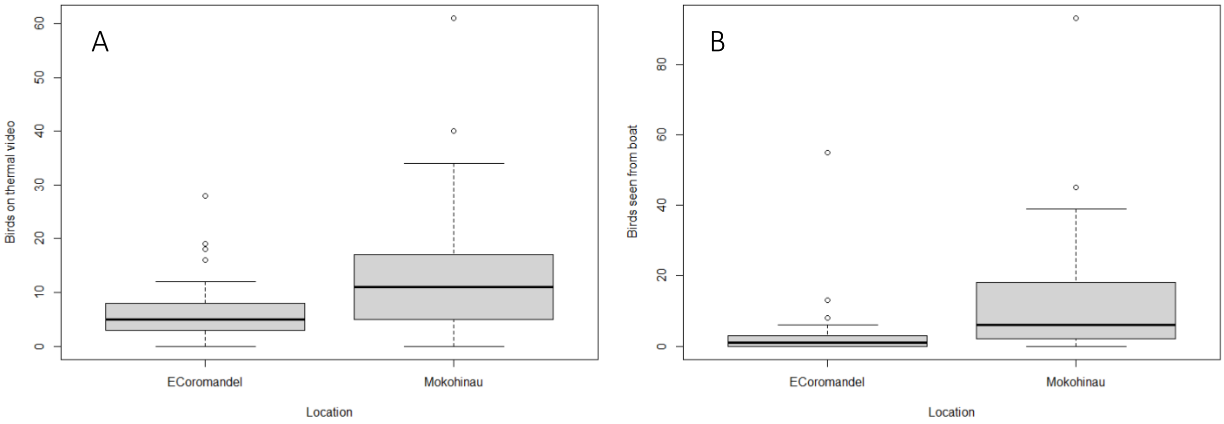


Figure 13. The number of birds seen in a) thermal imagery, and b) observed from the boat for the different locations.

Time of night

When using the number of birds active during trials based on the thermal imaging videos, we found significance based on the minutes from sunset/sunrise (P < 0.001, Fig. 12).

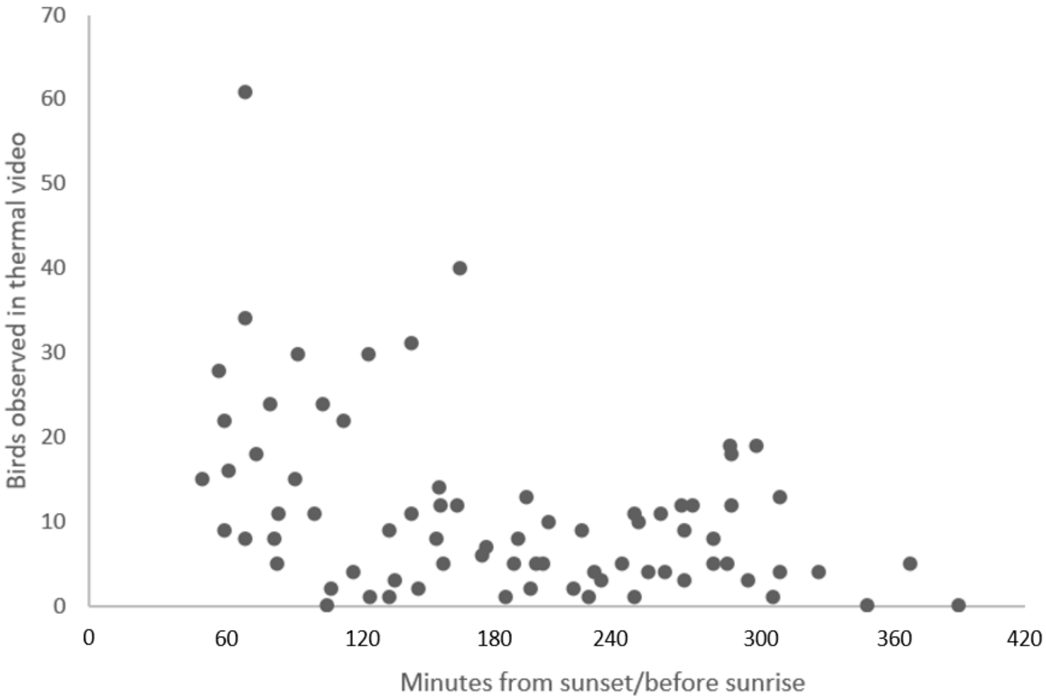


Figure 12. The number of birds seen in thermal imaging in relation to sunset and sunrise.

When using general linear mixed models to test for significance based on treatment and other ecological variables from observer data on the boat, we found no significance between any variables and birds seen except for minutes from sunset ($P < 0.001$).

Moon phase

The number of birds observed in thermal imagery was not significantly different for moon phase, but more birds were observed during the new moon than the first quarter moon (Fig. 14).

