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Investigation of fallout events in Hutton's shearwaters (*Puffinus huttoni*) associated with artificial lighting

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Abstract The risk of disorientation by artificial lights and subsequent 'fallout' has become a widely recognised issue for nocturnal procellariiform species. Using data from community-based rescue campaigns and systematic research, we assessed the characteristics of fallout events observed in fledglings of the threatened New Zealand endemic Hutton's shearwater (*Puffinus huttoni*) or Kaikōura tītī. Despite strong annual variation in observed fallout numbers, the proportion of annually produced fledglings collected as 'fallout birds' remained below 1% each year. Among those, more than 80% survived due to community rescue efforts. Fallout was found to increase significantly during new moon, while weather effects remained inconclusive. Most fallout occurred within brightly lit areas of Kaikōura township, particularly along its coastal roads. High light source densities and high wattage lights appeared to be influential in some areas but could only partly explain the spatial distribution of fallout at this small scale.

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Keywords Hutton's shearwater; *Puffinus huttoni*; Kaikōura; artificial light; disorientation; moon phase; weather effects; mortality; population impacts

INTRODUCTION

The term 'fallout' describes the phenomenon of large numbers of birds becoming grounded, often in a single event; it has been commonly referred to when migrating songbirds encounter adverse weather conditions, forcing them to land before reaching their destination (Theodore *et al.* 2004; Hameed *et al.* 2009). The term has also become associated with seabirds grounded due to attraction or disorientation by artificial lights (Ainley *et al.* 1987; Podolsky *et al.* 1998; Raine *et al.* 2007; Troy *et al.* 2011). Although on record since at least the 1960's (Imber 1975), the occurrence of fallout in seabirds is still far from understood, and has been predominantly described in nocturnal burrowing species such as shearwaters and petrels (Procellariidae). Birds are drawn off course and may land prematurely due to

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following a wrong cue, colliding with man-made structures, or because of exhaustion after circling above lit areas for extended periods of time (Reed *et al.* 1985; Le Corre *et al.* 2002; Raine *et al.* 2007; Troy *et al.* 2011; Rodriguez *et al.* 2012a, 2014). Once on the ground, the birds are often unable to get airborne again and are at risk of predation, being run over by cars, starving or succumbing to injuries sustained during the crash (Podolsky *et al.* 1998; Le Corre *et al.* 2002). While both adult and young birds can be affected, it appears that fledglings are particularly susceptible to light disorientation on their maiden flights after leaving their burrows for the first time (Reed *et al.* 1985; Le Corre *et al.* 2002, Rodriguez *et al.* 2012a and references therein).

Possible reasons for light attraction or disorientation have been discussed in the literature (e.g. summary in Rodriguez *et al.* 2017) but are not yet fully conclusive, likely due to species and location specific differences in the nature and occurrence of fallout events. Worldwide, observed fallout numbers can vary considerably at both inter- and intra-specific levels and indications are that fallout rates are higher for birds from inland colonies than those breeding at the coast (Rodriguez *et al.* 2014; Rodriguez *et al.* 2015b). Ambient light levels are 1 of the strongest factors driving animal behaviour and chronobiology of nocturnal species (Kyba *et al.* 2011). The assumption behind this is that birds would use the moon and stars as visual cues or at least would rely on their ambient light, especially for first time orientation and navigation (Telfer *et al.* 1987). As such, they would be innately attracted to illuminated areas as a visual reference (Raine *et al.* 2007). Another theory suggests that for species, such as petrels, which feed on bioluminescent prey, even inexperienced birds like fledglings have the behavioural imprinting to search for lights to optimise foraging (Imber 1975). As described for songbirds, weather conditions may influence the occurrence and magnitude of fallout, not least due to rain or fog affecting visibility, but also cloud coverage amplifying the sky luminance (Kyba *et al.* 2011). Increased fallout has been found in Newell's shearwaters (*Puffinus newelli*) and other species during low cloud cover and overcast skies (Telfer *et al.* 1987; Raine *et al.* 2007). In addition, moon phase appears to be an important factor regarding the magnitude and occurrence of fallout (Telfer *et al.* 1987; Le Corre *et al.* 2002; Rodriguez & Rodriguez 2009; Miles *et al.* 2010; Rodriguez *et al.* 2014).

Regardless of the 'why', fallout in shearwaters and petrels is a globally recognised threat, particularly in species which face other pressures and are listed as rare or endangered. A recent review by Rodriguez *et al.* (2017) counted at least 56 procellariiform species affected by artificial lights, which marks an increase of 35 species recognised in this respect since reports collated by Reed *et al.* (1985). Light pollution, causing a 'light dome' of sky glow over urban areas (Kyba *et al.* 2011), has been increasing due to human population growth and corresponding increase in electricity production, resulting in more and larger areas being affected on both local and global scales (Rodriguez *et al.* 2014; Ainley 1997).

