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Using observed seabird fallout records to infer patterns of attraction to artificial light

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ABSTRACT: Attraction of fledgling shearwaters, petrels, and storm-petrels to artificial light has been documented for decades on islands around the world and is considered a significant threat to many species. Although large numbers of downed birds have been observed after being disoriented by light, several important elements of this 'fallout' phenomenon are unknown, including the locations along the path from nest to ocean at which attraction and/or disorientation occurs and whether fledglings can be attracted back to land after reaching the ocean in numbers large enough to contribute significantly to fallout. To investigate these questions, we compared observed Newell's shearwater *Puffinus newelli* fallout records (from 1998 to 2009) on Kauai, USA, with expected numbers generated from several hypothetical models containing basic assumptions related to fledgling movement and attraction to light. Based on our results, the spatial pattern of observed fallout is consistent with the amount of light that fledglings may view along their first flights to and beyond the coastline. This suggests that even fledglings from dark regions of the island may not be safe because they may view light after reaching the ocean and still be susceptible to attraction. These findings support recent modeling efforts predicting that most birds fledging from Kauai are likely exposed to at least some anthropogenic light. As nocturnal use of light by humans is unlikely to be eliminated, research on the types of artificial light that are both useful to humans and safe for seabirds may be crucial for the conservation of these important marine animals.

KEY WORDS: Anthropogenic light · GIS-based modeling · Hawaii · Kauai · Light attraction · Procellariiformes · Newell's shearwater · Seabird conservation

INTRODUCTION

Artificial light is becoming a prevalent nocturnal feature of our planet (Cinzano et al. 2001), and documented cases of its effects on the natural activities of organisms are on the rise (Longcore & Rich 2004). Fledglings of certain seabird species, particularly in the families Procellariidae (shearwaters and petrels) and Hydrobatidae (storm-petrels), are attracted to artificial light on their maiden flights to the ocean (Harrow 1965, Imber 1975, Reed et al. 1985, Telfer et al. 1987, Le Corre et al. 2002, Salamolard et al. 2007, Rodriguez & Rodriguez 2009, Miles et al. 2010), although the cause of this attraction remains unknown. As these birds approach light sources, they can become disoriented and fall to the ground following physical exhaustion or collision with man-made structures and vegetation, a phenomenon known as 'fallout.' While many of these downed birds are found alive and are released each year through public rescue efforts, recent studies suggest that light-induced mortality may still significantly

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decrease long-term population recruitment (Ainley et al. 2001, Le Corre et al. 2002, Rodriguez & Rodriguez 2009, Fontaine et al. 2011, Griesemer & Holmes 2011, Rodriguez et al. 2012b).

Perhaps the most well known example of fallout occurs each autumn on the island of Kauai in the Hawaiian Archipelago, USA (Reed et al. 1985, Telfer et al. 1987, Ainley et al. 2001), during the fledging season of Newell's shearwater *Puffinus newelli*, a species listed as 'threatened' under the US Endangered Species Act and 'Endangered' on the IUCN Red List (IUCN 2012). More than 30 000 Newell's shearwater fledglings have been found as victims of fallout on Kauai during the past few decades (Griesemer & Holmes 2011), and thousands of other young shearwaters, petrels, and storm-petrels from different islands around the world are downed as a result of light annually (e.g. Le Corre et al. 2002, Miles et al. 2010, Fontaine et al. 2011, Rodrigues et al. 2012, Rodriguez et al. 2012b). Despite this large number of fallout observations, certain elements of this phenomenon remain unknown, including the locations along the path from nest to the ocean from which fledglings are consistently drawn off course and downed by artificial light (i.e. it is not known whether light viewable from natal colonies and/or light viewed along flight routes to the ocean is regularly involved in fallout). Some seabirds (including procellariids and hydrobatids) are attracted to gas flares and lights on offshore oil platforms (Wiese et al. 2001), and some (including fledgling procellariids; State of Hawaii unpubl. data) are attracted to light sources on ships at sea (Dick & Donaldson 1978, Montevecchi 2006), demonstrating that some birds are still attracted to light after reaching the ocean. In addition, an extremely small number of fledgling procellariids (compared to the tens of thousands of birds that have been rescued worldwide) have returned as repeat victims of fallout a short time after having been rescued, banded, and released at coastal sites (Podolsky et al. 1998, Fontaine et al. 2011). This suggests that a few individuals can indeed be drawn back to land from the ocean, but it remains unknown whether many birds can be attracted back to land after first reaching the sea (without human intervention) such that they contribute significantly to total island-wide fallout (as suggested by Podolsky et al. 1998).