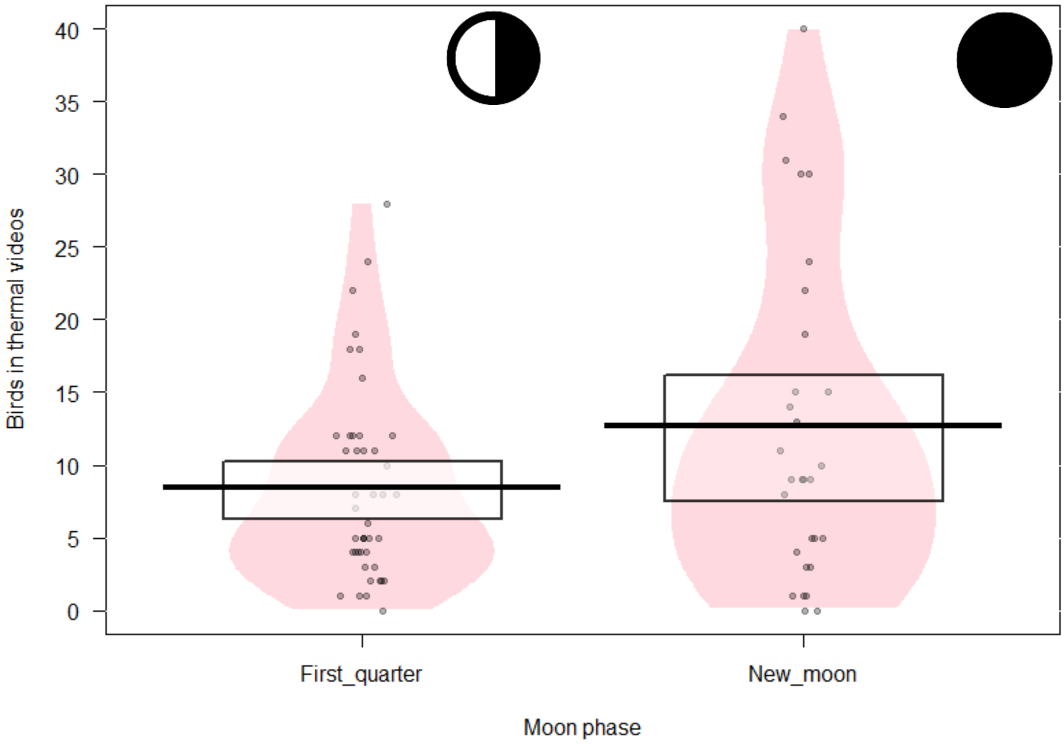


Figure 14. The number of birds seen in thermal imagery for the different moon phases.

Lighting treatment

There was no difference in the number of birds seen in thermal imagery for the different lighting treatments (Fig. 15).

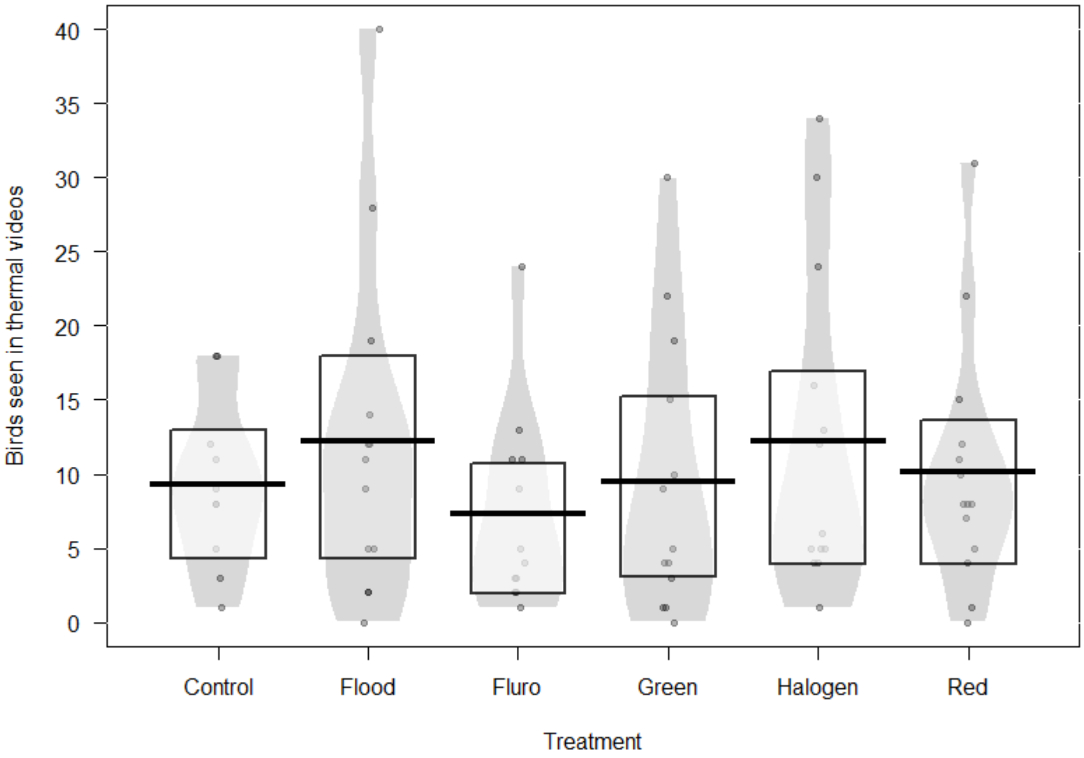


Figure 15. The number of birds seen in thermal imagery for the different lighting treatments.

We found that the flood and halogen light types had the highest average bird count (Fig. 16), however, there was no statistically significant difference in the number of birds seen by observers for the different lighting treatments.

