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Artificial light at night correlates with seabird groundings: mapping city lights near a seabird breeding hotspot

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Artificial light at night (ALAN) is a growing conservation concern for seabirds, which can become disoriented and grounded by lights from buildings, bridges and boats. Many fledgling seabirds, especially from the Procellariiformes such as petrels and shearwaters are especially susceptible to artificial light. The Hauraki Gulf, a seabird hotspot, is located near Tāmaki Makaurau/Auckland, which is Aotearoa New Zealand's largest urban city, with considerable ALAN and regularly documented events of seabird groundings. We aim to identify the characteristics of locations especially prone to seabird groundings. We used an online database of seabirds taken to a wildlife rescue facility by the public to map 3 years of seabird groundings, and test for correlations between seabird groundings and the natural night sky brightness/night sky quality. We found that areas with greater light pollution often had a higher number of seabirds becoming grounded. Further, we identified important seasonal patterns and species differences in groundings. Such differences may be a by-product of species ecology, visual ecology and breeding locations, all of which may influence light attraction. In general, seabird groundings are primarily determined by the brightness of the area and are species-specific. Groundings may not be indicative of human or seabird population abundance considering some areas have a lower human population with high light levels and had high amounts of seabird groundings. These findings can be applied to cities internationally to mitigate groundings by searching and targeting specific anthropogenic structures which are brightly lit. Those targeting structures and areas can then be the focus of mitigation efforts to reduce the light pollution of those areas which could lead to a reduction in seabird fallout. Also, this study illustrates how a combination of public awareness and concern for seabirds grounded from light attraction along with detailed animal welfare databasing and natural night sky brightness data can be a powerful, collaborative tool to improve conservation for highly-at-risk animals such as seabirds around the world.

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Abstract

Background. Artificial light at night (ALAN) is a growing conservation concern for seabirds, which can become disoriented and grounded by lights from buildings, bridges and boats. Many fledgling seabirds, especially from the Procellariiformes such as petrels and shearwaters are especially susceptible to artificial light. The Hauraki Gulf, a seabird hotspot, is located near Tāmaki Makaurau/Auckland, which is Aotearoa New Zealand's largest urban city, with considerable ALAN and regularly documented events of seabird groundings. We aim to identify the characteristics of locations especially prone to seabird groundings.

Methods. We used an online database of seabirds taken to a wildlife rescue facility by the public to map 3 years of seabird groundings, and test for correlations between seabird groundings and the natural night sky brightness/night sky quality.

pollution not natural

Results. We found that areas with greater light pollution often had a higher number of seabirds becoming grounded. Further, we identified important seasonal patterns and species differences in groundings. Such differences may be a by-product of species ecology, visual ecology and breeding locations, all of which may influence light attraction.

Discussion. In general, seabird groundings are primarily determined by the brightness of the area and are species-specific. Groundings may not be indicative of human or seabird population abundance considering some areas having a lower human population with high light levels and had high amounts of seabird groundings. These findings can be applied to cities internationally to mitigate groundings by searching and targeting specific anthropogenic structures which are brightly lit. Those targeting structures and areas can then be the focus of mitigation efforts to reduce the light pollution of those areas which could lead to a reduction in seabird fallout. Also, this study illustrates how a combination of public awareness and concern for seabirds grounded from light attraction along with a detailed animal welfare databasing and natural night sky brightness data can be a powerful, collaborative tool to improve conservation for highly-at-risk animals such as seabirds around the world.

Keywords:
ALAN, seabirds, light pollution, light attraction, groundings, conservation

1.0 Introduction

As urbanization expands into the rural landscape (Nechyba & Walsh, 2004) it can denaturalize the environment and encroach into the habitat of many animals (Sharma, Ram, & Rajpurohit, 2011; Yeo & Neo, 2010). In turn, this can alter species richness and diversity (Sol et al., 2017). It can also affect the physiology, ecology and behaviour of individual species (Fokidis, Orchinik, & Deviche, 2009). For example, for the dark eyed junco, *Junco hyemalis thurberi*, there are a suite of changes; urban individuals sing at a higher minimum frequency, display less aggression, have similar sex roles, have a longer breeding season and have a reduction in the white colour of the tail feathers compared to the juncos in the rural areas (Atwell et al., 2014; Reichard et al., 2020).

One aspect of urbanization that can change animal behaviour is artificial lighting at night (ALAN). ALAN can be from street lighting, vehicles and buildings (Gaston & Bennie, 2014) and is associated with changes to animals and plants (Da Silva, Valcu, & Kempenaers, 2015; Duarte et al., 2019). For birds, ALAN affects the behaviours and movements of young offspring and hatchlings (Lorne & Salmon, 2007) and increases the activity of brood nest predators (Foster et al., 2016). It can also decrease the activity of some species such as the mottled owl, *Ciccaba virgata* (Marín-Gómez et al., 2020).

Some animals avoid lit areas (Bliss-Ketchum et al,. 2016), but many studies document attraction to ALAN. Most of the literature focuses on avian songbirds and insects attracted to urban lights (Eisenbeis et al., 2009; Van Langevelde et al., 2017). Songbirds on annual migration routes are frequently documented being attracted to the lights, which leads to window strike and collisions with buildings (Hudecki & Finegan, 2018) and collisions with cruise ships (Bocetti, 2011). In both cases this is likely due to high rates of movement at night.

Another group of birds that are commonly active at night and likely to be affected by ALAN are the seabirds. Research shows ALAN can coincide with high rates of seabird fallout: seabirds can be grounded by lights and collide with anthropogenic structures, as a result of disorientation (Rodríguez, Dann, & Chiaradia, 2017; Troy et al,. 2013). ALAN-related deck strike is also a common occurrence on fishing vessels and cruise ships (Bocetti, 2011; Glass & Ryan, 2013; Holmes, 2017; Merkel & Johansen, 2011; Ryan, Ryan, & Glass, 2021). The collision itself, either on a fishing vessel or with an anthropogenic structure, can lead to various injuries for the seabird, and secondary effects including groundings (when a seabird lands on the ground and is unable to take off), starvation, dehydration, and predation events (Le Corre et al., 2002; Rodríguez et al., 2017a). Inexperienced seabird fledglings are the age group primarily grounded by ALAN, and groundings are especially common among burrow-nesting Procellariiformes (Rodríguez et al., 2017b). Procellariiformes can have acute vision and olfaction (Hayes, Martin, & Brooke, 1991; Martin & Crawford, 2015; Nevitt, 2000). However, fledglings of burrow-nesting seabird species have underdeveloped and poor vision, likely due to their lack of exposure to visual information while underground, making them more likely to be prone to disorientation from lights (Atchoi, 2020). Procellariiformes' sensitivity to sensory information make them uniquely vulnerable to sensory threats, including ALAN (Friesen, Beggs, & Gaskett, 2017; Heswall et al., 2021).

ALAN-related groundings occur internationally with records in Hawaii (Rodríguez et al., 2015; Telfer et al,. 1987), the Canary Islands (Rodriguez & Rodriguez, 2009), Maltese Islands (Laguna, Barbara, & Metzger, 2014), Canada (Wilhelm et al., 2021) the United Kingdom (Syposz et al., 2018) and New Zealand (Whitehead et al., 2019). For example, over 1,500 Barau's petrel (*Pterodroma baraui)*, and over 650 Audubon's shearwater, (*Puffinus lherminieiri bailloni*), were grounded on Réunion Island between 1996 and 1999, mainly attracted to streetlights (Le Corre et al., 2002). In Aotearoa's/New Zealand's Hauraki Gulf, near the major city of Auckland, almost 70 Buller's shearwater (*Puffinus bulleri*) and flesh-footed shearwater (*Ardenna carneipes*) succumbed to deck strike due to disorientation from the lights of a single cruise ship near Te-Hauturu-O-Toi (Morton, 2018).