An improved understanding of how attraction to artificial light results in the pattern of observed fallout exhibited by young seabirds is important for future seabird conservation efforts worldwide because it would aid in further assessing the severity of the threat that artificial light poses to these birds. The information necessary to directly measure patterns of fledgling movement in relation to the distribution of artificial light could potentially be acquired by fitting a large number of nestlings at breeding colonies with radio or satellite transmitters and monitoring flight paths leading to fallout locations. However, many seabird species whose fledglings are negatively affected by artificial light only breed in isolated and mountainous terrain of oceanic islands; thus, the locations of very few nests are usually known, often rendering such a large-scale effort unrealistic. This is especially true of Newell's shearwater, as the exact locations of only ~40 active natural burrows are currently documented (Kauai Endangered Seabird Recovery Project unpubl. data).

An indirect method, however, offers a more feasible and less invasive approach to estimate the pattern of fledgling fallout caused by attraction to artificial light. In this study, we compared observed numbers of Newell's shearwater fallout victims within established regions (known as 'fallout sectors') on Kauai to fallout expected from a series of hypothetical models containing basic assumptions concerning flight paths and attraction to light. These comparisons included models incorporating bird movement and the ability of birds to view light once at sea, allowing us to test where along presumed flight paths (from natal site to the sea) that attraction can occur and, importantly, whether these young birds could potentially be attracted back to land after reaching the ocean in numbers large enough to contribute significantly to island-wide fallout. We discuss the likely causes behind observed fallout on Kauai in the context of our hypothetical models; this is followed by a discussion of future research objectives to support the protection of these seabirds from the detrimental effects of artificial light.

METHODS

Fallout records

Residents of Kauai are encouraged to deliver seabirds found as victims of fallout to one of a number of aid stations on the island (Reed et al. 1985, Telfer et al. 1987, Rauzon 1991), and the pick-up location for many of these birds is recorded. We obtained a shapefile of 'fallout sectors' (regions with defined boundaries, ranging in size from 1236.68 to 96 925.81 km^2, in which fledglings found as victims of fallout are tallied each year) and Newell's shearwater fallout records on Kauai from 1998 to 2009 from the Save Our

Shearwaters program (Hawaii Division of Forestry and Wildlife). For a visual display of these fallout sectors, see Fig. 6 in Troy et al. (2011).

Fallout records were summed by fallout sector such that all observations of birds without information on pick-up location or fallout sector were not included in total sums (this initially resulted in 1372 fledglings that were excluded from the analyses). Peak fledging season is from October to November, but some fledglings also depart in September and December (Telfer et al. 1987); therefore, we included only birds found from September to December because birds identified as fledglings during other times of the year are expected to be misidentified adults. For the 2009 data, information on Newell's shearwater age (i.e. hatch-year versus adult) was not available. Because the vast majority (~98%) of Newell's shearwater recoveries from 1998 to 2008 collected from September through December were identified as fledglings (State of Hawaii unpubl. data), all birds from 2009 were considered fledglings for the purposes of this study. In addition, a small number of fledglings (n = 35) meeting the above requirements were not included in this study because they were associated with fallout sectors 33, 34, and 35. Fallout sector 33 is divided into 2 segments on opposite ends of the island (a vast expanse of the western portion of Kauai, in which there is no artificial light output, as well as a small section of the southeastern coast) and was not available in the shapefile used in this study. Sector 34 contains birds found at sea (i.e. on ships), and birds in which the fallout sector is unknown are sometimes placed into sector 35; therefore, sectors 34 and 35 do not exist spatially on the island of Kauai. Thus, 3175 birds (i.e. fallout records) and 32 sectors were available for analysis.

Some variation was observed in the annual number of fledglings found within fallout sectors. This variation was quantified by calculating a mean proportion of island-wide total fallout over all study years for each sector, subtracting this mean from the maximum proportion for that sector over this same time period, and calculating an overall mean, minimum, and maximum value for these differences over all sectors. This resulted in a mean difference in maximum and mean proportion over all sectors of 0.045 (minimum = 0.004; maximum = 0.241). This large maximum difference was found only within 1 sector (fallout sector 2), and this particular sector was removed from a second set of analyses in this study. Thus, the overall pattern was generally consistent from year to year, and only the total fallout from 1998 to 2009 was used in our modeling procedures.

Artificial light layers

A geographic information system (GIS) layer of artificial light intensity for the earth, excluding light originating from the sun, moon, and aurora, was obtained for both 1998 and 2009 from the National Geophysical Data Center (www.ngdc.noaa.gov/eog/dmsp/downloadV4composites.html). Stable average light layers were used for both years, meaning that light from ephemeral sources (such as wildfires) was identified and replaced with values of 0. Pixel values for both layers ranged from 0 to 63 relative units. The 1998 and 2009 layers were developed from satellite images with 913.47 × 913.47 m resolution and 911.25 × 911.25 m resolution, respectively. All contributing light originated from artificial light sources on cloud-free nights, including persistent sources such as gas flares. Pixels of this satellite layer also contain some artificial sky glow (i.e. illumination caused by the refraction and scattering of light by water, dust, and other molecules suspended in the air); this sky glow is most apparent close to cities (Elvidge et al. 2007, Kyba et al. 2011) and may somewhat inflate light intensity pixel values in the vicinity of urban sites and incorrectly depict dark areas very near urban light sources with lighted pixels. These light intensities represent an average over an entire year; therefore, any reduction in light output during the fledging season of Newell's shearwater is not completely accounted for, meaning that using this layer required the assumption that yearly average light intensities are a suitable approximation of light conditions during the fledging period of the species.