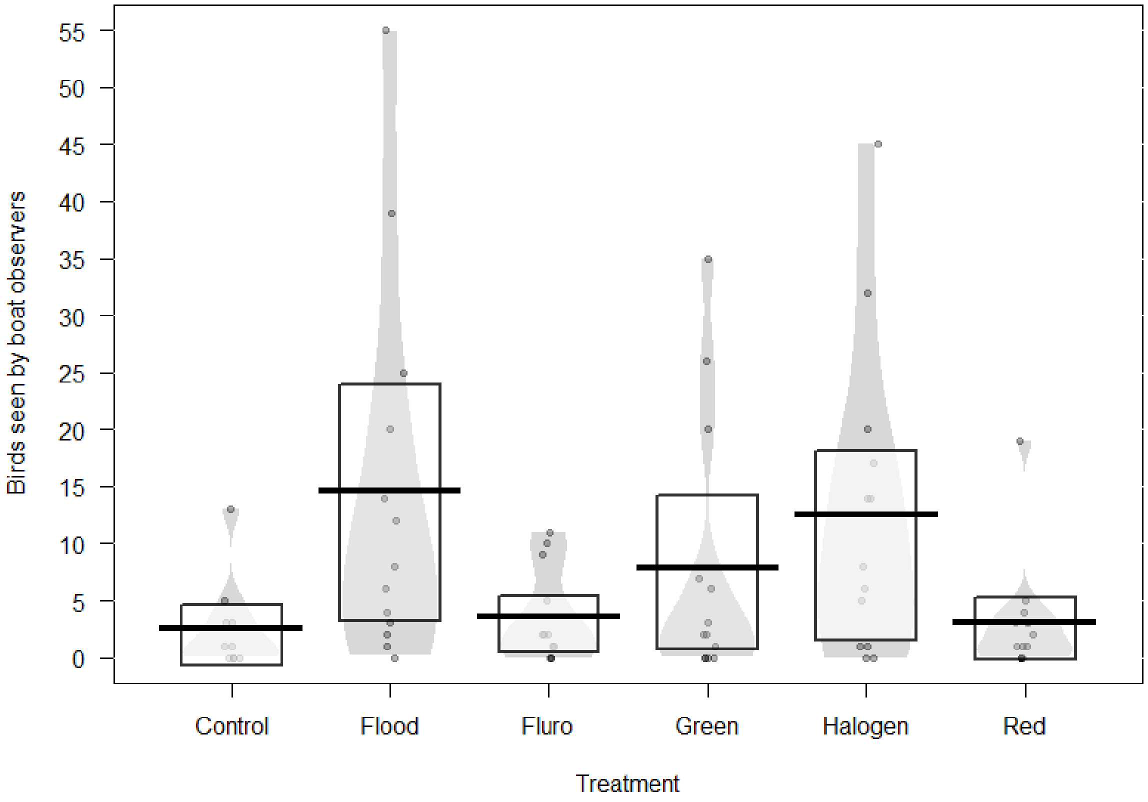


Figure 16. The number of birds seen by observers for the different lighting treatments.

Species observed

The seabird species observed near the Mokohinau Islands included fluttering shearwater (pakahā, *Puffinus gavia*), white-faced storm petrel (takahikare-moana, *Pelagodroma marina*), common diving petrel, Cook's petrel, black-winged petrel (tītī, *Pterodroma nigripennis*), grey faced petrel (ōi, *Pterodroma gouldi*)/flesh-footed shearwater (toanui, *Ardenna* (*Puffinus*) *carneipes*)/sooty shearwater (tītī, *A.* (*P.*) *grisea* (*griseus*)) (difficult to distinguish species from the vessel at night). Fewer species were observed near the Mercury and Aldermen Islands. Those observed were fluttering shearwater, common diving petrel, grey-faced petrel and possibly a New Zealand storm petrel (*Fregetta maoriana*).

Seabird behaviour around lights

We also tested to see if there was any correlation between behaviours exhibited by birds around the different light treatments. Behaviours observed included birds trapped in a beam of light while flying (n=121), birds landing on/colliding with the fishing vessel (n = 17, Fig. 17), and birds landing on the water (n=55, Fig. 18). We found none of these were statistically significant based on treatment.

In total, 32 of the treatment periods resulted in 117 birds trapped in a beam of light while flying. Most birds were trapped in the light beam for the flood LED (n=59), followed by halogen (n=28), green LED (n=18), fluro (n=11) and red LED (n=1). More birds were trapped in the light beam during the new moon (n=81) than during the first quarter (n=36), and more birds were trapped in the light beam near the Mokohinau Islands (n=97) than near the Mercury Islands (n=16) or Aldermen Islands (n=4).

In total, 10 of the treatment periods resulted in 17 birds landing on or contacting the vessel in what would be considered as ‘deck strikes’. These were mostly common diving petrels (n = 11) followed by fluttering shearwaters (n = 5). All of the deck strikes occurred near the Mokohinau Islands and all but one occurred in October during the new moon phase. No birds were harmed during the experiments and all were released overboard during periods of darkness.

In total, 18 of the treatment periods resulted in 55 birds landing on the water. These were mostly common diving petrels (n=38), followed by fluttering shearwaters (n=11) and one grey-faced petrel. Most birds (n=50) landed on the water near the Mokohinau Islands in October and November whereas only two birds landed on the water near the Mercury Islands and three near the Aldermen Islands in May. Most birds (n=45) landed on the water during the new moon phase and the remainder (n=10) during the first quarter phase.

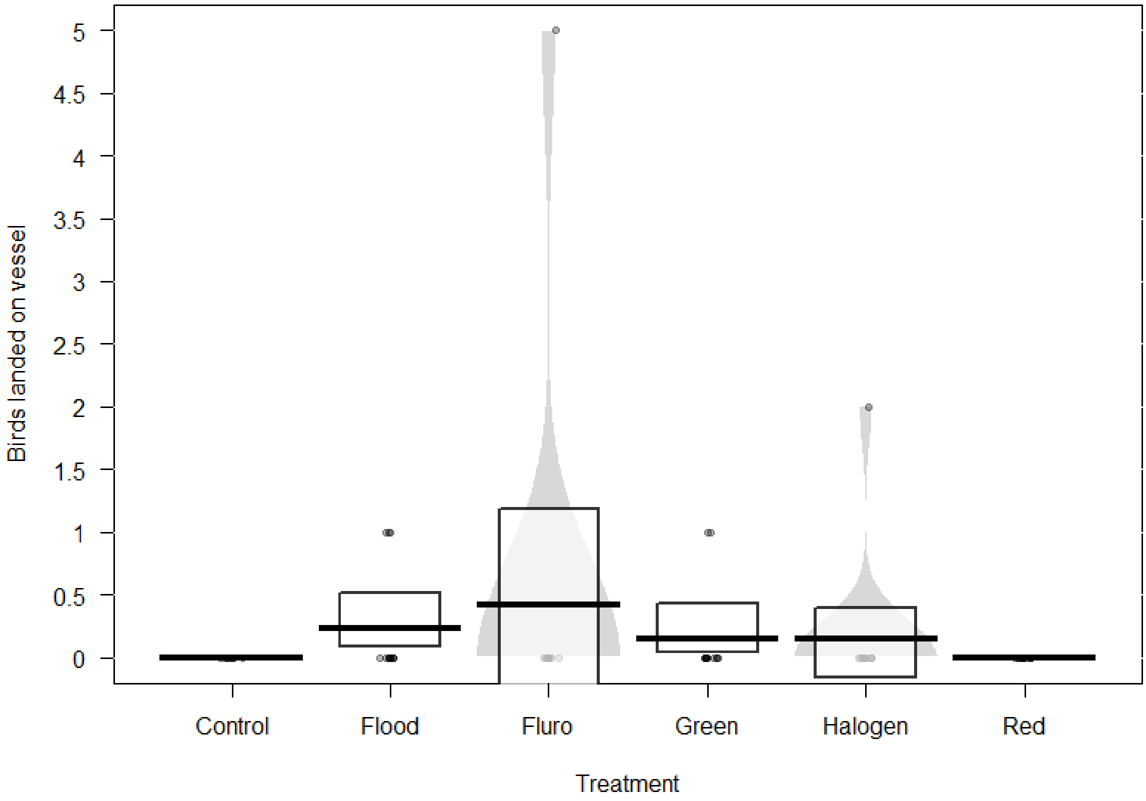


Figure 17. The number of birds that interacted with the vessel for the different lighting treatments.