Collisions and deck strike due to ALAN are likely to be more frequent when abundant seabird breeding colonies (especially burrow-nesting Procellariformes) are adjacent to large urban cities. Northern New Zealand is a seabird hotspot with over a quarter of the world's seabird species. The Hauraki Gulf, near the north of Te Ika-a-Māui/the North Island, is a key breeding habitat of global importance with approximately 27 seabird species in a region covering 1.2 million hectares (Online Supplementary Fig. 1a-c) (Council, 2012; Gaskin & Rayner, 2013; Whitehead et al., 2019). Within this area, there are many seabird colonies, both on land and on islands. Some species are relatively widespread with multiple colonies (e.g. Grey faced petrel, *Pterodroma gouldi*) whereas others are an endemic and only breed on specific islands of the gulf. For example, the Buller's shearwater, only breeds on the Poor Knights Islands, while the NZ storm petrel (*Fregetta maoriana)* only breeds on Te-Hauturu -O-Toi and the black petrel, Procellaria parkinsoni, only breeds on Aotea and Te-Hauturu-O-Toi (Gaskin & Rayner, 2013).

Burrow-nesting Procellariiformes are the most-common type of seabird in this region (Gaskin & Rayner, 2013).

In addition to hosting rare and diverse seabird species with traits most associated with risk of ALAN attraction, the Hauraki Gulf is also home to NZ largest and rapidly growing city: Auckland/Tāmaki Makaurau. The associated light pollution from the city likely threatens marine and native ecosystems (McNaughton et al,. 2021). Many of the seabirds which breed in the Hauraki Gulf often fly over Auckland to reach their foraging grounds in the Tasman Sea (e.g. Cook's petrels (*Pterodroma cookii*) (Gaskin & Rayner, 2013)). As they fly over, they may be at a high risk of disorientation and grounding due to ALAN. However, there has been little research on the characteristics of locations where seabirds are most likely to become grounded. Considering the Hauraki Gulf is home to many endemic and nationally vulnerable seabirds, it is important to determine whether there are grounding hotspots, and whether these correlate with the natural night sky brightness.

Here, we identify the characteristics of the locations most associated with seabird groundings, and test for correlations with natural night sky brightness. We do this by mapping fallout locations of key seabird species that members of the public have rescued and deposited at the local avian wildlife hospital and rehabilitation facility, BirdCare Aotearoa. We combine this with data on the natural night sky brightness/night sky quality, and test for relationships, any variation between species, and for urban vs. rural locations.

2.0 Materials & Methods

2.1 Study site:

Auckland is New Zealand's largest city with over 1.4 million residents (Auckland Council, 2018). The Auckland region is an isthmus surrounded by the Hunua Ranges in the south east, and the Waitakere Ranges to the north west, bordered by the Tasman Sea to the west and the Haruaki Gulf to the east (Fig. 1). The Auckland region is surrounded by two major bodies of water, The Tasman Sea to the west and the Pacific Ocean to the east.

2.2 Study species:

We included the seabird species most commonly taken to BirdCare Aotearoa with injuries consistent with collisions or groundings: Cook's petrel, grey-faced petrel, black petrel (*Procellaria parkinsoni*), Buller's shearwater, fluttering shearwater (*Puffinus gavia*), common diving petrel (*Pelecanoides urinatrix*), white-faced storm petrel (*Pelagodroma marina*), sooty shearwater (*Ardenna grisea*; Table. 1). These are all burrow-nesting seabirds which have breeding sites around Auckland and the Hauraki Gulf (Online Supplementary Fig. 1a-c) (Miskelly, 2013).

2.3 Data collection:

The wildlife rehabilitation medical database (WRMD; Project, 2021) is a database designed for wildlife rehabilitators to record, analyze and manage the data of the animals which enter into their care/facility. Commencing in 2016, the database is now used in over 25 different countries and almost 1000 rehabilitation centers (Project, 2021). We extracted data on seabirds that had been found in the Auckland region (city, suburbs and adjacent rural areas) and brought into BirdCare Aotearoa from January 2018 until September 2021.

Based off the literature and observations, cases were included in our analyses when the seabird species is normally associated with light attraction such as the Procellariformes (Zissis, 2020). We also used seabird species which were nocturnal and had sustained injuries consistent with collisions, e.g. head injuries, wing dislocations and fractures. Seabirds which were excluded included the Suliformes such as the Australasian gannet (*Morus serrator*), as well as the Charadriiformes such as the southern black-backed gulls (*Larus dominicanus*), and red-billed gulls (*Chroicocephalus novaehollandiae scopulinus*). These species are diurnal and less susceptible to light attraction considering as of yet, nothing has been recorded in the literature about those seabird orders and species being attracted to lights.

2.4 GIS analysis:

The physical address where the seabird was found was obtained using the WRMD (Project, 2021). For each location, the GPS coordinate (longitude/latitude) was identified in using the search engine Nominatum to search for the geographic coordinates using the street address which was used in OpenStreetMap (OSM). OSM is an open source mapping system that relies on user data to create publicly available maps (OpenStreetMap, 2021).

This was conducted in R studio using `tmaptools` and the function `geocode_OSM()` (Tennekes, 2021). If a coordinate was not found for an address, then it was filtered for matched addresses until all the coordinates for the addresses were found. Once all the addresses and coordinates matched, they were plotted out onto a map using the packages 'rJava' and 'OpenStreetMap' (Fellows, 2019).

2.5 Map projections:

OSM uses the Universal Transverse Mercator (UTM), as its projection, dividing the earth into an even grid creating less distortion at the poles and preserving distance. However, to obtain the minimum amount of distortion for our location in Auckland, New Zealand we had to define our zone as "Zone 1" for the code to function. Since our coordinates are in longitude/latitude and not UTM, our points were converted into a Spatial Points Data Frame (SPDF) for plotting onto the map using the packages 'sp', 'raster' (Hijmans, 2021) and 'ggplot2'. Once converted, dot plots and probability heatmaps were constructed to identify the grounding locations in Auckland for each individual seabird species as well as changes over time of the groundings.

2.6 Map construction:

To construct the probability heat maps we used the kernel density estimate (stat_density_2d; ggplot2). This enabled us to find the probability that a future point might occur in that area, given the current distribution of points per 5km2.

We also mapped the predicted natural night sky brightness, using data obtained from continuous measurements of the night sky (McNaughton et al., 2021). The predicted natural night sky brightness is a measure of the night sky quality and is an index. The higher the value, the greater the night sky quality/natural night sky brightness means there is less light pollution. Conversely a low value corresponds with heavily impacted and very bright night sky and a lower night sky quality/natural night sky brightness. Thus, perhaps counterintuitively, high values mean a darker sky, and low values mean a brighter sky.

2.7 Locations

To test for a relationship between the predicted natural night sky brightness and seabird groundings, the map of Auckland was divided into 30 raster grid squares in 10km by 10km using the package ‘raster’. The average, minimum and maximum brightness for each grid square was extracted. The seabird fallout coordinate points were imported into the raster and then extracted for each grid square. The 10km by 10km grid squares were used to avoid zero inflated data - smaller grid length generate many grid squares with 0 seabirds.