Both the 1998 and 2009 light layers were clipped by a shapefile of Kauai extended to 10 km past the shoreline of the island. Mean light intensity from 1998 and 2009 was obtained for each fallout sector, as well as the proportion of cover of light pixels within each sector. Mean light values were only calculated using fallout sector pixels representing light (i.e. pixels with light intensity values of 1 to 63 relative units); dark pixels (i.e. pixels with light intensity values of 0 relative units) were not included in the calculation. Because summary statistics within polygons are only performed on pixels whose centroids (i.e. pixel centers) fall within the polygon boundary, the pixel size for each light layer was resampled to 10 × 10 m so that calculations of mean values were more representative of pixel cover within the irregular shapes of the fallout sectors.

We tested the relationship between 1998 and 2009 artificial light using Pearson's correlation coefficient to demonstrate that the relative intensity and physical coverage of light (among fallout sectors) over time did not change on Kauai. For these analyses, fallout sector was the unit of observation and p-values were calculated using randomization tests; see the 'Analyses' subsection for further discussion on randomization tests. Mean light intensity in 1998 and 2009 was highly correlated ($r = 0.95$, $p < 0.001$), as was proportional cover of light pixels ($r = 0.89$, $p < 0.001$); therefore, 2009 light was used to weight estimates of expected fallout within sectors calculated from our hypothetical models. The slight differences in pixel sizes between the original 1998 and 2009 layers (mentioned above) were considered negligible for these analyses. In addition, slight differences in light intensity values in certain locations between 1998 and 2009, as well as minor differences in the proportion of fallout sectors covered by light between these years, were considered unimportant because of the large scale of this study and the fact that mean light intensity values were used as relative weights in calculations of expected numbers of downed fledglings within fallout sectors.

Suitability of light layer pixel size for fallout research

In this study, the satellite layer pixels from 2009 were 911.25 × 911.25 m in size, and these pixels displayed light intensity as a yearlong average output. Because each pixel represents an average value over such a large area, pixel values likely reflect a combination of different light intensities (some of which may be greater than the actual pixel value) and numbers of light sources. Despite whether pixel values represent the actual light intensity being emitted by lights or the numbers of lights within the pixel area (or both), this satellite layer is suitable for research investigating the threat that light may pose to fledgling seabirds (e.g. Troy et al. 2011), as well as the relationship between light and seabird fallout (e.g. Rodrigues et al. 2012, Rodriguez et al. 2012b), on a large scale. Even if one considers the extreme assumption that all light sources on the island emit a light intensity equal to 63 relative units (the highest pixel value for the planet), meaning that differences in pixel values were only due to the number of lights within the pixel area, it is highly likely that pixel-sized areas with more light sources can attract more fledglings than areas with fewer lights. Such a large pixel size, however, precludes use of this light layer for investigating how light intensity emitted from individual light sources affects fledgling fallout.

Model overview

Expected fallout numbers in this study were calculated for 8 hypothetical models. Concise model descriptions are provided in Table 1, and expanded descriptions of the models and their assumptions are provided in Supplement 1 at www.int-res.com/articles/n022p225_supp.pdf. For all models, fallout sectors were the unit of observation, and an overall weight was calculated for each fallout sector in order to derive expected fallout numbers for each sector. Calculation of weights for the light intensity, stationary, island movement, and ocean movement models assumed a linear relationship between light intensity and seabird fallout; calculation of weights for the stationary, island movement, and ocean movement models were based on more complex factors than the other models. These weights were converted to proportions (of the island-wide total for all fallout sector weights) that were then used to calculate the expected number of fallout birds for each sector. To generate expected numbers for each fallout sector, the calculated proportion for each sector was multiplied by the total island-wide observed fallout ($n = 3175$ fledglings). Fallout sector 2 (located on the northern shore of Kauai) contained a large number of fledglings relative to the other fallout sectors ($n = 1045$; approximately one-third of the island-wide total; Fig. 1), and the vast majority of these birds were found in a single location. Because of the disparity between observed fallout in sector 2 and the other sectors, expected numbers from all models were calculated a second time without input from fallout sector 2 and based on a reduced observed fallout number ($n = 2130$) available for expected number calculation (i.e. neither the spatial analyses related to fallout sector 2 nor fledglings found within this sector were used in this second modeling scenario).