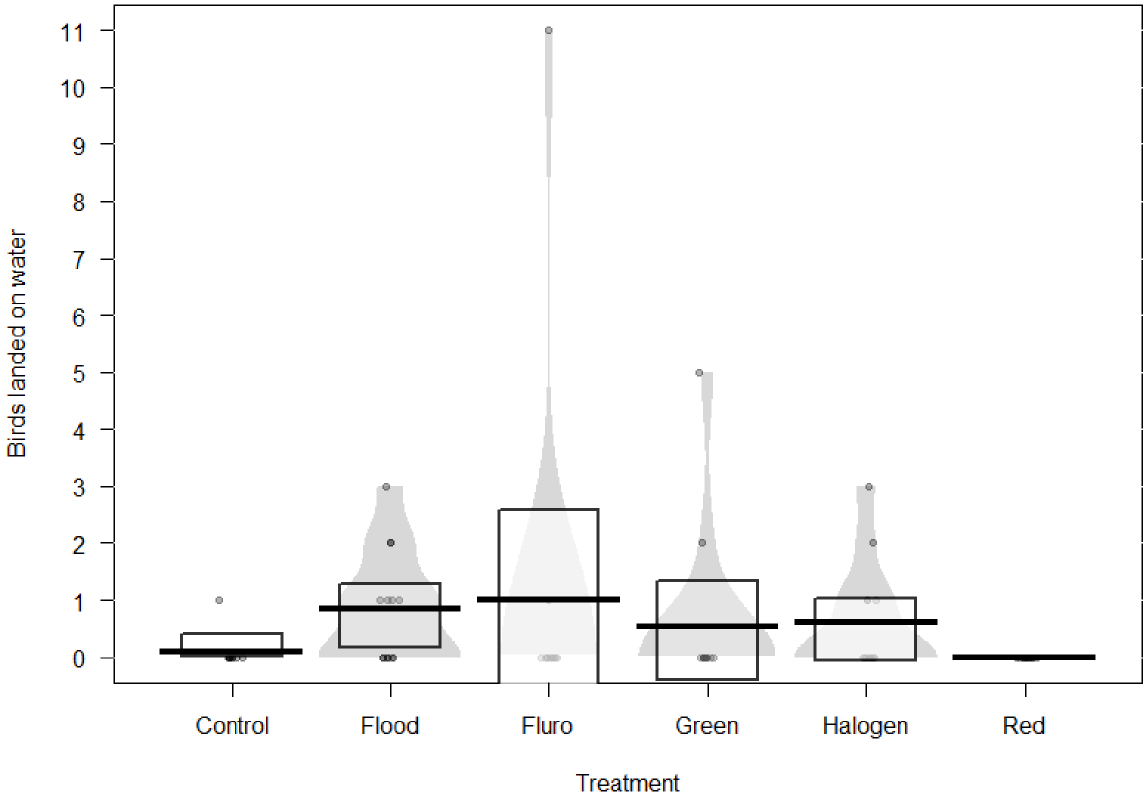


Figure 18. The number of birds that landed on the water for the different lighting treatments.

Other observations

Other species observed during the boat-based behavioural experiments included a New Zealand fur seal (kekeno, *Arctocephalus forsteri*) and a common dolphin (aihe, *Delphinus delphis*) which by their behaviour appeared to be pursuing small prey also attracted to the lights. Also attracted were an eel/sea snake, squid (*Nototodarus* spp.), numerous fish species including one active school, and flying fish (*Cypselurus* spp.*)*.

Discussion

This study aimed to test which colours and intensities of lights are least attractive to seabirds to minimise the impact of light-induced collisions in the Hauraki Gulf, a region of high seabird diversity. There were some differences observed in seabird behaviour and the potential reasons are discussed below.

Limitations

This study faced several limitations. The greatest limitation to this study was a small sample size and an experiment that was conducted during different times of the year and with different seabird species present. While this research is especially important in New Zealand due to the number of seabird species able to interact with fishing vessels, we were also limited by our inability to control for the differences in seabird acuity and responsiveness to various stimuli based on species. Inclement weather limited the number of nights available for the experiments to take place and one night of thermal imaging videos were lost when the hard drive storing the videos corrupted.

One limitation that became apparent when conducting the boat-based behavioural experiments was that using the same light array for both island and boat-based behavioural experiments, seabirds' attraction to lights was markedly different on land compared to at sea. On an island, the light array is essentially right amongst the nesting birds, whereas at sea, especially in open waters away from islands, birds were likely to be much more scattered, and therefore the attraction of lights not as immediate.

This was not so noticeable on the charter vessel *El Pescador*, which for safety reasons had to operate close to islands. Bird activity near islands at both ends of the night, i.e., the hours immediately after sunset, and immediately before sunrise, is likely to be much greater with birds returning to and leaving colonies. Although, this can vary at different stages of breeding and between islands. On many of the Hauraki Gulf islands (from Poor Knights to the Aldermen Islands) this can mean thousands of birds close to islands.

On the commercial fishing vessel which could drift safely over open waters the attraction from the light array was diminished. Also, the level of lights used on a commercial fishing vessel are likely to be much greater than the array we used. Although, the number of lights used and their intensity is unlikely to be as great on a longliner as those used on a trawler, as observed off the Aldermen Islands in May (authors, pers obs). That notwithstanding, there was a marked difference between the light array used in the boat-based behavioural experiments and those used when the *Southern Cross* is in operation.

Location

The observed difference in birds seen both in thermal imagery and from the deck between locations may have been due to the different species on each of the islands. For example, at least seven Procellariiformes breed on the Mokohinau Islands (Gaskin & Rayner, 2013; Ismar et al., 2014), and a similar number breed on the Mercury Islands (8 species) and Aldermen Islands (7 species) off the eastern Coromandel (Gaskin & Rayner, 2013; Rankin & Jones, 2021). Therefore, the species composition and the attraction of the different species to ALAN may have been the reason for the results we observed.