An urban/rural delineation was generated using the urban boundary data from Auckland Council (2021). We used the addresses where the grounded seabirds were found in order to categorize the grounding into either a rural or urban area using the delineation. These categories were used in statistical analysis to look for relationships between seabird fallout and urban/rural areas.

3.0 Statistical analyses

3.1 Seabird groundings, location and dates:

We used our calculated the average, minimum and maximum brightness in the 10km by 10km grid to test whether the number of seabird groundings depended on the natural night sky brightness. We did this by building three linear models in R, using the stats package.

To investigate how location whether urban or rural (also proxy for human population) and date influenced the probability of each of the nine species being grounding , we performed a set of multinomial logistic regressions using the R package ‘nnet’ (Venables & Ripley, 2002). These models predict the probability that a seabird species is grounded according to the corresponding location or season. Predictions are made in turn for each variable location, while all other variables are considered fixed. Goodness of fit for the model was assessed using a pseudo-R2. Models were fit using three types of data: (1) (Folland & Karl, 2001) the date of the grounding (numeric), (2) (Folland & Karl, 2001) the type of location of the grounding (binary: urban or rural), (3) the season (factorial: winter, spring, summer, autumn). Model selection was performed using Akaike's Information Criterion (AIC), where we chose the model with the lowest AIC, and effects estimated using type-III analysis-of-variance ('car' package) (Fox & Weisberg, 2018). In several instances, perfect separation occurred as seabirds were only ever recorded as grounded in Autumn 2018. In these cases, season was excluded and our final model predicted the probability of a species grounding from date and location. We calculated predicted probabilities for pairwise contrasts using the package 'lsmeans' (Lenth, 2016) in R.

4.0 Results

A total of 356 seabirds from 8 different seabird species were brought into BirdCare Aotearoa from January 2018 - December 2021, with evidence of collision-related injuries most likely due to light attraction (Table. 1). For all the seabird species, the majority tend to be grounded within the central business district (CBD) (Fig 2.), with fewer groundings reported in the rural areas with the exception of seabird groundings in brightly lit rural areas (Fig. 2).

4.1 Associations with light brightness

The greatest density of light pollution/lowest night sky brightness in 2016 occurs in the CBD area as well as around the industrial areas and north and west Auckland (Fig. 3a). There is a negative correlation between seabird fallout and predicted night sky brightness, such that there is more fallout in areas with more ALAN (Fig. 4; Table. 2) (note that, as previously mentioned, high values of night sky brightness actually mean a darker sky). The majority of the seabird fallout occurs in the more brightly lit areas with great amount of ALAN (Fig. 3b; Fig. 4; Table. 2).

4.2 Urban vs Rural

Most seabird species were likely to be grounded in rural areas (Online Supplementary Table 1; p 0.05-0.001*). For example, black petrel and grey-faced petrels were grounded in the rural areas more often compared to the urban area (Online Supplementary Table. 1; Fig. 5). However, the Cook's petrel had a greater chance of becoming grounded in the urban area (Online Supplementary Table. 1; Fig. 5).

4.3 Species specific groundings

Cook's petrels were most often grounded close to the central business district (CBD), with some scattered across Auckland (Fig. 6a). The black petrel groundings are more broadly distributed with occasional groundings around rural coastal areas in both eastern areas (Takapuna) to the highly lit western areas (Piha and Muriwai) (Fig. 6b). The grey-faced petrels were also broadly scattered but there was a greater concentration of groundings near the rural western beaches which were lit up towards (Bethells and Piha; Fig. 6c). The fluttering shearwaters tended to be grounded north of the CBD being a hotspot with some groundings in the western beaches (Fig. 6d). The white-faced storm petrels were rarely grounded but if so they were found in the CBD or in western suburbs (Henderson; Fig. 6e). The Buller's shearwaters groundings were restricted to south Auckland (Fig. 6f). The common diving petrels were found scattered across central Auckland (Fig. 6g). The sooty shearwater groundings were also widely scattered, but with the majority by in the CBD, the western beaches and northern Auckland (Fig. 6h).

any correlation with locations of colonies?

4.4 Changes over time

The proportion of grounded seabirds varied according to season and species (Fig. 7). More Cook's petrels are grounded during late summer/early utumn, with another smaller peak in late spring (Fig. 7). Black petrels and occasionally grey-faced petrels tend to become grounded later than the Cook's petrels, in late autumn (Fig. 7).

any relationship with fledging timing?

From 2018-2021, generally the number of seabirds groundings have increased, especially in the CBD locations, but also the rural areas (Fig. 8a-d).

5.0 Discussion

Overall, we found solid evidence that ALAN is influencing grounding probabilities in seabirds. Groundings were more common in the CBD and industrial areas, coinciding with a higher light pollution and predicted natural night sky brightness. We also documented that suburban and rural regions near the coast (e.g. north Auckland) often have a high number of seabird groundings, again correlating with higher light pollution or low natural night sky brightness. Internationally, ALAN tends to affect seabird fledglings, as they take their maiden flight (Rodríguez et al., 2017a; Rodríguez et al., 2017b). Our data is consistent with this. The majority of the seabirds found grounded in Auckland and brought to BirdCare Aotearoa were fledglings, and many of the groundings occurred during the fledgling season (Table.1). This is similar to the previous finding that most of the seabirds which collided with the cruise ship at Te-Hauturu-O-Toi were fledglings (Morton, 2018). This also reflects the large numbers of seabirds and the diversity of seabird species that nest and breed in the Hauraki Gulf area close to Auckland (Gaskin, 2012; Gaskin & Rayner, 2013).

In terms of the total number of grounded seabirds, we found more in urban than rural areas. Rural areas tend to have less light pollution in general since there is a lower density of human population in these areas (Falchi et al., 2019). This could lead to fewer groundings of seabirds since there is less light to become disorientated. Also, in the rural areas, there may also be fewer reports of seabird groundings, underrepresenting the true numbers in the rural areas (Laguna et al., 2014).

However, at the species level, the predicted probability of the seabird species being grounded in an urban location was quite low, with the important exception of the Cook's petrel. For example, the grey-faced petrel and black petrel had a greater probability of grounding in the rural areas compared to urban areas. There are specific light hotspots in those rural areas such as along the western beaches of Bethells, Muriwai and Piha where is more light pollution which could lead to an increase in groundings in the rural areas for those seabird species. It may not be a case of that more seabirds are picked up where there are more people because there are some rural areas which have not many people, but still have fallout (western beaches) and some urban areas which have fewer people but lots of brightness which still have fallout such as at the airport.

Another possible explanation of seabird fallout occurring in rural areas for some seabird species could be due to their breeding locations - grey-faced petrel breed around the western beaches of Bethells, Muriwai and Piha (Bethells, Muriwai and Piha; Gaskin & Rayner, 2013) and are therefore more likely to become grounded at those locations.

5.1 Risk of ALAN: species differences

We have discussed that the brightness of an area is influential in determining groundings. Now we will now cover some other important factors which may be influencing species differences in light attraction leading to differences in groundings. These include the species population sizes, migration routes, breeding locations and sensory ecology.