It is unclear whether increased fallout and light-induced mortality contribute to population decline. However, Troy *et al.* (2011) mention several studies (e.g. Ainley *et al.* 2001, Griesemer & Holmes 2001) indicating this to be the case. The instigation of rescue programmes and increased community awareness in many places have proven beneficial in reducing light-induced mortality which may contribute to population stability (e.g. Le Corre 2002; Rodriguez *et al.* 2014; Ainley *et al.* 2001; Gineste *et al*. 2017). Measures which reduce light spill are widely recommended to mitigate the effect of artificial lighting (see Raine et al. 2007 for a collation thereof). However, sensible and effective implementation of mitigation measures requires a good understanding of the phenomenon on both a species and location specific basis.

The Hutton's shearwater (*Puffinus huttoni*) or Kaikōura tītī is classified by Robertson *et al.* (2017) as Threatened, Nationally Vulnerable. This species is endemic to New Zealand and breeds in only 2 remaining colonies at altitudes between 1200 m and 1800 m above sea level in the Seaward Kaikōura Ranges of the South Island. Chicks fledge during March/April, departing the colonies at night to undertake their maiden flight to the sea. The Kaikōura township lies within the estimated flight path of birds from the larger of the 2 colonies (Fig. 1) and for many seasons fledglings have been found grounded in and around town (Imber 1975). Until recently, recovery of fallout birds was erratic and mostly off-record, with data on fallout events collected only from 2006 onwards in the form of banding records from rescued birds. The Hutton's Shearwater Charitable Trust (HSCT) has been instrumental in raising public awareness; in 2014 rescue campaigns were initiated to improve recovery of grounded birds, enhance data collection, and to inform potential mitigation measures. Here we report on data recorded since 2006, with specific aims to: a) establish a reliable estimate of the overall magnitude of fallout in and around Kaikōura; b) estimate mortality rates and corresponding population effects; c) investigate the effect moon phase and weather conditions have on local fallout events; and d) further assess the spatial distribution of fallout in relation to the presence of artificial lights.

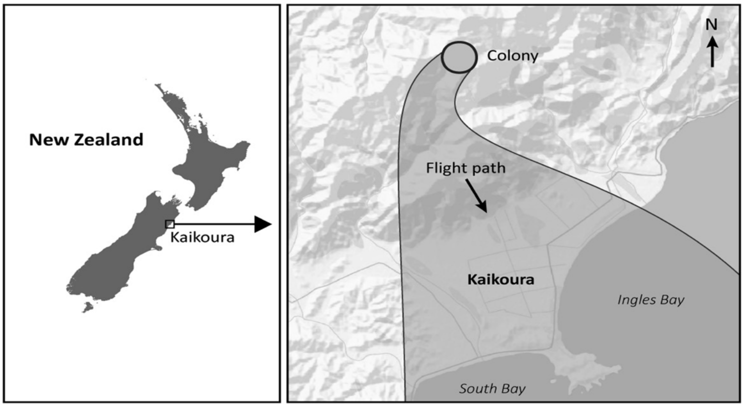

Fig. 1. Location of Kaikōura and estimated flight path of adult Hutton's shearwaters from their southern mountain colony. (Map recreated from http://www.doc.govt.nz/nature/native-animals/birds/birds-a-z/huttons-shearwater-kaikoura-titi/).

MATERIALS AND METHODS

Ethics statement

No permits were required to collect fallout birds as this was carried out initially on an *ad hoc* basis by members of the public. Collected birds were taken to the Department of Conservation (DOC) or HSCT for processing by people with the appropriate DOC banding/handling permits and then released at sea.

Data sources and recording of annual fallout numbers

Data presented in this study are derived from 8 fledging periods: 2006, 2007, 2008, 2012, 2013, 2014, 2015 and 2016 (no comprehensive recordings of fallout events were available for 2009, 2010 and 2011). We distinguished between years with and without rescue campaigns due to differences in search effort and recording schemes regarding the recovery of fallen birds (i.e., factors affecting the comparability of annual fallout numbers). Alongside public awareness campaigns (2014–2016), fallout data was collected in a more coordinated and detailed manner by establishing local drop off points for birds recovered by the public and the provision of data recording sheets ('public logs') which gathered information on the fallout date, location, the presence of artificial light, weather conditions and whether the bird was found dead or alive. Accordingly, most of the subsequent analysis of fallout events is based on data sets from 2014, 2015 and 2016.