Fledgling petrels and shearwaters are particularly vulnerable to land-based artificial lighting on their maiden flight and peak fledging dates coincide with increased fallout throughout the world (Barros et al., 2019; Deppe et al., 2017; Fontaine et al., 2011; Imber, 1975; Le Corre et al., 2002; Miles et al., 2010; Reed et al., 1985; Rodríguez et al., 2017c; Rodriguez & Rodriguez, 2009; Telfer et al., 1987). Common diving petrels are probably the species in the Hauraki Gulf region most impacted by ALAN and frequently appear in deck strike records (e.g. Abraham & Richard, 2019; Glass & Ryan, 2013; Holmes, 2017). This species is common on Burgess Island in the Mokohinau Island group and juveniles typically fledge in November-December when the experiments were conducted. This may be the reason that higher numbers of seabirds were seen near the Mokohinau Islands. However, sooty shearwaters, flesh-footed shearwaters, and black-winged petrels are all species found on the Mercury and Aldermen Islands off the eastern Coromandel (Forest & Bird, 2015) and juveniles of those species fledge in April-May, yet we did not observe any of these species during our experiments.

During the land-based experiments, significantly more birds were trapped in the light beam on the Mokohinau Islands than Hauturu for all light types and trapped in the light beam and observed in thermal imagery for the small LED lights only (Lukies et al., 2020). We suspect this result was due to the different species that breed on each of the islands and the timing of fledging for those species.

Alternatively, the observed differences in location for the boat-based experiments may have been due to another factor such as the time of year or the vessel used. Our experiments near the Mokohinau Islands were in October and November when 7 species are breeding and, therefore, frequently returning to their island colonies (Forest & Bird, 2015). The experiments off eastern Coromandel took place during May, when only 5 species are breeding (Forest & Bird, 2015) and, therefore, potentially less birds would encounter the lights when returning to their colonies.

Time of night

Our results showed that more seabirds were observed closer to sunset and sunrise than at other times during the night. This is not surprising considering that nocturnal seabirds, such as many of those in the Hauraki Gulf, are returning to or departing their island colonies during those times (Gaskin & Rayner, 2013). Commercial fishing activity in the Hauraki Gulf primarily occurs in the hours before sunrise (Figs. 2 & 3, Data provided by Ministry of Fisheries) and bright lights from vessels have the potential to attract seabirds departing from island colonies. Similarly, vessels anchored at night near seabird islands may attract birds even when deck lights are not in use.

Moon phase

In terms of moon phase, our results, although not significant, show a similar pattern to other studies where greater fallout occurred during the new moon for Newell's shearwaters (*Puffinus newelli*), Leach's storm-petrels (*Oceanodroma leucorhoa*), Manx shearwaters (*Puffinus puffinus*), Hutton's shearwater (Kaikōura tītī*, Puffinus huttoni*) and Cory's shearwaters (*Calonectris borealis*)

(Deppe et al., 2017; Forest & Bird, 2014; Miles et al., 2010; Reed et al., 1985; Rodriguez & Rodriguez, 2009; Telfer et al., 1987). Several suggestions have been made as to why light-induced collisions are generally reduced on moonlit nights. Ambient light from a full moon may limit the intensity of artificial light and allow birds to see structures, thus reducing the rates of collisions (reviewed in Montevecchi, 2006; Reed et al., 1985). Alternatively, petrels visit their colonies less on moonlit nights compared to dark nights which would reduce the likelihood of encountering artificial light when travelling to or from their colonies (Imber, 1975; Montevecchi, 2006; Mougeot & Bretagnolle, 2000), and thirdly, fledging may be inhibited by a bright moon (Rodriguez & Rodriguez, 2009).

Lighting treatment

Our non-significant results for the number of birds seen for the different lighting treatments was surprising considering how the birds perceive the different lights (Lukies et al., 2020) and the results seen in some other studies of nocturnal birds. For example, red and yellow lights were less attractive to tropical shearwaters (*Puffinus bailloni*) on Réunion Island than green and blue lights (Salamolard et al., 2007). Similarly, using red filters on power station floodlights reduced light-induced avian mortality by up to 80% in Ontario, Canada (reviewed in Wiese et al., 2001) and the replacement of white lights with green lamps on offshore oil rigs in the Netherlands reduced collisions by nocturnally migrating songbirds (Poot et al., 2008). Fewer migrating songbirds at sea in northern Germany were attracted to a continuous red LED light than yellow, white, green or blue LED’s but blinking lights of each colour were less attractive than their continuous counterpart (Rebke et al., 2019). A similar result was seen during the land-based behavioural experiments (Lukies et al., 2020) and it is likely that our small sample sizes were the reason no differences were detected for the different light types tested.

Seabird behaviour around lights

While no statistically significant differences were seen in both the land and sea-based behavioural experiments, the lights that appeared to be the least disorientating to birds were the red LED, green LED or halogen lights. Conversely, the light that appeared most disorientating to birds was the flood LED, despite the sea-based experiments using a less powerful version of the light used on land. The lights with the next highest rates of fallout were the other ‘white’ lights: the small white LED during the land-based trials and the fluorescent at sea. These ‘white’ lights reflect more short wavelength light (300-470 nm; UV, violet, indigo, blue) which are the colours most disorientating to nocturnal animals, including seabirds (Commonwealth of Australia, 2020; Hart, 2004; Longcore et al., 2018; Rodríguez et al., 2017a; Tanaka, 2015).

The results from the boat-based experiments differed to those during the land-based behavioural experiments where more birds were trapped in the light beam during the third quarter moon phase than the new moon for all lights and a similar result was seen when comparing small LEDs only (Lukies et al., 2020).

Recommendations from the land-based behavioural experiments addressed

- We avoided the issue of different lenses used in the land-based experiments by switching the lens over when we needed to change the thermal scope halfway through the experiments each night due to memory capacity issues.
- We had the thermal imagery from the land-based behavioural experiments recounted to reduce observer bias. We qualitatively compared the observations of two independent and unbiased observers to see if general patterns in thermal scope video analysis remained constant. Results compared between different observers using thermal imaging showed that while there was some variability in the number of birds counted in thermal videos, differences were consistent for each observer. As a result, trends appear to be congruent based on a large data sample and show similarity between treatments (Fig. 21 in the Appendix).
- We had planned to replace the thermal imaging scopes with a thermal imaging camera such as the FLIR Tau 2 model 324 to capture a wider field of view. However, during testing it was evident the FLIR camera was not high resolution enough to detect birds flying in the distance, nor could it withstand the conditions at sea (i.e., salt spray, rain). Therefore, we persisted using the Pulsar Helion Thermal Imaging Scopes.
- We were unable to increase the sample size for each light due to the cost of vessel charter and the limited number of nights available where the weather was suitable to run the experiments. We were also unable to target a greater range of moon phases and weather conditions due to the limited number of nights available.