The difference groundings between the species may not indicative of seabird abundance. Some seabird species such as the Cook's petrel and black petrel which have a smaller population size were actually grounded more often compared to other species with a larger population size such as the common diving petrel and white-faced storm petrel (Table. 1). Also, we cannot purely rely on the population data as accurate estimates of population sizes considering different methodologies were used for sampling the different sites (Friesen et al., 2021; Gaskin & Rayner, 2013; Rayner et al., 2007). Therefore, other factors could be influencing species differences in groundings.

During the breeding season, at night, some Cook's petrels fly across the Auckland isthmus from the islands of the Hauraki Gulf to the Tasman Sea to forage and then back across Auckland from the Tasman Sea to the Hauraki Gulf (Rayner et al., 2007; Rayner et al., 2008; Gaskin & Rayner, 2013). Since Cook's petrels have to cross the Auckland isthmus, and the associated city lights, there may be a greater chance of them becoming disoriented and grounded when compared to the other seabird species. For example, Buller's shearwater and sooty shearwater migrate to the North Pacific (Guzman & Myres, 1983; Spear & Ainley, 1999; Warham, 1996). Therefore, since they migrate northward during the non-breeding season there is a smaller chance of them crossing over the Isthmus and being attracted towards the lights, however micro-migrations during breeding seasons can occur where they could be vulnerable to groundings by lights.

Similar to Cook's petrels, the majority of black petrels were grounded in the CBD, again suggesting ALAN is critical. However, there were also some groundings close to the western beaches of Auckland where there is less people but also had a low amount of natural night sky. Considering the black petrel migrates to Chile and South America during the non-breeding season (Cabezas et al., 2012) it seems unusual that a substantial number are grounded around Auckland, including along the Western beaches. However, black petrels often forage during the breeding season around the west and east coast of the North Island of New Zealand, off the continental shelves (Bell, Sim, & Scofield, 2009). They may travel over the CBD en route to their foraging sites.

In general, the species that are rarely grounded in Auckland are those that do not need to cross the Auckland isthmus for their foraging, breeding or migration (fluttering shearwaters, Buller's shearwaters, white-faced storm petrels, common diving petrels and sooty shearwaters). Fluttering shearwaters tend to remain around their local breeding area after the breeding season (Whitehead et al., 2019). However, they have been observed occasionally to cross over to the Tasman Sea (Gaskin, 2013). Since they tend to remain close to their breeding colony, they could be less likely to interact with Auckland's city lights. Similarly, Buller's shearwaters are rarely grounded on land in Auckland although many were attracted to a single cruise ship in 2018 (Morton, 2018). Buller's shearwater is so far only known to breed on the Poor Knights Island and has even been documented since the late 1970s to migrate to northern Pacific areas during the non-breeding season (Friesen et al., 2021; Guzman & Myres, 1983; Nakamura & Hasegawa, 1979). Therefore, mainly avoiding the Auckland area and is less likely to become grounded by the lights.

White-faced storm petrels had very few groundings, but when they were found, they were grounded in the CBD and in west Auckland (Henderson). Once again, these areas had a greater amount of night sky pollution and therefore it suggests that ALAN is an important factor (McNaughton et al., 2021). Similar to the other seabird species which were rarely grounded in the Auckland region, the white-faced storm petrel migrates to the south pacific and South America during the non-breeding season (Imber, 1984). Therefore, this species is less likely to cross over the isthmus during the fledgling season and become susceptible to light attraction. Common diving petrels also had a fewer groundings. These species often migrate south east towards the Antarctic polar front (Rayner, Taylor, Gaskin, & Dunphy, 2017). Furthermore, these species also forage locally within a 45km radius of their burrow (Dunphy et al., 2020). This results in this species also not crossing over the Auckland isthmus regularly and therefore less likely to become grounded by the lights compared to other species. However, when they were grounded they were found close to the CBD and Mangere which are industrial areas which would have the greatest number of light sources (McNaughton et al., 2021), suggesting that ALAN is an important factor for this species.

The sooty shearwater also migrates to the north Pacific during the non-breeding season to forage (Spear & Ainley, 1999). They tend to generate a figure of eight pattern on their journey before returning to New Zealand and Australia to breed (Shaffer et al., 2006), rarely crossing over Auckland city.

In general, susceptibility to city lights appears to correlate strongly with the location of seabirds foraging, breeding and migration paths.

5.2 Changes over time

Between 2018 and 2020, there was a decline in seabird groundings, but decline reversed in 2021. The decline in 2019 and 2020 could be a result of the coronavirus (COVID-19) which resulted in a nationwide and then city-wide lockdowns (Henrickson, 2020). This could have caused more people to stay in their homes, so they were less likely to discover grounded seabirds, and there may have been less ALAN, though this was not measured.

The increase in grounded seabirds from 2020-2021 could be a result of many different, non-mutually exclusive factors. Auckland's main lockdown ended on October 7th 2020 (Government, 2021), leading to more people about on the streets, and potential more probability of finding grounded seabirds. This uptick might also be due to an increase in Auckland's light pollution over the years (McNaughton et al., 2021), which could result in more seabirds becoming grounded in Auckland. However, the increase could also be a result of a greater public awareness of seabird fallout and groundings in Auckland. Therefore, there is a greater chance of people reporting a grounding and taking it to the bird rehabilitation facility, BirdCare Aotearoa. Campaign efforts have been made with news media articles and radio interviews have been conducted (Dexter, 2022). Other articles for the local magazines and articles for the Department of Conservation currently being written. Furthermore, regular patrols of the CBD is currently being established with volunteers patrolling sections of the CBD at least 2-3 times a week between March-May every year. This was observed in other locations including Hawaii and the Canary islands when more members of the public were alerted to seabird groundings (Rodríguez, Rodríguez, & Negro, 2015; Travers et al., 2021). This helps build the awareness of the need for better conservation for seabirds grounded by ALAN.

5.3 ALAN and sensory ecology

Along with differences in breeding, foraging and migration routes, another reason for species differences in the number of seabird groundings may be differences in their visual ecology. For example, black petrels were grounded at a much higher rate than common diving petrels. In addition to differences in migration and foraging locations affecting the seabird groundings, black petrels and common diving petrels also differ in their visual anatomy. Black petrels have a much larger eye socket volume relative to its body size compared to the common diving petrel (Heswall et al., 2021). Potentially, seabirds with relatively larger eyes may be more susceptible to light attraction. However more research quantifying correlations between species specific sensory anatomy and threats associated with visual signals is required. Previous work has shown such differences related to bycatch numbers with seabirds (Heswall et al., 2021).

Auckland's increased economic growth, expansion of the human population, and increased light pollution (Bennie et al., 2014; Gallaway, Olsen, & Mitchell, 2010; Jiang et al., 2017; McNaughton et al., 2021) follows a trend in cities across the globe (Czarnecka, Błażejczyk, & Morita, 2021; Operti et al., 2018). Given the negative consequence for these vulnerable species, mitigation techniques should be employed to reduce the light attraction of seabirds. Some studies have shown that using shields over their lights can reduce seabird light attraction (Reed, Sincock, & Hailman, 1985). Changing the type and colour of light could have an effect on seabird attraction (Rodríguez, Dann, et al., 2017; Syposz et al., 2021). Cities in the US have had great success getting buildings in the CBD to turn off lights at night during migration, effectively reducing fallout and groundings (Smith, 2009).