To quantify the effect of removing fallout sector 2 (and its fledglings) in the second modeling scenario, we subtracted the proportions of the island-wide total fallout expected for each fallout sector under the modeling scenario with sector 2 from those calculated without sector 2. A mean of this difference in proportion was calculated over all sectors for each model, and a grand mean was then calculated for these 8 model means (because there was no proportion for sector 2 in the second modeling scenario, sector 2 was not included in the calculation of mean difference in proportion for models). Removing sector 2 from the analyses only increased expected fallout within sectors by an average proportion of 0.0009 (grand mean = 0.0009; minimum mean = 0.0004; maximum mean =

Table 1. Descriptions of hypothetical models used to calculate expected Newell's shearwater *Puffinus newelli* fallout for comparison with observed fallout within fallout sectors on Kauai, Hawaii, USA

Model	Hypotheses/assumptions	Calculation of expected fallout for each sector
Sector area	Fallout is greater in larger sectors	Based on surface area of the sector
Light area	Fallout is greater in sectors containing a greater coverage of lighted terrain	Based on surface area of the lighted portion of the sector (surface area excludes pixels representing no light)
Light intensity	Fallout is greater in sectors with a greater mean intensity of light, regardless of the location of natal sites	Based on the mean intensity of light for the sector (excluding pixels representing no light)
Stationary	Fledglings are only attracted by light from their natal sites	Based on: (1) surface area of known shearwater activity sites viewable from the lighted portion of the sector (a proxy for the number of fledglings that can view light from their natal sites), (2) distance from each activity site to the lighted portion of the sector, and (3) mean intensity of light for the sector (excluding pixels representing no light)
Island movement	Fledglings are attracted to light viewable along their flight paths from their natal sites to the coastline	Extension of stationary model for watersheds containing known shearwater activity sites to also include: (1) surface area of the portion of watershed viewable from the lighted portion of the sector (a proxy for the number of fledglings that can view light along flight paths from natal sites to the coastline) and (2) distance from the viewable portion of the watershed to the lighted portion of the sector
Ocean movement (to 1, 5, and 10 km beyond coastline)	Fledglings are attracted to light viewed from their natal sites out to 1 of 3 cutoff distances beyond the coastline (1, 5, and 10 km)	Extension of island movement model for ocean regions connected to watersheds containing known shearwater activity sites to also include: (1) surface area of the ocean region(s) viewable from the lighted portion of the sector and (2) the distance from the viewable portion of the watershed and ocean region(s) to the lighted portion of the sector

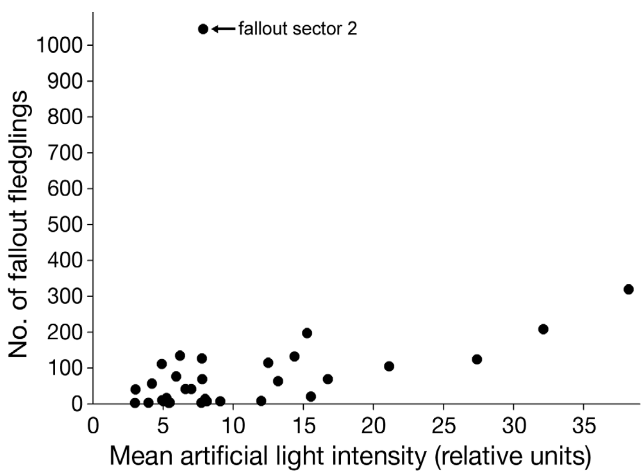

Fig. 1. Fledging Newell's shearwaters *Puffinus newelli* found as victims of fallout plotted by mean artificial light intensity from 2009 within fallout sectors (n = 32) on the island of Kauai, Hawaii, USA. Fledglings were summed by fallout sector from 1998 to 2009. Because artificial light attracts and/or disorients fledglings, mean light calculations excluded dark areas. Fledglings were observed in all fallout sectors, although <5 ind. were found in some sectors. Fallout sector 2 is labeled to highlight the exceptionally large number of fledglings observed there during the study period

0.0011). This only converts to an approximate increase of between 1 and 2 birds for all fallout sectors. Therefore, because expected fallout increases by an almost identical amount across all fallout sectors for all models, and because the increase is so small compared to the island-wide fallout totals under both scenarios, this increase is considered negligible. Thus, comparing observed fallout with expected fallout calculated under the second modeling scenario (i.e. without fallout sector 2) is a valid comparison.

Development of GIS layers for pixel summaries and calculation of expected numbers from the hypothetical models are described in Supplement 2 at www.int-res.com/articles/suppl/n022p225_supp.pdf, and the treatment of viewable light in certain models, model limitations, and analyses are described below. All spatial analyses were conducted using ArcGIS 9.3.1 (ESRI).