Bird recovery was classified as either 'incidental' (birds were found by chance or people searched for birds without a predetermined search strategy) or 'systematic' (date, time and area covered during searches were predetermined and repetitive). Systematic searches were carried out during the 2016 season in order to investigate and validate fallout numbers resulting from incidental recoveries. These searches were undertaken between 5-30 March 2016, alongside a 'Fly Safe' public awareness campaign organised by the HSCT. Teams searched every second night until 13/14 March, increasing search effort to nightly trips thereafter, following previous observations of increased fallout occurring during the second half of the month. Searches ran from 2300-0100 h and 0500–0700 h since highest fledging activity, and therefore fallout, was expected 1 to 4 hours after nightfall (Reed *et al.* 1985; Rodriguez *et al.* 2015b), and to account for birds which may fall later in the night. The route taken remained the same on each trip and included similar proportions of dark and lit areas, covering both coastal and inland parts of Kaikōura and surroundings (Fig. 2). All search trips were done by car with handheld torches to ensure good area coverage (32 km per trip), and to allow scanning of the road, drive ways, across lawns and roadside barriers. For each bird recovered, data was recorded in public logs.

Mortality and population effects

During years with public awareness campaigns (2014–2016) the public was encouraged to report both live and dead birds in the log sheets. Resulting data was used to calculate mortality rates as the percentage of birds found dead out of the total number of fallout birds per year. To estimate the proportion of fledglings potentially lost from the population pool due to fallout, a formula established by Le Corre *et al.* (2002) was applied: PL = FL / FP x 100; where PL = percent lost from overall population, FL = number of fledglings lost due to fallout and FP = number of fledglings produced that year.

Information on Hutton's shearwater population size and annual breeding success was provided by DOC, resulting from ongoing population studies

Fig. 2. Search route of systematic searches conducted during the 2016 fledging season. Star shapes demarking lit areas. (Map sourced from the LINZ Data Service and licensed for re-use under the Creative Commons Attribution 3.0 New Zealand licence).

(Scofield *et al.* in prep.; M. Aviss; G. Taylor *pers. comm.* 2 May 2016). Based on expert judgement, the current estimate of the Hutton's shearwater population size stands at 600,000 individuals and the proportion of breeders within the population would be about 50% (i.e., 300,000 individuals or 150,000 breeding pairs). We note that at time of publication, both mountain colonies had been affected by major earthquakes in the Kaikōura region on 14 November 2016 when birds were incubating and resulting losses to the population are yet to be assessed. Annual fledging success was reported to fluctuate around 60% and as such the number of fledglings produced per year would be 90,000 (i.e., 60% of 150,000 breeding pairs). To compare the population effect of theoretic loss against actual loss of fledglings and to evaluate the efficiency of rescue campaigns, the formula was run using the count of all fallout birds (considered to be lost if no rescue effort is made, e.g., Le Corre *et al.* 2002), as well as only those reported dead.

Fallout events in relation to environmental factors

A common date tag was established to standardise data sets in order to link fallout events to environmental conditions on a certain night. As such, the date on which the night started was assigned to all records of that night, regardless of whether a recording occurred before or after midnight (e.g., 19 or 20 March). This was necessary as not all data sets held respective information.

Moon Phase

Information on 'percent visible disc' per night was retrieved from https://www.etime.zone/moon-calendar-New_Zealand-2016_03.html and used as a quantitative description for lunar phase, where 0% and 100% indicate a new and full moon respectively.

Weather Conditions

Two different data sources were explored: 1) data from the Meteorological Service of New Zealand Ltd (MetService) archives, containing continuous recordings across the whole fledging season; and 2) weather entries from public logs, referring to conditions at the time of bird recovery and as such only available for those nights upon which fallout was recorded. The MetService data sets were used in statistical analyses, while weather information from public logs was used for qualitative assessment.

From the MetService data, mean values of rainfall (mm/h), wind speed (km/h) and visibility (m) per night were derived from hourly recordings at the MetService weather station on the Kaikōura peninsula. The first and last observations of fallout per season were used as cut-off dates for the selection of weather data.

From the public log data, weather conditions observed upon bird recovery were subject to individual bias and often missing or incomplete. In 2016, weather was recorded during the systematic searches, providing a more thorough coverage. For the 2015 and 2016 seasons, weather recordings were assigned to the following categories: clear, overcast / dry, overcast / wet (showers or rain) and haze / fog. Weather information recorded in 2014 was only available as summarised data, i.e., a count of overcast versus dry nights across the fledging season but no distinction was made as to whether it was dry or rainy on an overcast night. For the purpose of the current study, however, it appeared sensible to make this distinction and as such, data from 2014 were excluded from the comparative analysis done for 2015 and 2016.

Statistical Analysis

Generalized linear models (GLMs) were used to model the relationship between fallout numbers from 2014-2016, moon phase, rainfall, visibility and wind speed. Due to high over-dispersion of count data (residual deviance: 15,996 on 69 degrees of freedom) a negative binomial error distribution and log link were used. All statistical analyses were performed in R (R Core Team, 2014, version: 3.1.0).

Spatial distribution of fallout events in relation to artificial light

Fallout

Information on the spatial distribution of fallout was only available for the 2014 and 2016 seasons.