Conclusion and recommendations for further vessel-based behavioural experiments

Our experiment provides a preliminary study to show that there are some locations, times of night and times of year (based on moon phase) where birds are more likely to ‘participate’ in boat-based behavioural experiments that could be used in the future for increasing sample size and further testing light attraction at sea. The logistical challenges and resource constraints that occurred during this study were key limitations resulting in small sample sizes and, therefore, we were unable to detect any significant differences in seabird attraction to the different lighting treatments. Further research into the effects of ALAN in the Hauraki Gulf, and globally, is urgently required to address the increasing threat of ALAN to nocturnal seabirds, especially near their breeding colonies.

The recommendations for future boat-based behavioural experiments should:

- Use a fishing vessel as a platform for future work. Despite limitations in scheduling trips around weather and a vessel’s commercial fishing operation, the ability to drift safely throughout the light experiments is a major factor.
- Attempt to target specific seabird species (although we were unable to identify differences in thermal videos) such as common diving petrels. This species is frequently mentioned in deck strike literature and targeting a high-density period (e.g. fledging)

could help to determine the attractiveness of the different lights to a locally abundant and vulnerable species.

- Time experiments to incorporate a greater range of moon phases and weather (e.g. foggy nights) as these are important factors influencing artificial light attraction in seabirds. It should be noted that forecasting of foggy or misty nights and coinciding with the availability of working fishing vessels will be difficult.
- At-sea experiments should be augmented so that we can obtain much more data for each treatment (and preferably without confounding variables, such as time of year and location).
- Investigate the difference in the number and power of the lights used on the different types of fishing vessels operating at night.
- Aim to increase the number of each light type to be more consistent with the level of deck lighting commonly used on fishing vessels.
- Invest in automation of detection to reduce the labour involved in manually detecting birds in thermal videos. This would increase accuracy and remove human error.
- Switch the red LED light for phosphor converted amber LED as the brighter orange light would likely be more conducive to human activity than the red LED. Like the red LED, phosphor converted amber LED filters out blue light and reflects a wavelength of 590 – 610 nm. These LED's are used as street lights in some parts of New Zealand near to dark sky sanctuaries to minimise the impact of ALAN (Hearnshaw, 2021).
- Consider testing strobing light, in addition to continuous light, as this has been shown to minimise collisions by nocturnally migrating songbirds (Rebke et al., 2019).

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References

Abraham, E., & Richard, Y. (2019). Estimated capture of seabirds in New Zealand trawl and longline fisheries, to 2016–17. *New Zealand Aquatic Environment and Biodiversity Report, 226*, 85.

Abraham, E. R., Richard, Y., Berkenbusch, K., & Thompson, F. (2016). *Summary of the capture of seabirds, marine mammals, and turtles in New Zealand commercial fisheries, 2002–03 to 2012–13.* (169). Retrieved from http://mpi.govt.nz/document-vault/12180

Barros, R., Medrano, F., Norambuena, H. V., Peredo, R., Silva, R., de Groote, F., & Schmitt, F. (2019). Breeding Phenology, Distribution and Conservation Status of Markham's Storm-Petrel Oceanodroma markhami in the Atacama Desert. *Ardea, 107*(1), 75-84.

Black, A. (2005). Light induced seabird mortality on vessels operating in the Southern Ocean: incidents and mitigation measures. *Antarctic Science, 17*(1), 67-68.

Bowmaker, J. (1991). Photoreceptors, photopigments and oil droplets. *Vision and visual dysfunction, 6*, 108-127.

Commonwealth of Australia. (2020). *National Light Pollution Guidelines for Wildlife Including marine turtles, seabirds and migratory shorebirds*. Commonwealth of Australia Retrieved from https://www.environment.gov.au/biodiversity/publications/national-light-pollution-guidelines-wildlife

Croxall, J. P., Butchart, S. H., Lascelles, B., Stattersfield, A. J., Sullivan, B., Symes, A., & Taylor, P. (2012). Seabird conservation status, threats and priority actions: a global assessment. *Bird Conservation International, 22*(1), 1-34.

Department of Conservation. (2019). Cruise ships protecting seabirds [Press release]. Retrieved from https://www.doc.govt.nz/news/media-releases/2019/cruise-ships-protecting-seabirds/

Deppe, L., Rowley, O., Rowe, L. K., Shi, N., Gooday, O., & Goldstien, S. J. (2017). Investigation of fallout events in Hutton's shearwaters (Puffinus huttoni) associated with artificial lighting. *Notornis, 64*(4), 181-191.

Dias, M. P., Martin, R., Pearmain, E. J., Burfield, I. J., Small, C., Phillips, R. A., . . . Croxall, J. P. (2019). Threats to seabirds: a global assessment. *Biological Conservation*.

Fontaine, R., Gimenez, O., & Bried, J. (2011). The impact of introduced predators, light-induced mortality of fledglings and poaching on the dynamics of the Cory's shearwater (Calonectris diomedea) population from the Azores, northeastern subtropical Atlantic. *Biological Conservation, 144*(7), 1998-2011.

Forest & Bird. (2014). *New Zealand Seabirds: Important Bird Areas and Conservation* (0473285215). Retrieved from Wellington, New Zealand: https://www.dropbox.com/s/f9yydy4im1wbgvf/IBAforSeabirds.pdf?dl=0

Forest & Bird. (2015). *New Zealand Seabirds: Sites on Land, Coastal Sites and Islands*. Retrieved from Wellington, New Zealand: https://www.dropbox.com/s/75j58oe7ugrg5pm/IBAIslandsCoastalSites.pdf?dl=0

Gaskin, C., & Rayner, M. J. (2013). *Seabirds of the Hauraki Gulf: natural history, research and conservation*. Retrieved from Aukland, New Zealand: https://www.aucklandcouncil.govt.nz/about-auckland-council/how-auckland-council-works/harbour-forums/Documents/seabirds-hauraki-gulf.pdf

Glass, J., & Ryan, P. (2013). Reduced seabird night strikes and mortality in the Tristan rock lobster fishery. *African Journal of Marine Science, 35*(4), 589-592.