Treatment of viewable light in particular models

Weights for the stationary, island movement, and ocean movement models were based in part on lighted portions of fallout sectors that could be viewed from locations on the island that the birds may encounter (locations depending on particular model assumptions). To accomplish this, viewsheds, i.e. analyses that highlight the landscape viewable from a feature, would ideally be conducted from each location that a fledgling could potentially visit (raised to a biologically relevant flight height). However, fledglings could potentially visit millions of locations (10 × 10 m pixels of a digital elevation model [DEM] of this island). Thus, we used a surrogate measure that is much less analytically intensive, yet very appropriate for such a landscape-scale analysis. This measure involved generating viewshed layers from the perimeter of the lighted portion of each fallout sector (i.e. from the perspective of the fallout sector) to highlight the areas of the island that could be viewed from the lighted portion of the fallout sector; see Supplement 2 for details of viewshed layer development.

A limitation of this method is that at each pixel of our DEM (used as an input layer for viewshed analyses), fledglings were forced to view light from ground level. Therefore, when birds are at the same elevation as light sources, raising the height of light sources above the ground is equivalent to raising birds the same height while keeping light sources on the ground. However, this relationship is not always identical when birds and/or light sources are on sloped terrain with rugged topography. For example, a bird flying (and viewing light from above ground level) near a ridgeline that separates the bird and a particular light source could potentially view that light source. However, because the light source is positioned above ground level and the bird is positioned at ground level, the viewshed analysis from the perspective of the light source may not necessarily indicate that a bird at this location could view that light source. Despite this limitation, we consider this measure a very suitable approximation of the area from which birds could view light sources existing in particular fallout sectors.

Model limitations

Because our stationary and movement models contain only basic assumptions, we anticipated that several factors unaccounted for in our models would generate expected numbers for various fallout sectors that differed somewhat from observed numbers. First, although 2-dimensional Newell's shearwater site area is likely to be more or less positively correlated with the number of breeding adults, and thus the number of fledglings (see Table 1 and Supplement 1), some variation in the numbers of fledglings produced at activity sites was expected. In addition, our models did not account for the locations of multiple unknown breeding sites. Nor did they account for the possibility that fledglings could be attracted toward a particular lighted region and subsequently be drawn away from that trajectory toward a different lighted region. In addition, the light layer used in this study contains artificial sky glow (mentioned previously), and this additional glow (which may attract fledglings) was not separately accounted for by our models. Finally, factors such as weather conditions may influence the direction of fledgling movement or contribute to sky glow (Kyba et al. 2011), but were not factored into our calculations.

Analyses

Observed fallout numbers were compared to fallout numbers expected from each of our 8 hypothetical models using 2 measures of relationship. Pearson's correlation coefficient (Pearson's r) was used to measure the linear relationship between the observed and expected numbers. In addition, the mean fallout sector ratio (MFSR) was calculated for each model to further assess how well the pattern of fallout expected from our models matched the observed pattern. To calculate MFSR for a particular model, a fallout sector ratio was first calculated for the observed and expected fallout pairs for each fallout sector as the minimum (i.e. the smaller of the observed and expected fallout values for the fallout sector) divided by the maximum (i.e. the larger of the observed and expected fallout values for that fallout sector). This ratio indicated the difference between the observed and expected numbers for each fallout sector without being affected by the direction of the difference (i.e. observed and expected values of 50 and 100, respectively, give the same fallout sector ratio as do values of 100 and 50). A mean overall fallout sector ratio was then calculated for the model. Because fallout sectors are arbitrary sampling units, we devised a randomization test to assess the significance of r and MFSR.

We used a series of randomization tests, in which there are no distributional assumptions (Manly 2007), to calculate the probability that measures for these observed and expected comparisons (Pearson's r and MFSR) could have been produced solely by random pairing of observed and expected fallout values. We randomly assigned, without replacement, each observed fallout value to one of the expected values and compared those fallout numbers using r and MFSR as before. We repeated this process 1000 times for each model. This yielded a sampling distribution of 1000 values for each measure (r and MFSR). Essentially, the randomization test created the distributions of r and MFSR values that would be obtained if observed fallout numbers were randomly distributed to any sector and then compared to the expected numbers for that sector. For each of our hypothetical models, we compared the actual values of Pearson's r and MFSR to the 2 respective sampling distributions. For both measures, p-values were determined as the proportion of the sampling distribution that was greater than or equal to the actual values. These tests were conducted for both modeling scenarios (i.e. with and without fallout sector 2) using Program R version 2.15.1 (R Development Core Team 2012).

RESULTS

Based on the 2 measures of relationship considered in this study, several of our hypothetical models generated expected numbers consistent with the observed pattern of Newell's shearwater fallout. Under both modeling scenarios (i.e. with and without fallout sector 2), expected numbers from both the sector area and light area models exhibited very low, non-significant correlations with the observed data, as well as the lowest MFSRs (Table 2). When all fallout sectors were included in analyses, only the ocean movement models and the light intensity model exhibited MFSRs that differed significantly from random; these same models also exhibited positive correlation coefficients with the observed fallout data, although these coefficients were somewhat low and not significant (Table 2).