Table 1. Overview of annual fallout events in Hutton's shearwaters in Kaikōura, showing the period during which fallout was recorded, fallout numbers and the estimated proportion of annual fledglings becoming grounded. (Notes: Years with rescue campaigns are in bold. Proportion of annual fledglings was only calculated for years with rescue campaigns due to more reliable fallout numbers as well as population size estimates being available for these periods.)

Year	Recording period	Fallout total	Alive	Dead	% Annual fledglings
2006	22-25 March	156	n/a	n/a	n/a
2007	27 March – 3 April	10	n/a	n/a	n/a
2008	10 March – 10 April	16	n/a	n/a	n/a
2012	21 March – 23 April	51	n/a	n/a	n/a
2013	15 March – 10 April	29	n/a	n/a	n/a
2014	**22 March – 13 April**	**68**	**56**	**12**	**0.1**
2015	**15 March – 9 April**	**274**	**273**	**1**	**0.3**
2016	**7 March - 12 April**	**87**	**72**	**15**	**0.1**

Bird recovery locations were recorded via handheld GPS or from descriptions such as street address in the public logs. In 2014, fallout locations could be assigned to 97% of all recovered birds, whereas in 2016 this was only possible for 90% of the birds.

Fallout densities were calculated in ArcGIS 10.2 / Spatial Analyst (ESRI 2015) using Kernel Density Estimation (KDE), applying a 100m search radius to detect fine scale clustering. High density or core areas were identified via percent volume contours (pvc), which were estimated using the Geospatial Modelling Environment (Beyer 2012). Clustering of fallout locations in 2014 is depicted by 25 pvc while in 2016 this is represented by 50 pvc due to the different distributional properties of the 2 data sets.

Artificial Light Sources

A street light map, covering the Kaikōura township and surrounding areas, was provided by MainPower New Zealand Ltd in 2014. The map contained information on location, bulb type and wattage of each light fixture. Inquiry with Kaikōura District Council confirmed that no significant changes in light fixtures had occurred since 2014.

Spatial density of artificial light sources was used as a proxy for overall light spill and light intensity. Densities were calculated via KDE (as described for fallout densities) from the locations of street lights in combination with other light sources (OLS) such as outdoor lighting of residential property, motels or shops, car park or mall lighting, industrial lighting at dairy farms or lighting in school yards or parks, which were recorded during the 2016 season via handheld GPS.

A point system was established to account for differences in brightness or extent of light spill of the various OLS types, e.g. shop light = 1 pt per shop; Motel sign + outdoor lighting = 2 pts, bright floodlight = 2 pts, car park, industrial lighting = 3 pts. To address the question whether certain street light types may attract comparatively more birds, the number of fallout locations within a 25m buffer around each light fixture was counted to identify potential clustering (measured as > 1 and up to 2 birds in 2014 and >2 and up to 4 birds in 2016) around certain fixtures using geoprocessing tools in ArcGIS.

RESULTS

In all 8 years where fallout was recorded, Hutton's shearwater fledglings were found grounded between early or mid-March and mid-April (Table 1). The total number of fallout birds recorded each season was highly variable among years with no relationship to rescue campaigns; ranging from 10–156 birds in 2006–2013 (years without rescue campaigns) and 68–274 birds in 2014–2016 (years with rescue campaigns). Similarly, fallout numbers recorded at any given night differed considerably within and among years, ranging from 3 to 113 birds per night during fledging periods 2006–2013, and from 8 to 98 birds per night during fledging periods 2014–2016.

The majority of birds recorded in 2016 resulted from incidental recoveries by community members and only on 2 occasions systematic searches recovered more birds per night. Many birds appeared to become grounded sooner after night fall than expected, with 60% of incidental bird recoveries (of those where the time of recovery was recorded) occurring in advance of patrol time

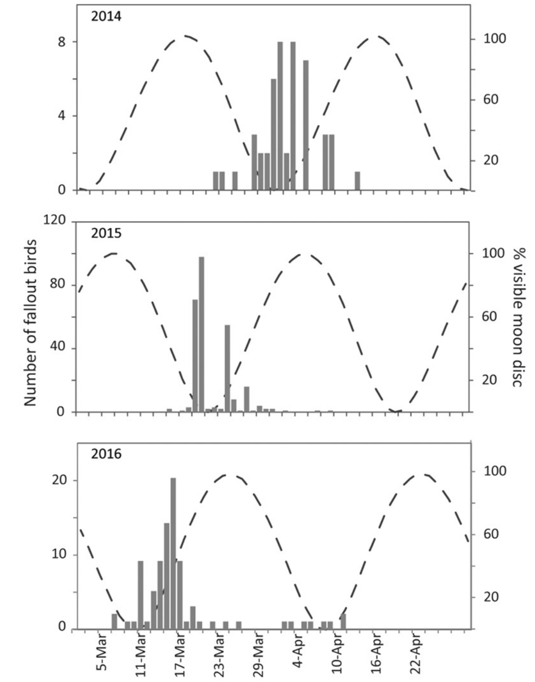

Fig. 3. Temporal distribution of fallout numbers in relation to moon phase. The latter displayed as percent visible disc of the moon, where the highest amplitude indicates full moon and the lowest amplitude indicates new moon. (Note different scales on y-axis due to variations in annual fallout numbers).