Our study suggests light pollution and ALAN predict groundings in specific locations, suggesting modifications to the lighting of specific structures and buildings could make a strong and positive improvement in avoiding bird collisions. This study also emphasizes the benefit of diverse collaborations. We show here the power of combining community awareness, databasing of wildlife species, and ecologists' statistical modelling of seabird groundings with natural night sky brightness data can help provide information about locations where seabird groundings and why there is a higher seabird groundings in that location. Due to this collaboration we were able to correlate seabird groundings with ALAN which can aid in mitigation management, conservation and can be applied to cities across the world.

Conclusions

We identified the hotspots and characteristics of the areas associated with seabird groundings. The brightness of a location impacts seabird groundings, with a more brightly lit areas having a greater chance of seabird groundings compared to a dimmer area which has a lower chance of seabird groundings. It is not necessarily urban vs rural or population sizes but more to do with the specific seabird species and the amount of ALAN. This research can be used to identify areas which are more brightly lit resulting in more grounded seabirds. Specific buildings and other anthropogenic structures which are brightly lit could be identified and the lights could be modified to reduce the ALAN and consequently seabird groundings. This can be applied internationally to other countries and cities to reduce the light pollution and keep natural dark areas to reduce seabird groundings from ALAN and help in their conservation.

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Figure 1

Map of the major cities and suburbs of Auckland with the red line indicating urban/rural boundary.

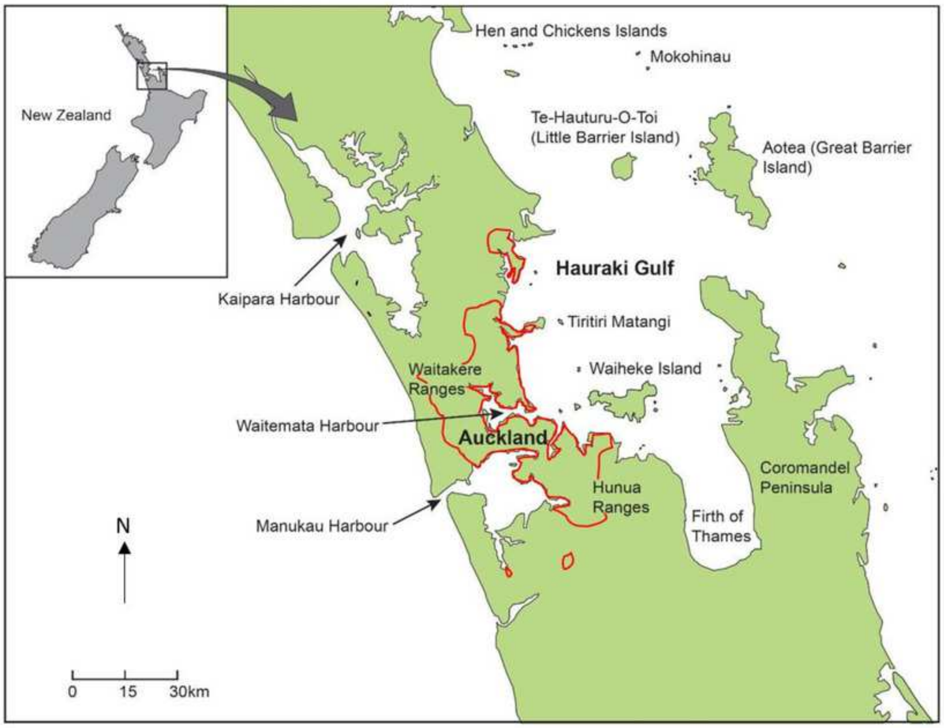


Figure 1: Map of the major cities and suburbs of Auckland with the red line indicating urban/rural boundary.

Figure 2

The number and location of the seabird groundings across Auckland in 5km2 for all species from 2018-2021.

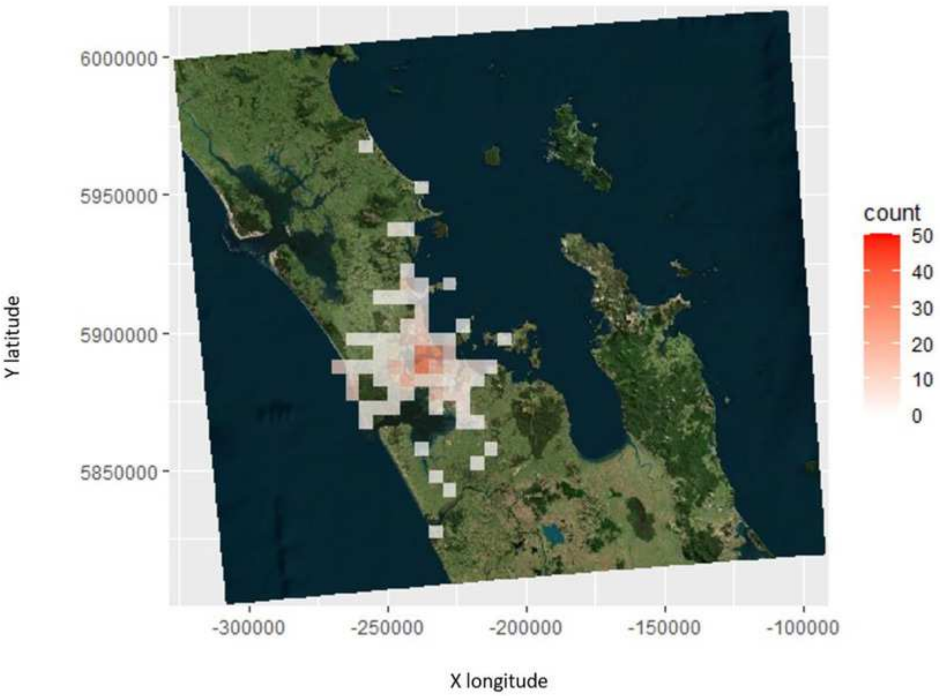
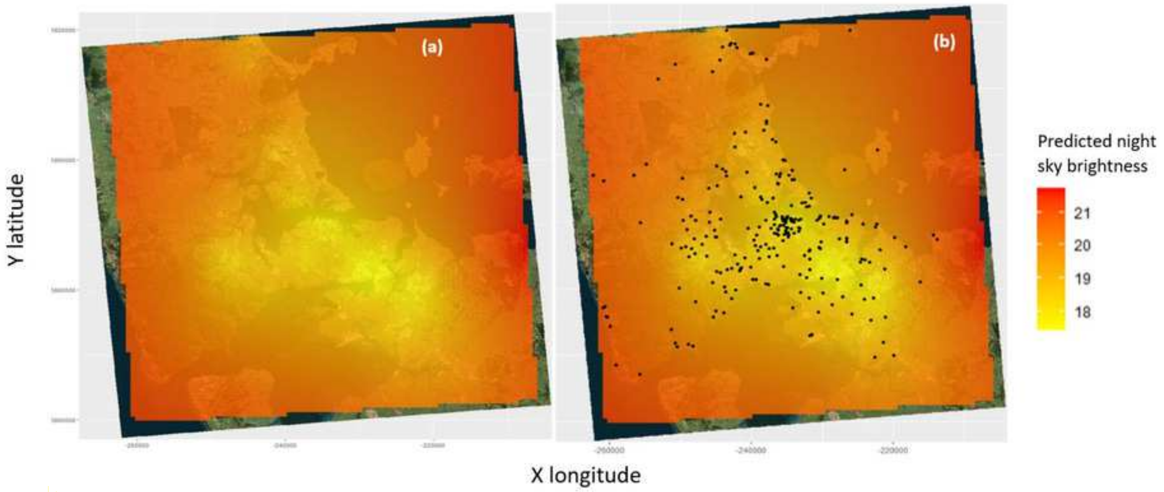


Figure 2. The number and location of the seabird groundings across Auckland in 5km^2 for all species from 2018-2021

Figure 3

Heat map of the light pollution data in Auckland in 2016 (McNaughton et al., 2021).