However, when fallout sector 2 was removed from the analyses, stronger positive (and significant) correlations between observed and expected numbers were achieved for all models except for the sector area and light area models, and all models yielded improved MFSRs, although only the ocean movement models and the light intensity model exhibited MFSRs that differed significantly from random (Table 2). The ocean movement and light intensity models yielded the highest correlation coefficients and MFSRs, with numbers from the light intensity model exhibiting the strongest positive linear relationship with the observed data (Table 2). Although expected numbers generated from the stationary and island movement models were moderately and significantly correlated with observed fallout, when considering both measures of the relationship simultaneously, the ocean movement models and the light intensity model generated expected numbers that were more consistent with observed fallout.

Table 2. Results of comparisons of expected fallout numbers from 8 hypothetical models to total Newell's shearwater *Puffinus newelli* fallout observed on Kauai, Hawaii, from 1998 to 2009. Shown are Pearson's correlation coefficient (r), the mean fallout sector ratio (MFSR) of expected and observed numbers within each sector (see 'Methods' for explanation of MFSR), and p-values for these measures of relationship determined using randomization tests. Comparisons are shown for 2 modeling scenarios (one with all fallout sectors included and one without fallout sector 2). Models are arranged by decreasing values of r

Model	r	p (r)	MFSR	p (MFSR)
All fallout sectors				
Ocean movement to 10 km	0.276	0.091	0.428	0.005
Ocean movement to 5 km	0.244	0.113	0.426	0.004
Light intensity	0.241	0.096	0.432	0.011
Ocean movement to 1 km	0.180	0.166	0.423	0.003
Island movement	0.098	0.299	0.341	0.249
Stationary	0.066	0.280	0.343	0.242
Light area	0.011	0.475	0.313	0.886
Sector area	–0.078	0.608	0.296	0.916
Without fallout sector 2				
Light intensity	0.762	<0.001	0.451	0.002
Ocean movement to 10 km	0.628	<0.001	0.440	0.008
Ocean movement to 5 km	0.597	0.002	0.442	0.011
Ocean movement to 1 km	0.542	0.005	0.440	0.003
Island movement	0.475	0.008	0.373	0.198
Stationary	0.436	0.012	0.379	0.148
Light area	–0.075	0.610	0.321	0.878
Sector area	–0.197	0.855	0.329	0.742

DISCUSSION

Fledgling movement and viewable light

Overall, our results suggest that the spatial pattern of observed seabird fallout is consistent with the amount of light that fledglings may view along their first flights to and beyond the coastline. Moreover, it appears that the observed pattern of fallout cannot be explained merely by fallout sector area or the physical area covered by light sources within sectors. Good support was shown for the ocean movement models and the light intensity model when fallout sector 2 was removed from the analyses. As distance from the coastline increased for the ocean movement models (allowing birds to view light from increasingly more area), we found stronger positive correlations between observed and expected numbers (with values of r ranging from 0.542 to 0.628), progressively approaching the value obtained for the light intensity model (r = 0.762). Although there was some deviance from this pattern in values of MFSR among the ocean movement models, the light intensity model again exhibited the highest value.

The findings of our study support and build upon those of a recent study, in which light intensity was positively correlated with the number of downed fledgling shearwaters (Rodrigues et al. 2012). Expected numbers from the light intensity model were based only on the mean intensity of light within fallout sectors; however, given known information related to mechanics of light attraction and the biology of the species, this model carries assumptions of bird movement that were not previously discussed. First, fledglings likely follow river valleys and other topographical depressions from their high-elevation natal sites to the ocean (Telfer et al. 1987, Podolsky et al. 1998) and, therefore, should generally continue to do so prior to viewing light (which may draw them off course from their initial trajectory). In addition, from a stationary perspective (i.e. without considering bird movement), it was recently shown that light could not be viewed from approximately 30 % of the island of Kauai (Troy et al. 2011), and these dark locations mostly included regions in the interior and northwestern portion of the island where many known Newell's shearwater activity sites are located. Given this additional information concerning viewable light on Kauai, the expected behavior of the species in the absence of light, and the results of this study, it appears likely that many birds could successfully reach the coastline and ocean, where they are then exposed to a range of light intensities emanating from multiple fallout sectors (spanning a large portion of the island) and are more likely to be attracted to sectors with greater light intensities and/or greater densities of light sources. Therefore, these results provide support for the idea that fledglings could indeed be attracted back to land after reaching the ocean in numbers large enough to contribute significantly to island-wide fallout. Consequently, these findings are disconcerting because they suggest that birds fledging from 'dark' breeding sites (i.e. those from which no light can be viewed) could be drawn off course by light along their journey to the sea, and even those flying through 'dark' watersheds may still not be safe once they reach the ocean.