(2300h) of the systematic searches. This lead to birds being collected prematurely from parts of the pre-set search route introducing an 'incidental search bias' to the numbers resulting from systematic searches. Moreover, small numbers of birds were recorded as incidental recoveries later in the season when systematic searches had finished. Together, the data collection methods ensured full area coverage and reduced spatial bias in search effort.

Population effects and mortality rates

The number of fallout birds recovered during the 2014–2016 fledging seasons account for 0.1–0.3% of the estimated number of fledglings produced per year (Table 1). Among recovered individuals, 17% were found dead in both 2014 and 2016 fledging seasons, compared to less than 1% in 2015. Considering these confirmed fatalities only, the percentage of fledglings lost from the population pool per year amounts to less than 0.02%. However, the true mortality (i.e., whether rescued fallout birds will survive) cannot be determined until the return of fledglings as adults is assessed, which is beyond the scope of this study. Where recorded, only a few fatalities were assigned solely due to the crash but instead due to secondary causes of death, predominantly roadkill and to a lesser extent predation.

The impact of moon phase and weather conditions on fallout events

In all years on record, the general occurrence of fallout, and peak numbers of birds per night, appeared to coincide with periods around new moon. For the 3 years included in the GLM analysis (2014–2016), moon phase was the only significant predictor for the magnitude of fallout (Negative binomial regression, $df = 80$, $P < 0.001$). Fallout was greatest during periods of low percent visible moon disc (Fig. 3). Rainfall, visibility and wind speed were not significant predictors of fallout.

Weather conditions observed at time of bird recovery were assigned to 76% of fallout birds on 15 different nights in 2015, while this was the case for 95% of the birds recorded on 19 different nights in 2016. In both years, the majority of nights during which fallout was recorded had clear skies (Fig. 4A), but the highest number of birds per night were recorded during overcast conditions (Fig. 4B). In 2015 more birds were recovered during dry overcast than during wet conditions (Fig. 4B); whereas the opposite was true for fallout in 2016 with most birds recovered during wet overcast conditions (Fig 4B). Interestingly, weather conditions during the 3 'big nights' of the 2015 season varied considerably: 71 birds were recorded during showery and windy conditions on the night of 18 March, 98 birds during dry overcast conditions on 19 March, and 55 birds during clear conditions on 23 March. Similarly, in the 2014 fledging season, more fallout was recorded during overcast than clear nights but no distinction was made between wet or dry conditions on overcast nights.

Spatial distribution of fallout in relation to artificial lights

During the 2016 fledging season, 32 systematic searches were conducted on 17 nights, covering 20 km of unlit area and 12 km of lit area on each run. Of 17 birds recorded on these trips, none were found in unlit areas. From incidental recoveries, 9% of birds were reported as being found in unlit areas during both 2014 and 2016 seasons, while this was only 1% in 2015. Dead birds were only found in lit areas in all years. In both 2014 and 2016 (years where fallout locations were recorded), the majority of birds were found along the Kaikōura township's coastal roads, stretching along Ingles Bay north of the Kaikōura Peninsula (Fig. 5). Almost no fallout occurred along other lit areas, including the coastal roads south of the peninsula (i.e., along residential areas of South Bay or adjacent sections of the coastal highway) and no birds were recorded within Ocean Ridge, a distinct subdivision south of Kaikōura.

In 2014, detectable spatial clusters of bird recovery locations were small and scattered. Contrastingly, in 2016 a large core area could be identified along a distinct section of coastal road (The Esplanade). Additional smaller clusters were mostly concentrated around this area and not as scattered as in 2014 (Fig. 5). Large areas of high light density were identified in the 'Westend' region of Kaikōura township (encompassing a big street crossing, railway bridges and in-town strip mall) and at Ocean Ridge subdivision (Fig. 6). To a lesser extent, light clusters occur along the main road through town (Beach Road), as well as parts of The Esplanade (Fig. 6). Fallout did not occur in direct correspondence to the density or extent of artificial light clusters, and some fallout clusters were identified in areas with no amplified light density. Yet, the large fallout core area detected in 2016 did closely match the extent of increased light density at The Esplanade (Fig. 5 and Fig. 6). Moreover, the majority of fallout clusters overlapped with areas of medium to high light density within Kaikōura town during both 2014 and 2016 seasons.