Guilford, T., Padget, O., Bond, S., & Syposz, M. M. (2019). Light pollution causes object collisions during local nocturnal manoeuvring flight by adult Manx shearwaters Puffinus puffinus. *Seabird, 31*.

Hart, N. S. (2004). Microspectrophotometry of visual pigments and oil droplets in a marine bird, the wedge-tailed shearwater Puffinus pacificus: topographic variations in photoreceptor spectral characteristics. *Journal of Experimental Biology, 207*(7), 1229-1240.

Håstad, O., Victorsson, J., & Ödeen, A. (2005). Differences in color vision make passerines less conspicuous in the eyes of their predators. *Proceedings of the National Academy of Sciences, 102*(18), 6391-6394.

Hearnshaw, J. (2021, 22nd May). Prof John Hearnshaw: Dark skies and light trespass. *RNZ*. Retrieved from https://www.rnz.co.nz/national/programmes/saturday/audio/2018796547/prof-john-hearnshaw-dark-skies-and-light-trespass

Hölker, F., Wolter, C., Perkin, E. K., & Tockner, K. (2010). Light pollution as a biodiversity threat. *Trends in ecology & evolution, 25*(12), 681-682.

Holmes, M. (2017). Characterising deck strikes. In. Wellington, New Zealand: Department of Conservation.

Holveck, M.-J., Grégoire, A., Guerreiro, R., Staszewski, V., Boulinier, T., Gomez, D., & Doutrelant, C. (2017). Kittiwake eggs viewed by conspecifics and predators: implications for colour signal evolution. *Biological Journal of the Linnean Society, 122*(2), 301-312.

Imber, M. (1975). Behaviour of petrels in relation to the moon and artificial lights. *Journal of the Ornithological Society of New Zealand*, 302.

Ismar, S. M., Baird, K. A., Gaskin, C. P., Taylor, G. A., Tennyson, A. J., Rayner, M. J., . . . Imber, M. J. (2014). A case of natural recovery after the removal of invasive predators–community assemblage changes in the avifauna of Burgess Island. *Notornis, 61*, 188-195.

Kelber, A. (2016). Colour in the eye of the beholder: receptor sensitivities and neural circuits underlying colour opponency and colour perception. *Current opinion in neurobiology, 41*, 106-112.

Kyba, C. C., Kuester, T., De Miguel, A. S., Baugh, K., Jechow, A., Hölker, F., . . . Guanter, L. (2017). Artificially lit surface of Earth at night increasing in radiance and extent. *Science advances, 3*(11), e1701528.

Le Corre, M., Ollivier, A., Ribes, S., & Jouventin, P. (2002). Light-induced mortality of petrels: a 4-year study from Réunion Island (Indian Ocean). *Biological Conservation, 105*(1), 93-102.

Longcore, T., & Rich, C. (2004). Ecological light pollution. *Frontiers in Ecology and the Environment, 2*(4), 191-198.

Longcore, T., Rodríguez, A., Witherington, B., Penniman, J. F., Herf, L., & Herf, M. (2018). Rapid assessment of lamp spectrum to quantify ecological effects of light at night. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology, 329*(8-9), 511-521.

Lukies, K., Gaskett, A., Heswall, A.-M., Gaskin, C., & Friesen, M. (2020). *Lighting adjustments to mitigate against deck strikes/vessel impacts*. Retrieved from https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-conservation-services/reports/draft-reports/mit2019-03-lighting-adjustments-to-mitigate-against-deck-strikes-draft-report-yr1.pdf

Merkel, F. R., & Johansen, K. L. (2011). Light-induced bird strikes on vessels in Southwest Greenland. *Marine Pollution Bulletin, 62*(11), 2330-2336.

Miles, W., Money, S., Luxmoore, R., & Furness, R. W. (2010). Effects of artificial lights and moonlight on petrels at St Kilda. *Bird Study, 57*(2), 244-251.

Mitkus, M., Nevitt, G. A., Danielsen, J., & Kelber, A. (2016). Vision on the high seas: spatial resolution and optical sensitivity in two procellariiform seabirds with different foraging strategies. *Journal of Experimental Biology, 219*(21), 3329-3338.

Montevecchi, W. A. (2006). Influences of artificial light on marine birds. *Ecological consequences of artificial night lighting*, 94-113.

Morton, J. (2018). Conservationists saddened after seabirds die in boxes. *New Zealand Herald*. Retrieved from https://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=12057912

Mougeot, F., & Bretagnolle, V. (2000). Predation risk and moonlight avoidance in nocturnal seabirds. *Journal of Avian Biology, 31*(3), 376-386.

Ndez-Juric, E. F. (2016). The role of animal sensory perception in behavior-based management. *Conservation Behavior: Applying Behavioral Ecology to Wildlife Conservation and Management, 21*, 149.

Nguyen, K. Q., & Winger, P. D. (2019). Artificial light in commercial industrialized fishing applications: a review. *Reviews in Fisheries Science & Aquaculture, 27*(1), 106-126.

Poot, H., Ens, B. J., de Vries, H., Donners, M. A., Wernand, M. R., & Marquenie, J. M. (2008). Green light for nocturnally migrating birds. *Ecology and society, 13*(2).

R Core Team. (2019). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Ramm, K. (2010). *Conservation Services Programme Observer Report: 1 July 2008 to 30 June 2009*. Retrieved from Wellington, New Zealand: https://www.doc.govt.nz/our-work/conservation-services-programme/csp-reports/archive/2008-2009/csp-observer-report-1-july-2008-to-30-june-2009/

Rankin, L. L., & Jones, H. P. (2021). Nearshore ecosystems on seabird islands are potentially influenced by invasive predator eradications and environmental conditions: a case study at the Mercury Islands, New Zealand. *Marine Ecology Progress Series, 661*, 83-96.

Rebke, M., Dierschke, V., Weiner, C. N., Aumüller, R., Hill, K., & Hill, R. (2019). Attraction of nocturnally migrating birds to artificial light: The influence of colour, intensity and blinking mode under different cloud cover conditions. *Biological Conservation, 233*, 220-227.

Reed, J. R., Sincock, J. L., & Hailman, J. P. (1985). Light attraction in endangered procellariiform birds: reduction by shielding upward radiation. *The Auk, 102*(2), 377-383.