Susceptibility to light attraction and future research

Fallout caused by attraction to artificial light is thought to be a contributing factor to the decline of several procellariid and hydrobatid species (Ainley et al. 2001, Le Corre et al. 2002, Rodriguez & Rodriguez 2009, Fontaine et al. 2011, Rodriguez et al. 2012b), and our findings further underscore the severity of the threat that anthropogenic light poses to these birds. Annual public participation in the rescue of fledglings downed by lights has resulted in thousands of birds reaching the ocean that would otherwise not have arrived there, and reduction in light use through awareness campaigns has undoubtedly prevented many instances of light-induced mortality (e.g. Ainley et al. 2001, Le Corre et al. 2002, Rodriguez & Rodriguez 2009, Fontaine et al. 2011, Rodriguez et al. 2012b). Methods to reduce overall light output, including attaching shields to bright light sources (which prevents direct upward radiation; Reed et al. 1985) and simply decreasing total light output (King & Gould 1967, Miles et al. 2010), have been shown to reduce total fledgling fallout in local areas. However, in these instances, young Newell's shearwaters were still attracted to areas in which many of the brighter lights were shielded (Reed et al. 1985), and fledgling Manx shearwaters *Puffinus puffinus* were still attracted when most lights were turned off or shielded during a period of very diminished moonlight, suggesting that certain species are still attracted to very weak lighting (Miles et al. 2010). Although rescue efforts for downed fledglings appear to save many birds annually, it is estimated that some birds still perish due to fallout because they are never found (Ainley et al. 2001). Furthermore, it is unknown whether the experience of fallout leaves rescued fledglings unscathed enough to survive their first few weeks of pelagic life (Ainley et al. 2001, Le Corre et al. 2002, Rodriguez & Rodriguez 2009, Rodriguez et al. 2012a). Thus, while the continuation of these rescue and light reduction efforts is crucial, populations could still be declining due to the effects of anthropogenic light despite these measures, albeit at a slower rate.

Rescue of downed seabirds accompanied by reduction in artificial light output, though clearly important, may not be the ultimate solution to this problem because long-term recruitment of new breeders to the population could still be hindered by light-induced mortality. Therefore, additional research on light types and intensities that may be associated with decreased fallout may be necessary (Rodriguez & Rodriguez 2009). For example, although some species are apparently attracted to weak lighting (Miles et al. 2010), a threshold of light intensity (below which fledglings may disregard light and safely reach the ocean) could potentially be required for attraction to light to occur, although the possible existence of such a threshold has not been investigated. Perhaps more importantly, manipulating the wavelength of light (i.e. altering its color) could be a promising area of further research. Tropical shearwaters (also known as Baillon's shearwaters *Puffinus lherminieri bailloni*) were less attracted to lights with longer wavelengths (i.e. red and yellow) than to green or blue lights (see Salamolard et al. 2007). King & Gould (1967) also reported that no Newell's shearwater fledglings were downed after bright white ground lights were replaced by subdued colored lights at a particular location on Kauai in the 1960s. Furthermore, altering the wavelength of light significantly reduced the impact of light on the behavior of other avian groups (i.e. fewer nocturnally migrating passerines were affected by shorter wavelengths, i.e. green and blue light, relative to white light or light with longer wavelengths; Poot et al. 2008). Given the results of our study and previous fallout research, studies further investigating the effects of light wavelength and/or intensity on fallout may be an important next step in the conservation of these birds.

CONCLUSION

In Hawaii, watersheds of the northern and northwestern portions of Kauai hold the majority of known Newell's shearwater breeding sites, and the northern shore of Kauai receives the highest volume of flight activity (Day & Cooper 1995), as further demonstrated by the disproportionately high numbers of fledglings recovered in fallout sector 2 relative to other sectors and to our model predictions. Thus, our results have important conservation value in the Hawaiian Islands because focusing light mitigation strategies on the northern shore of Kauai will likely have the greatest benefit for the highest number of fledglings. Although only 1 species was examined in this study, the general similarity of the fallout phenomenon in other locations and the close relatedness of many species affected by fallout both suggest that our findings are likely relevant to many of the shearwaters, petrels, and storm-petrels that are attracted to artificial light in other parts of the world. Therefore, the results of this study are also important for shearwater and petrel conservation worldwide because they provide evidence for the locations of fledgling attraction to light and further highlight the severity of this phenomenon by demonstrating that fledglings may indeed be attracted to land from the ocean on an island-wide scale versus only a few isolated occurrences of previously rescued individuals being recaptured. It seems doubtful that nocturnal light use will ever be fully eliminated on islands during the fledging seasons of these long-lived seabirds, and without additional research, a comprehensive understanding of the relationship between the various forms of visible light and seabird attraction may elude us. Therefore, in addition to shielding light sources, reducing total light use, and increasing public involvement in assisting downed fledglings (all of which are necessary at this time), studies investigating the intensities and types of light that are potentially useful for human purposes and safe for fledgling seabirds may be crucial. The more that is known about the mechanics of seabird attraction to light, the greater the likelihood that conservation biologists can influence government officials and citizens to initiate measures that will further reduce or eliminate the detrimental effects of anthropogenic light on these charismatic animals.