The street light map provided by MainPower NZ Ltd included 472 light fixtures of 16 different types with regards to bulb type and wattage. Sodium high pressure bulbs at 70 Watt and 150 Watt (SHP 70W; SHP 150W) were the most common types, making up 41% and 31%, respectively, of all street lights. All other light types made up less than 10% each. While the SHP 150W type dominated the highway leading through Kaikōura as well as major parts of the town's coastal roads, SHP 70W was the main light type found in Ocean Ridge subdivision and South Bay, occurring rather interspersed through Kaikōura town ship, mostly away from the coast (Fig. 7). In both 2014 and 2016, fallout was recorded within a radius of up to 25 m at about 10% of all street lights consisting of 6 or 11 different types, respectively. Among those, the most common light type to be associated with fallout was SHP 150W in both years. Accumulations of birds around certain light types were rare and only occurred at high wattage light types (predominantly SHP 150W and Metal Halide MH 150W) and LED 252mA fixtures.

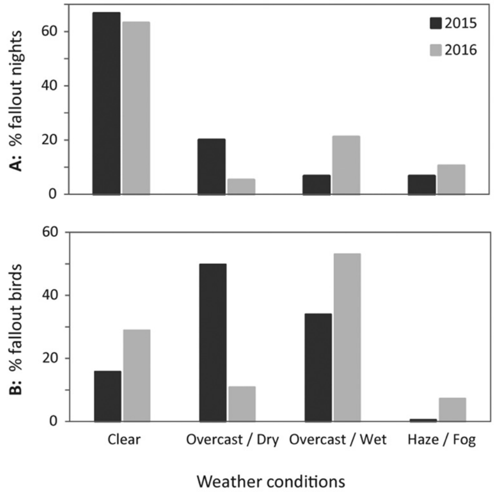

Fig. 4. Weather conditions observed upon bird recovery in 2015 and 2016: A) Percentage of fallout nights (from a total of 15 in 2015 and 19 in 2016) with clear, overcast (dry *vs.* wet) or hazy conditions; B) Percentage of birds recovered during respective weather conditions.

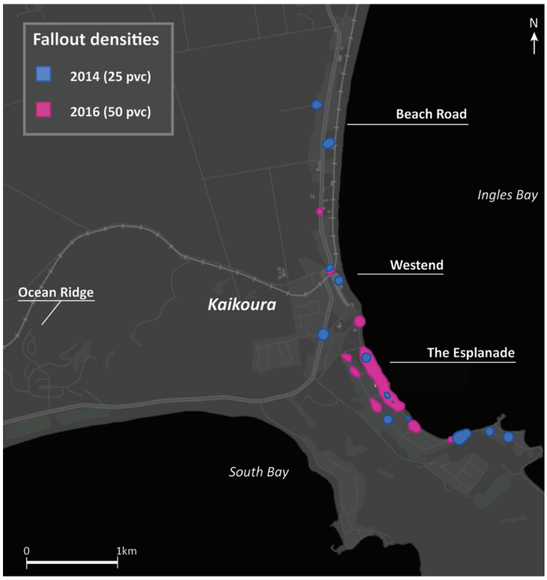

Fig. 5. High density fallout areas depicted by 25 percent volume contours (pvc) for 2014 (blue) and 50 pvc for 2016 (purple) seasons. (Map sourced from the LINZ Data Service and licensed for re-use under the Creative Commons Attribution 3.0 New Zealand licence).

DISCUSSION

Magnitude of fallout, mortality and population impacts

The results presented here indicate that considerable annual variation in fallout numbers of Hutton's shearwater fledglings appears to be a common pattern, irrespective of search and rescue

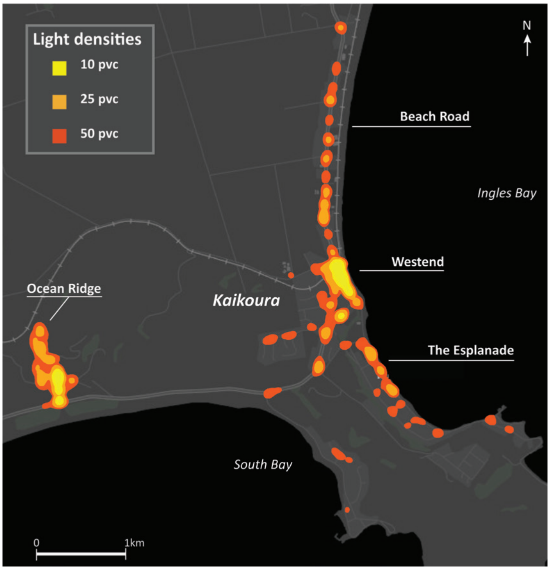

Fig.6. Artificial light source densities (decreasing from light to dark shading) depicted by 10, 25 and 50 percent volume contours (pvc). (Map sourced from the LINZ Data Service and licensed for re-use under the Creative Commons Attribution 3.0 New Zealand licence).