Rodríguez, A., Arcos, J. M., Bretagnolle, V., Dias, M. P., Holmes, N. D., Louzao, M., . . . Rodríguez, B. (2019). Future directions in conservation research on petrels and shearwaters. *Frontiers in Marine Science, 6*, 94.

Rodriguez, A., Burgan, G., Dann, P., Jessop, R., Negro, J. J., & Chiaradia, A. (2014). Fatal attraction of short-tailed shearwaters to artificial lights. *PLoS One, 9*(10).

Rodríguez, A., Dann, P., & Chiaradia, A. (2017a). Reducing light-induced mortality of seabirds: high pressure sodium lights decrease the fatal attraction of shearwaters. *Journal for Nature Conservation, 39*, 68-72.

Rodríguez, A., Holmes, N. D., Ryan, P. G., Wilson, K. J., Faulquier, L., Murillo, Y., . . . Rodríguez, B. (2017b). Seabird mortality induced by land-based artificial lights. *Conservation Biology, 31*(5), 986-1001.

Rodríguez, A., Moffett, J., Revoltós, A., Wasiak, P., McIntosh, R. R., Sutherland, D. R., . . . Chiaradia, A. (2017c). Light pollution and seabird fledglings: targeting efforts in rescue programs. *The Journal of Wildlife Management, 81*(4), 734-741.

Rodriguez, A., & Rodriguez, B. (2009). Attraction of petrels to artificial lights in the Canary Islands: effects of the moon phase and age class. *Ibis, 151*(2), 299-310.

Ryan, P. (1991). The impact of the commercial lobster fishery on seabirds at the Tristan da Cunha Islands, South Atlantic Ocean. *Biological Conservation, 57*(3), 339-350.

Salamolard, M., Ghestemme, T., Couzi, F.-X., Minatchy, N., & Le Corre, M. (2007). Impacts des éclairages urbains sur les pétrels de Barau, Pterodroma baraui sur l'Ile de la Réunion et mesures pour réduire ces impacts. *Ostrich-Journal of African Ornithology, 78*(2), 449-452.

Sandager, F. (1890). *Observations on the Mokohinou Islands and the birds which visit them.* Paper presented at the Transactions of the New Zealand Institute.

Tanaka, K. D. (2015). A colour to birds and to humans: why is it so different? *Journal of Ornithology, 156*(1), 433-440.

Telfer, T. C., Sincock, J. L., Byrd, G. V., & Reed, J. R. (1987). Attraction of Hawaiian seabirds to lights: conservation efforts and effects of moon phase. *Wildlife Society Bulletin (1973-2006), 15*(3), 406-413.

Troy, J. R., Holmes, N. D., Veech, J. A., & Green, M. C. (2013). Using observed seabird fallout records to infer patterns of attraction to artificial light. *Endangered Species Research, 22*(3), 225-234.

Whitehead, E., Adams, N., Baird, K., Bell, E., Borelle, S., Dunphy, B., . . . Russell, J. (2019). *Threats to seabirds of northern Aotearoa New Zealand*. Retrieved from Auckland, New Zealand: https://www.aucklandcouncil.govt.nz/about-auckland-council/how-auckland-council-works/harbour-forums/Documents/threats-to-seabirds-northern-aotearoa.pdf

Wiese, F. K., Montevecchi, W., Davoren, G., Huettmann, F., Diamond, A., & Linke, J. (2001). Seabirds at risk around offshore oil platforms in the North-west Atlantic. *Marine Pollution Bulletin, 42*(12), 1285-1290.

Appendix

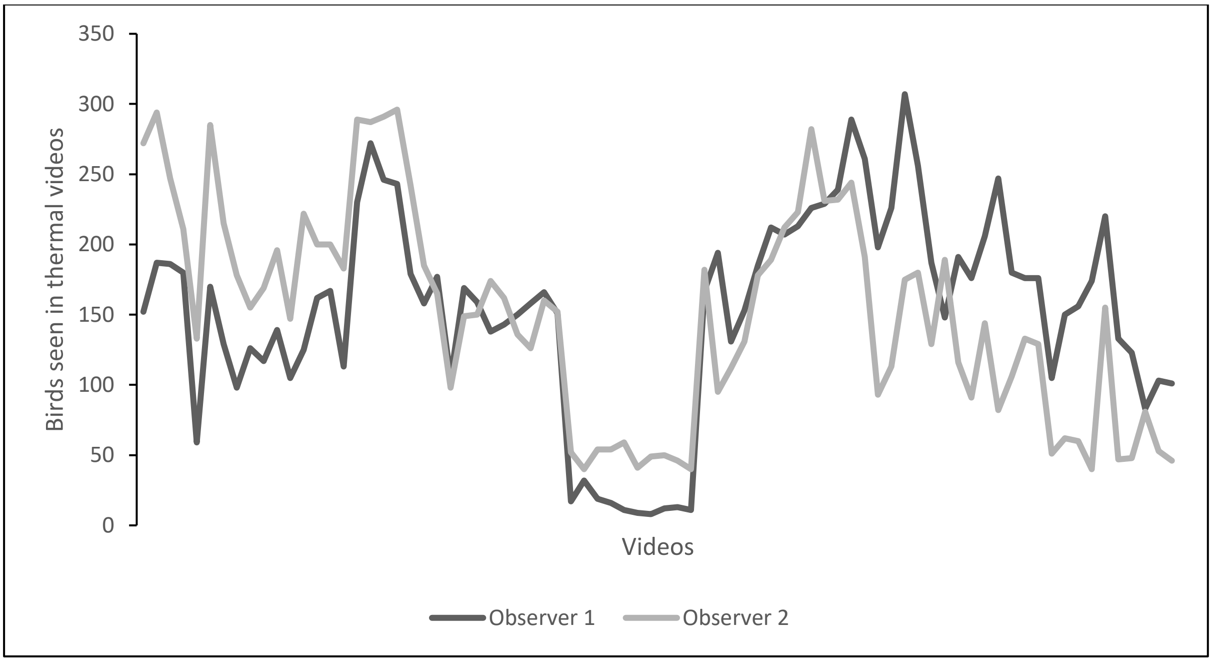

Figure 19. Seabird counts from thermal imagery from the land-based behavioural experiments from two independent observers.