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LITERATURE CITED

Ainley DG, Podolsky R, Deforest L, Spencer G, Nur N (2001) The status and population trends of the Newell's shearwater on Kauai: insights from modeling. Stud Avian Biol 22:108–123

Cinzano P, Falchi F, Elvidge CD (2001) The first world atlas of the artificial night sky brightness. Mon Not R Astron Soc 328:689–707

Day RH, Cooper BA (1995) Patterns of movement of dark-rumped petrels and Newell's shearwaters on Kauai. Condor 97:1011–1027

Dick MH, Donaldson W (1978) Fishing vessel endangered

by crested auklet landings. Condor 80:235–236
Elvidge CD, Cinzano P, Pettit DR, Arvensen J and others (2007) The Nightsat mission concept. Int J Remote Sens 28:2645–2670
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. Biol Conserv 144: 1998–2011
Griesemer AM, Holmes ND (2011) Newell's shearwater population modeling for habitat conservation plan and recovery planning. Tech Rep 176. The Hawaii Pacific Island Cooperative Ecosystem Studies Unit and Pacific Cooperative Studies Unit, Honolulu, HI
Harrow G (1965) Preliminary report on discovery of nesting site of Hutton's shearwater. Notornis 12:59–65
Imber MJ (1975) Behaviour of petrels in relation to the moon and artificial lights. Notornis 22:302–306
IUCN (International Union for Conservation of Nature) (2012) The IUCN Red List of Threatened Species. Version 2012.1. Available at www.iucnredlist.org
King WB, Gould PJ (1967) The status of Newell's race of the Manx shearwater. Living Bird 6:163–186
Kyba CCM, Ruhtz T, Fischer J, Hölker F (2011) Cloud coverage acts as an amplifier for ecological light pollution in urban ecosystems. PLoS ONE 6:e17307
Le Corre M, Ollivier A, Ribes S, Jouventin P (2002) Light-induced mortality of petrels: a 4-year study from Reunion Island (Indian Ocean). Biol Conserv 105:93–102
Longcore T, Rich C (2004) Ecological light pollution. Front Ecol Environ 2:191–198
Manly BFJ (2007) Randomization, bootstrap and Monte Carlo methods in biology, 3rd edn. Chapman & Hall/ CRC Press, Boca Raton, FL
Miles W, Money S, Luxmoore R, Furness RW (2010) Effects of artificial lights and moonlight on petrels at St. Kilda. Bird Study 57:244–251
Montevecchi WA (2006) Influences of artificial light on marine birds. In: Rich C, Longcore T (eds) Ecological consequences of artificial night lighting. Island Press, Washington, DC, p 94–113
Podolsky R, Ainley DG, Spencer G, Deforest L, Nur N (1998) Mortality of Newell's shearwaters caused by collisions with urban structures on Kauai. Colon Waterbirds 21: 20–34
Poot H, Ens BJ, de Vries H, Donners MAH, Wernand MR, Marquenie JM (2008) Green light for nocturnally migrating birds. Ecol Soc 13:47
R Development Core Team (2012) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Available at www.R-project.org
Rauzon MJ (1991) Save our shearwaters! Living Bird Q 10: 28–32
Reed JR, Sincock JL, Hailman JP (1985) Light attraction in endangered procellariiform birds: reduction by shielding upward radiation. Auk 102:377–383
Rodrigues P, Aubrecht C, Gil A, Longcore T, Elvidge C (2012) Remote sensing to map influence of light pollution on Cory's shearwater in Sao Miguel Island, Azores Archipelago. Eur J Wildl Res 58:147–155
Rodriguez A, Rodriguez B (2009) Attraction of petrels to artificial lights on the Canary Islands: effects of the moon phase and age class. Ibis 151:299–310
Rodriguez A, Rodriguez B, Curbelo AJ, Perez A, Marrero S, Negro JJ (2012a) Factors affecting mortality of shearwaters stranded by light pollution. Anim Conserv 15: 519–526
Rodriguez A, Rodriguez B, Lucas MP (2012b) Trends in numbers of petrels attracted to artificial lights suggest population declines in Tenerife, Canary Islands. Ibis 154: 167–172
Salamolard M, Ghestemme T, Couzi F, 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 78: 449–452
Telfer TC, Sincock JL, Byrd GV, Reed JR (1987) Attraction of Hawaiian seabirds to lights: conservation efforts and effects of moon phase. Wildl Soc Bull 15:406–413
Troy JR, Holmes ND, Green MC (2011) Modeling artificial light viewed by fledgling seabirds. Ecosphere 2:art109, doi:10.1890/ES11-00094.1
Wiese FK, Montevecchi WA, Davoren GK, Huettmann F, Diamond AW, Linke J (2001) Seabirds at risk around offshore oil platforms in the North-west Atlantic. Mar Pollut Bull 42:1285–1290

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