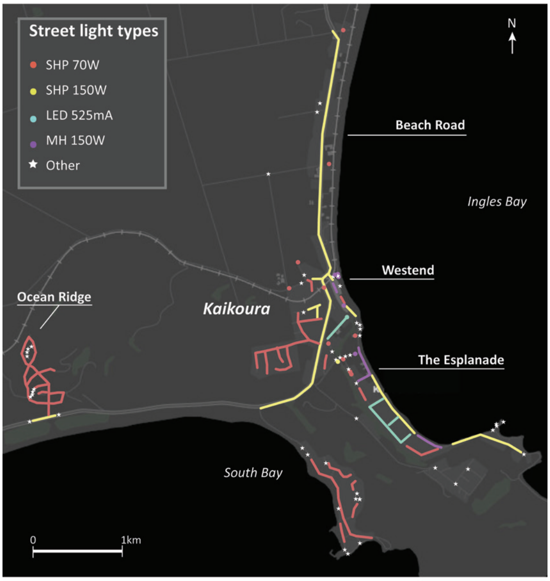

Fig. 7. Distribution of different street light types across Kaikōura, South Bay and Ocean Ridge. Sections where a single light type dominates are depicted as coloured lines. (Map sourced from the LINZ Data Service and licensed for re-use under the Creative Commons Attribution 3.0 New Zealand licence).

efforts. Comparatively high fallout numbers (>150 birds) were recorded both during years with low and high search effort and public awareness (in 2006 and again 2015), while during years with similar search effort and public awareness (2014 and 2015) annual fallout numbers differed by about 200 birds. Moreover, fallout recorded in 2016, the first year where systematic searches were carried out across the whole fledging season, did not exceed maximum numbers from previous years. Intra-specific variation in the magnitude of fallout has been observed in several other shearwater and petrel species (e.g., Ainley *et al.* 2001; Le Corre *et al.* 2002; Rodriguez & Rodriguez 2009; Rodriguez *et al.* 2012b) and it was proposed that environmental factors may influence annual fallout numbers. The proportion of annually produced Hutton's shearwater fledglings recorded as grounded each year (0.1–0.3%), compares to the lower end of the spectrum of what is reported for related species worldwide, where annual fallout rates range from less than 1% to about 46–60% (Rodriguez *et al.* 2017).

Mortality rates (percentage of total recovered birds per year) of fallen Hutton's shearwaters of 17% compare to the mid-range of mortality rates listed for other shearwater and petrel species (5-41%; Rodriguez *et al.* 2017), which are likely subject to locality and rescue campaign regime. Generally, the estimates of both fallout and mortality rates presented here must be considered as minimum numbers since we can assume that not all grounded birds were found (e.g., due to birds hiding in vegetation, being preyed on straight away or because dead birds might be less likely to be collected or reported by the public).

Rescue rates of fallout birds (i.e., the proportion of recovered birds released alive) have been high in most studies reporting rescue campaigns (e.g., Telfer *et al.* 1987; Le Corre *et al.* 2002; Rodriguez & Rodriguez 2009). While indications are that public awareness and campaigning have a positive effect with regards to population impacts, the fate of released birds is, in fact, uncertain and difficult to monitor; for example, only 5 of greater than 10,000 rescued Newell's shearwaters banded over a period of 7 years were subsequently recovered in Hawaii (Telfer *et al.* 1987). At this stage, we can assume that rescue efforts for Hutton's shearwater in Kaikōura will remain high in the future, and the sustained losses of up to 1% of the annually produced fledglings will continue to range below the currently estimated annual population growth rate of 3.5% for the species since 2002 (Taylor, G. *pers. comm.* 2 May 2016). However, continued observations are required to confirm the identified magnitude of fallout, and to assess the impact of the November 2016 earthquake on the population.

Impact of moon phase and weather parameters

Our data showed that the occurrence of fallout in general, but particularly high fallout numbers per night, coincided significantly with periods around new moon (i.e., low moon disc visibility and as such darker nights). This pattern corresponds with results of many other studies reporting on fallout in relation to moon phase; either finding reduced fallout during full moon (Reed *et al.* 1985; Telfer *et al.* 1987; Le Corre *et al.* 2002; Rodriguez & Rodriguez 2009) or increased fallout during new moon (Rodriguez *et al.* 2014; Miles *et al.* 2010) for several shearwater and petrel species. Possible interpretations for this apparently common phenomenon or behaviour include that full moon might either inhibit fledging, or reduce the impact of artificial lighting due to increased natural ambient light levels, with birds being able to use the moon and other landmarks to orientate (Reed *et al.* 1985). Indications are that fledging occurrence is not correlated to moon phase (e.g., Telfer *et al.* 1987, Miles *et al.* 2010 and Pinet *pers. comm.* 20 September 2016). Furthermore, it was shown that when full moon coincided with the estimated fledging peak (or mean date of first flight), the total number of fallout birds was comparatively lower than during other years (Ainley *et al*. 2001; Rodríguez *et al*. 2012b). Accordingly, the magnitude of fallout could be affected by the timing of moon phase in relation to fledging activity.