(a) overlayed with the locations of the seabird fallout of all species from 2018-2021 (b). Predictions indicate the predicted night sky brightness or night sky quality, the higher the number the greater the night sky quality (magSQM/arcsec−2).



are a and b reversed?

Figure 3. Heat map of the light pollution data in Auckland in 2016 (McNaughton et al., 2021) (a) overlayed with the locations of the seabird fallout of all species from 2018-2021 (b). Predictions indicate the predicted night sky brightness or night sky quality, the higher the number the greater the night sky quality ($mag_{SQM}/arcsec^{-2}$).

Figure 4

The seabird fallout frequency in 10km by 10km grid squares against the mean predicted night sky brightness. Note that high values of night sky brightness actually mean a darker sky with less Artificial Light at Night (ALAN)

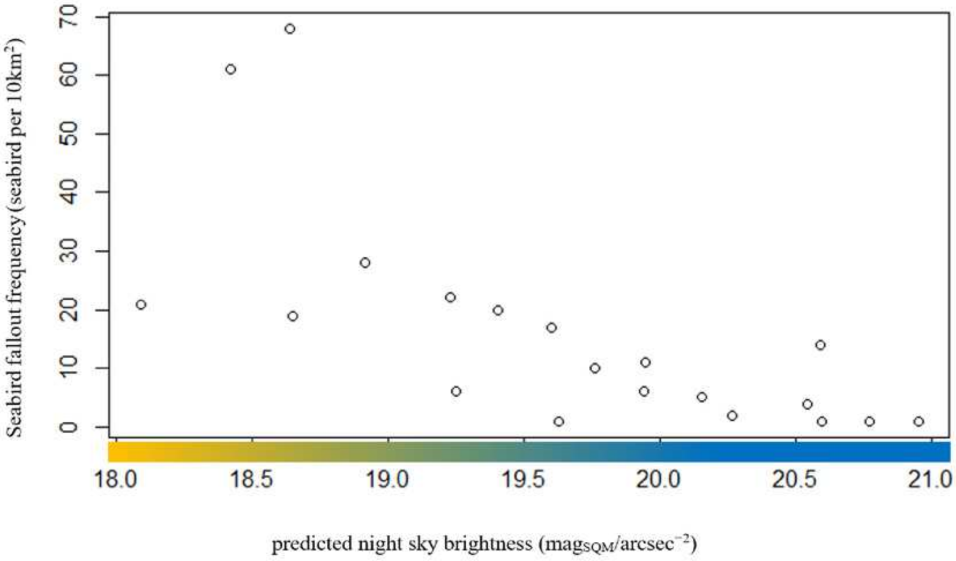


Figure 4: The seabird fallout frequency in 10km by 10km grid squares against the mean predicted night sky brightness. Note that high values of night sky brightness actually mean a darker sky with less Artificial Light at Night (ALAN)

Figure 5

The predicted probability (SE) of each seabird species landing in a grounded or rural area

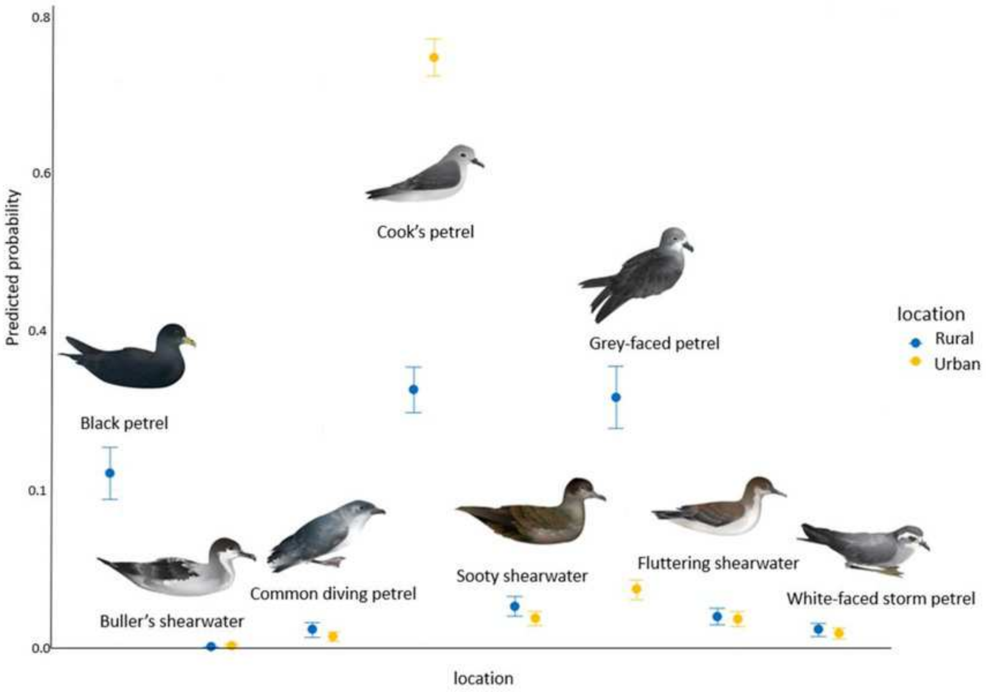
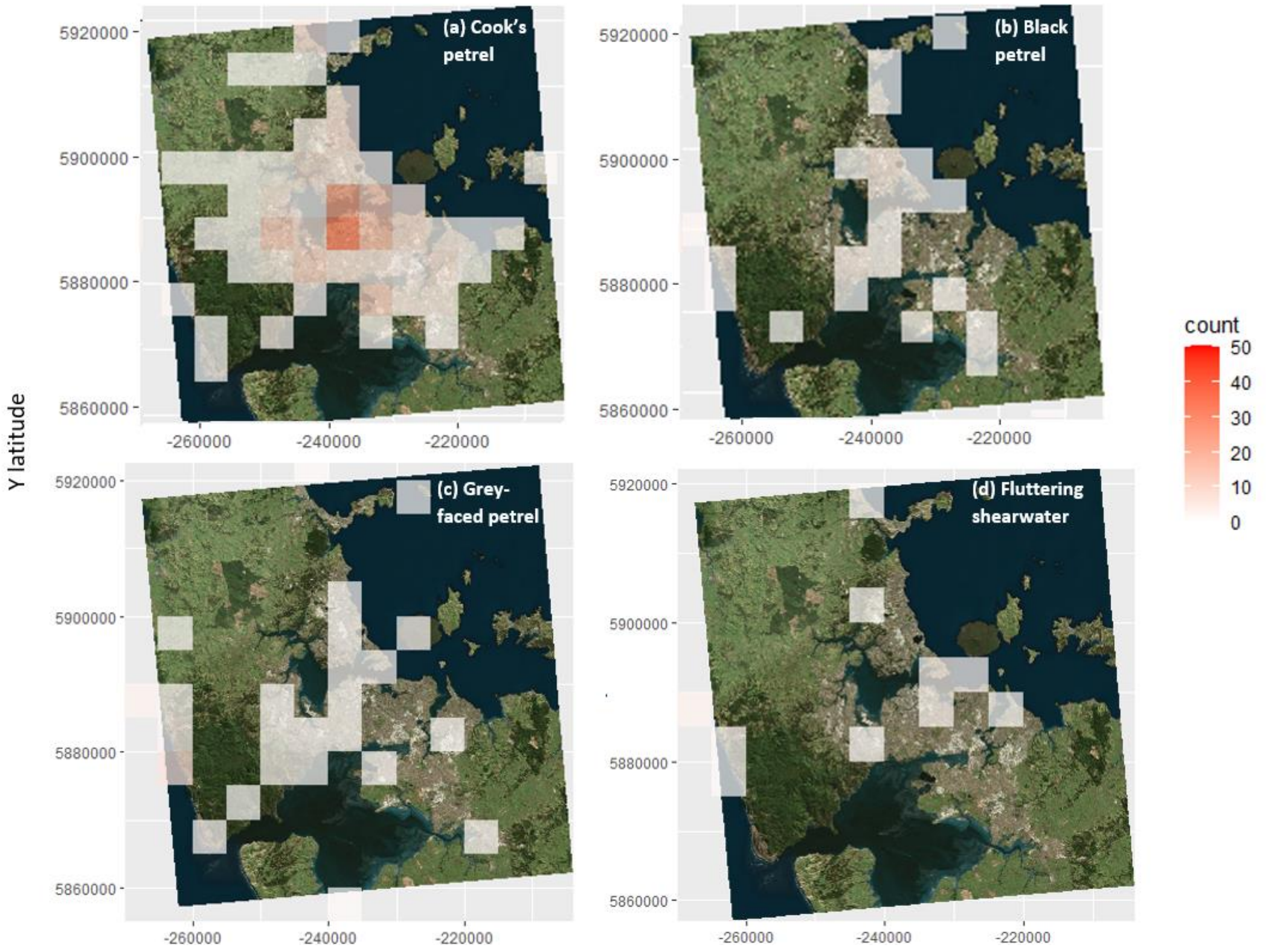


