The following supplements accompany the article

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

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Supplement 1. Detailed hypothetical model descriptions

Sector area model

Expected numbers from this model were based only on the 2-dimensional surface area of each fallout sector. This model tested the hypothesis that greater numbers of birds are observed in larger fallout sectors, regardless of the geographical coverage of light sources, light intensity being emitted by light sources, or how distance from light sources to birds could potentially affect the probability of attraction. A proportion of the total area of Kauai covered by all fallout sectors was calculated for each sector and multiplied by the observed total fallout under the 2 modeling scenarios, i.e. with (n = 3175) and without (n = 2130) the inclusion of fallout sector 2.

Light area model

Expected numbers from this model were based only on the 2-dimensional surface area of the lighted portion of each fallout sector. This model tested the hypothesis that greater numbers of birds are grounded by artificial light in fallout sectors containing a greater coverage of lighted terrain (regardless of the light intensity being emitted by light sources within sectors or how distance between light sources and birds could potentially affect the probability of attraction). A proportion of the total lighted area within all fallout sectors was calculated for each sector and multiplied by the observed total fallout under the 2 modeling scenarios, i.e. with (n = 3175) and without (n = 2130) the inclusion of fallout sector 2.

Light intensity model

Expected numbers from this model were based only on the mean value of 2009 artificial light within fallout sectors, a value calculated only from lighted portions of fallout sectors; dark pixels were not included in the calculation. This model tested the hypothesis that birds are attracted to sectors with a greater mean intensity of artificial light, regardless of the location on the island from which particular birds originated (i.e. their natal sites); thus, this model contains some general assumptions pertaining to fledgling movement that are described in the 'Discussion' in the main text. Additionally, this model did not account for how distance between light sources and birds could potentially affect the probability of attraction. A proportion of the total light intensity within all fallout sectors was calculated for each fallout sector and multiplied by the observed total fallout under the 2 modeling scenarios, i.e. with (n = 3175) and without (n = 2130) the inclusion of fallout sector 2.

Stationary model

This model assumed that birds could only be attracted by artificial light viewed from, or from the air above, known Newell's shearwater (hereafter simply 'shearwater') activity sites, which were assumed to be their natal sites. The Kauai Endangered Seabird Recovery Project provided a shapefile of the estimated boundaries of these sites (see Supplement 2 for treatment of this shapefile). Expected numbers from this model were based on several factors, beginning with the 2-dimensional surface area of all known shearwater activity sites viewable from the lighted portions of each fallout sector. An assumption of this measure was that this surface area positively correlated with the number of breeding shearwaters and, therefore, with the number of fledglings available to be attracted to fallout sectors. If a shearwater site fully or partially overlapped with a viewshed, suggesting that at least some of the site could be viewed, then the entire 2-dimensional area for that site was factored into the expected number calculation for that fallout sector. This accounted for the possibility that young shearwaters may circle their natal colony aloft before departing, in which case a fledgling taking flight from any part of a breeding site could view light emanating from that sector.

To calculate the overall weight for each fallout sector, the 2-dimensional surface area of each shearwater site that could be viewed from the lighted portion of that fallout sector was divided by the mean distance from that shearwater site to the nearest boundary of the lighted portion of that sector (based on 2-dimensional surface area). For each sector, these values were then summed and the summed value was multiplied by the mean intensity of artificial light emanating from that sector to obtain the overall weight for that sector. A proportion of the total for all fallout sectors was then calculated for each sector and multiplied by the observed island-wide fallout under the 2 modeling scenarios, i.e. with (n = 3175) and without (n = 2130) the inclusion of fallout sector 2.

Many areas of Kauai, including some shearwater activity sites, were viewable from the lighted portions of more than one fallout sector. Accounting for the distance from shearwater sites to lighted portions of sectors, as well as the mean artificial light intensity within those sectors, appropriately weighted the calculations of expected numbers for each sector, relative to one another. Both of these measures accounted for instances in which lights from more than one fallout sector were viewed from a single shearwater site (i.e. when a certain site was viewed by lighted portions of more than one fallout sector) by directly relating to the likelihood that birds could be attracted from that site to each sector.