With regards to possible impacts of weather conditions on the intensity of fallout, we did not detect any significant patterns in relation to rainfall, visibility or wind speed using continuous weather data. Based on only 3 years of data, however, we cannot confidently conclude that results have not been biased by the high variance in the weather data (e.g., whether rainfall averaged per night reflects the conditions at time of fallout in a reliable manner). We did find a relationship of increased fallout and overcast skies, which has been reported for Newell's shearwaters in Hawaii, and attributed to obstruction of moonlight and possible light spill amplification effects of cloud cover (Telfer *et al.* 1987; Kyba *et al.* 2011).

Spatial distribution of fallout in relation to artificial lights

In the 2 seasons during which fallout locations were recorded (2014 and 2016), more than 90% of bird recoveries across the Kaikōura region were recorded within lit areas. While this suggests a clear link between the presence of artificial lighting and the occurrence of fallout in Hutton's shearwater fledglings, we noted that all but 1 bird was found within Kaikōura township, rendering lit areas in South Bay and Ocean Ridge subdivision south of Kaikōura to have no effect. As we eliminated in-town search bias through our systematic search set up, possible reasons for this could lie in the spatial characteristics (e.g., location and size) of these 3 distinct lit areas.

Generally, our results are in line with the literature regarding related species; for example, Le Corre *et al.* (2002) and Rodrigues *et al.* (2012) reported that about 80% of fallout at Réunion Islands and the Azores was found in brightly lit urban areas. This is also comparable to study results from Hawaii (Reed *et al.* 1985; Telfer *et al.* 1987; Ainley *et al.* 1997; Podolsky *et al.* 1998), Canary Islands (Rodríguez & Rodríguez 2009) or Outer Hebrides (Miles *et al.* 2010). Moreover, several studies found that intensity and distribution of fallout were related to the spatial extent of urban areas, and that fallout increased in coastal cities and tourist resorts while little to no attraction was observed towards lights inland and off the flyway (Telfer *et al.* 1987; Rodriguez & Rodriguez 2009; Rodrigues *et al.* 2012).

While all lit areas included in our study were coastal, chances are that the impact of a large lit area like Kaikōura town could overrule the effect of smaller ones like Ocean Ridge and South Bay. Another consideration would be that the flyway of Hutton's shearwater fledglings is in fact different from what was found based on radio-tracking adult birds (Taylor, G. *pers. comm*. 2 May 2016; shown in Fig. 1) and either excludes areas south of Kaikōura or has fledglings see the township first when coming down from the mountain colonies (located to the north-west of Kaikōura) on their maiden flights.

Assessing whether light spill intensity (measured via proxies like light source density or light type and wattage) would influence the distribution of fallout at a smaller scale (i.e., within Kaikōura township), our results remained inconclusive in that we did not detect clear linear relationships in this respect. Indications are, however, that vicinity to the sea in combination with increased light spill could be a factor explaining the observed concentration of fallout along Kaikōura's coastal stretch or even fallout hotspots at a small scale, as found at The Esplanade in 2016. Procellariform species like Hutton's shearwaters with advance nasal networks may follow the smell of the ocean but mistake its location due to becoming disorientated by artificial light, causing them to land prematurely or collide with manmade structures or tall vegetation due to reduced flight height and impaired vision (Podolski *et al.* 1998; Raine *et al.* 2007; Rodriguez *et al.* 2012a).

Furthermore, the occurrence in our study of fallout in relation to certain street light types, pointed towards a possible negative impact of high wattage lamps or bright lights like LED. However, if high wattage was influencing the impact of artificial light spill on fallout in our scenario, it might work at a large rather than a small scale, considering that Sodium High Pressure (SHP) 150 Watts was the predominant light type in Kaikōura township (main fallout area), while South Bay and Ocean Ridge (no fallout) were dominated by SHP 70 Watts. Yet, at this stage we cannot discern whether this is actually an effect of light type contributing to overall light spill intensity or whether we observe a location bias (i.e., respective light types just happen to be in areas where the occurrence of fallout depends on other factors as discussed above).

Mitigation measures

Successful measures to reduce artificial light spill and consequently reduce fallout in seabirds have been discussed extensively in the literature (Raine *et al.* 2007); among them, changing wavelength or shielding upward radiation in outdoor light fixtures (Reed *et al.* 1985; Miles *et al.* 2010), closing curtains in residential areas or switching lights off completely (Rodriguez *et al.* 2014). In conjunction with tighter control around sensitive periods for fallout, these measures can provide effective mitigation of fallout numbers (Telfer *et al.* 1987), but to reduce mortality once birds are grounded, public awareness and rescue campaigns are crucial (Rodriguez *et al.* 2014). Furthermore, Raine *et al.* (2007) recommend the adoption of legislations to reduce light pollution in future developments into local law with replacement of other street lighting with a full cut-off design in a rolling programme.

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