Figure 5: The predicted probability (± SE) of each seabird species landing in a grounded or rural area

Figure 6(on next page)

Locations of the groundings of Cook’s petrels (a). Locations of the groundings of the black petrels (b). Locations of the groundings of the grey-faced petrels (c). Locations of the groundings of the fluttering shearwaters (d). Locations of the groundings

missing text?
list as 6a, 6b etc
axes?


(a) Cook's petrel
(b) Black petrel
(c) Grey-faced petrel
(d) Fluttering shearwater
Y latitude
5920000
5900000
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-220000
count
50
40
30
20
10
0

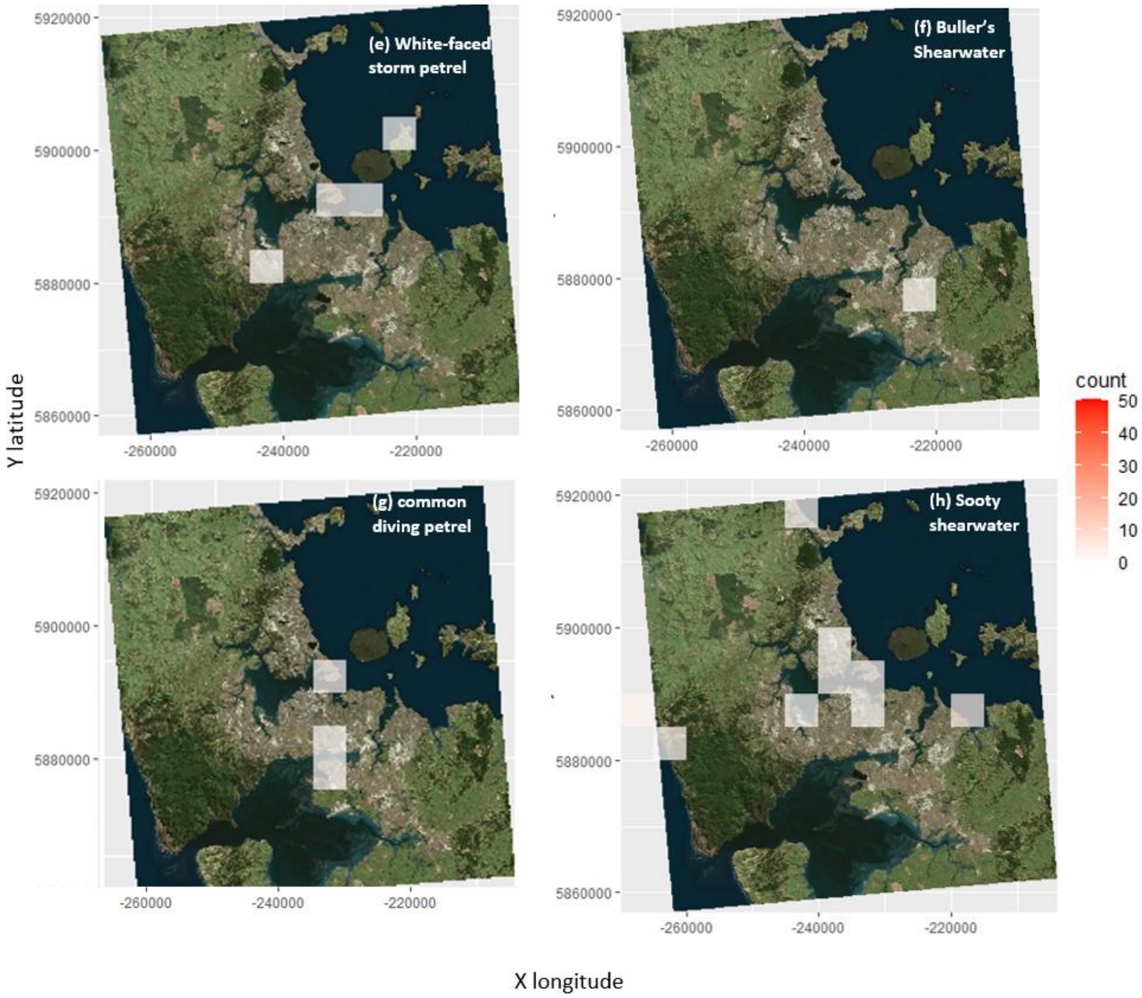

Figure 6. Locations of the groundings of Cook's petrels (a). Locations of the groundings of the black petrels (b). Locations of the groundings of the grey-faced petrels (c). Locations of the groundings of the fluttering shearwaters (d). Locations of the groundings of the white-faced storm petrels (e). Locations of the groundings of the Buller's shearwaters (f). Locations of the groundings of the common diving petrels (g) Location of the groundings of the sooty shearwaters (h) The count is the number of seabirds grounded in every 5km

Figure 7

The absolute number of seabird groundings from each species from January 2018-September 2021 including the seasons.

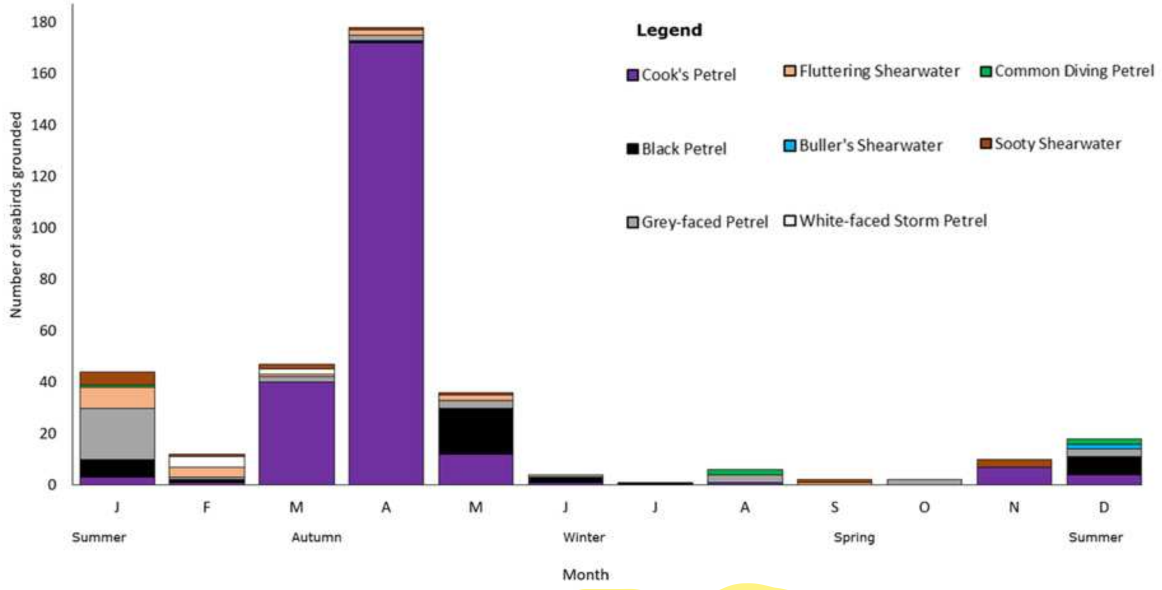

Figure 7: The absolute number of seabird groundings from each species from January 2018-September 2021 including the seasons.

Figure 8

The groundings of all seabird species in 2018 (a), 2019 (b), 2020 (c) and 2021 (d). n represents the number of seabirds grounded.

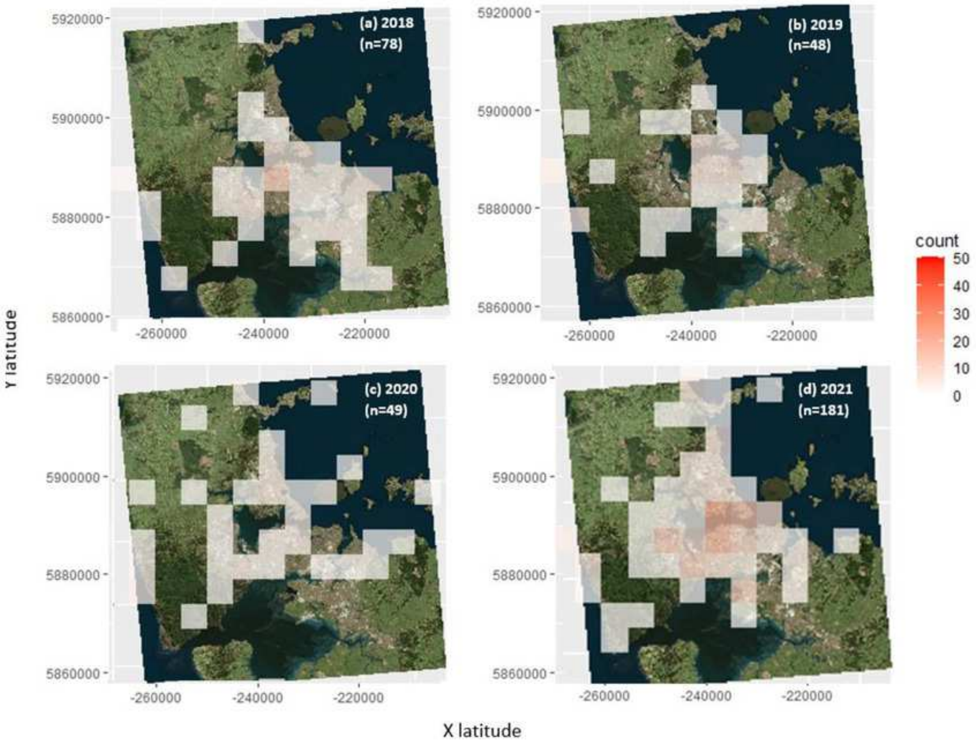

Figure 8. The groundings of all seabird species in 2018 (a), 2019 (b), 2020 (c) and 2021 (d). n represents the number of seabirds grounded.

Table 1(on next page)

Seabird species brought into BirdCare Aotearoa from 2018-2021[1]. Cases were included in our analyses when birds had sustained injuries consistent with collisions, e.g. head injuries.

Table 1: Seabird species brought into BirdCare Aotearoa from 2018-2021[1]. Cases were included in our analyses when birds had sustained injuries consistent with collisions, e.g. head injuries.

	Species Name	**Te Reo Name**	**IUCN rank[2]**	**NZ conservation status[3]**	**Breeding Population numbers[3, 4, 5,6,8]**	**Total patient number[1]**	**% released[1]**	**Time of year of grounded seabirds[1]**	**Fledgling months[7,8]**
Cook's petrel	*Pterodroma cookii*	Tītī	Vulnerable	Relict	>300,000[9]	247	73%	December-May	February-March[7]
Grey-faced petrel	*Pterodroma gouldi*	ōi	Least Concern	Not threatened	~300,000[3]	41	46%	Throughout	December-January[8]
Black petrel	*Procellaria parkinsoni*	Tāiko	Vulnerable	Nationally vulnerable	~5000[4]	38	58%	December-January; May-August	April-July[8]
Fluttering shearwater	*Puffinus gavia*	Pakahā	Least concern	Relict	>100,000[3,7]	18	22%	January-April	January-February[8]
White-faced storm petrel	*Pelagodroma marina*	Takahikare-moana	Least concern	Relict	>1,000,000[3, 6]	7	29%	November-March	January-March[8]
Buller's shearwater	*Puffinus bulleri*	Rako	Vulnerable	Naturally uncommon	~78,000[5]	48	81%	May	April-May[8]
Common diving petrel	*Pelecanoides urinatrix*	Kuaka	Least concern	Relict	>1,000,000[3, 7]	6	33%	August; December-January	November-January[8]
Sooty shearwater	*Ardenna grisea*	Hākoakoa	Near threatened	Declining	>20,000,000 [3,7]	14	36%	October-February February-June	April-May[8]

[1](Project, 2021), [2](International, 2021); [3](Miskelly, 2013); [4](Bell, 2013); [5](Friesen et al., 2021); [6](Southey, 2013); [7](Gaskin & Rayner, 2013), [8](Taylor & Rayner, 2013) [9](Rayner et al., 2007).

Table 2(on next page)

Results from three linear models models examining the relationship between seabird fallout and the mean, max and min predicted night sky brightness for every 10km by 10km.

Table 2: Results from three linear models models examining the relationship between seabird fallout and the mean, max and min predicted night sky brightness for every 10km by 10km.

Night sky brightness	Estimate	Standard error	T value	P value
mean	-15.769	3.711	-4.250	0.0001×10^{-06}
max	-21.960	3.725	-5.895	0.0001×10^{-06}
min	-11.038	3.572	-3.090	0.0001×10^{-06}