Island movement model

Expected numbers of fallout birds calculated from this model were based on several factors and assumptions. As adult shearwaters likely follow topographic depressions such as river valleys to reach the ocean (Telfer et al. 1987, Podolsky et al. 1998), these models assumed that fledglings fly topographically least-cost paths (i.e. following depressions such as watersheds) to the sea. To simulate downhill movement, watershed boundaries were redefined to be equal to or lower in elevation than the highest elevation pixel from a shearwater site within that watershed (see Supplement 2 for details). Another assumption was that the proportion of the redefined watershed area viewable from the lighted portion of a particular fallout sector was positively correlated with the likelihood that fledglings from that watershed would be attracted to arrive in that sector; this was a less analytically intensive surrogate measure for the lighted portions of each fallout sector viewable from every location that a fledgling could visit on its flight to the coastline. Under this assumption, birds from known shearwater sites could view light emanating from fallout sectors, but only from portions of sites viewable from the lighted portions of each sector. This differed slightly from the stationary model, which assumed that birds could view light from an entire activity site, whether that site overlapped fully or only partially with a fallout sector viewshed. However, the area of shearwater activity sites viewable from a particular fallout sector is likely to be substantially smaller than the area of a watershed viewable from that sector, and, therefore, the island movement model builds upon the stationary model because it accounts for light that can be viewed from shearwater sites, as well as light potentially viewed by birds as they travel to the coastline.

To calculate the overall weight for each fallout sector from this model, weights for each redefined watershed were first calculated. The total shearwater site area within that watershed was multiplied by the proportion of that watershed viewable from the lighted portion of each fallout sector and then divided by the mean 2-dimensional distance from all viewable pixels within the watershed to the nearest boundary of the lighted portion of that sector. For each fallout sector, these watershed weights were then summed, and this summed value was multiplied by the mean intensity of artificial light emanating from that sector. Accounting for mean distance and artificial light intensity in this manner appropriately weighted calculations of expected numbers of fledglings for each fallout sector, relative to one another, in the event that a particular location in a watershed was viewable from more than one sector. A proportion of the total for all fallout sectors was then calculated for each fallout sector and multiplied by the observed island-wide fallout under the 2 modeling scenarios, i.e. with (n = 3175) and without (n = 2130) the inclusion of fallout sector 2.

Ocean movement models

Like the island movement model, expected numbers of fallout birds calculated from these models were based on several factors and assumptions. Each model extended the island movement model out to 1 of 3 distances beyond the watershed coastline (which allowed birds to view light from the ocean and potentially be attracted back to land). The distance categories of ocean regions were 0–1, 1–5, and 5–10 km in all directions from the coastline and only included areas of ocean surface (see Supplement 2). The assumptions of the land-based portion of each of these models were the same as those of the island movement model, with the additional assumptions that birds were allowed to fly any direction from the coastline (as long as they remained over the ocean) and that the proportion of an ocean region viewable from the lighted portion of a particular fallout sector was positively correlated with the likelihood that fledglings from that ocean region would be attracted to that sector.

Calculating expected numbers from each of these models required multiple steps. For each redefined watershed, the proportion of that watershed viewable from the lighted portion of each fallout sector was divided by the mean 2-dimensional distance from all viewable pixels (within the watershed) to the nearest boundary of the lighted portion of that sector to calculate a watershed weight. Likewise, the proportion of each ocean region viewable from the lighted portion of each fallout sector was divided by the mean 2-dimensional distance from all viewable pixels within the ocean region to the nearest boundary of the lighted portion of that sector to calculate a weight for that region. The watershed weights were added to the weights for the individual ocean region(s) of interest before being multiplied by the shearwater site area within the watershed, ensuring that ocean movement model weights were additive in the calculation. For example, in the ocean movement model extending to 10 km past the coastline, the watershed weight was added to the weight for each of the 3 ocean regions. The total 2-dimensional area of shearwater activity sites within the watershed was then multiplied by this additive weight. For each fallout sector, these values were then summed, and the summed value was multiplied by the mean intensity of artificial light emanating from that sector. A proportion of the total for all fallout sectors was then calculated for each fallout sector and multiplied by the observed island-wide fallout under the

2 modeling scenarios, i.e. with (n = 3175) and without (n = 2130) the inclusion of fallout sector 2.

Calculating weights in this additive manner was appropriate for dark watersheds (those from which no light can be viewed) that led into regions of ocean from which light could be viewed. Likewise, it appropriately weighted watersheds from which light could be viewed that led into ocean regions from which light could not be viewed. Additionally, when light could be viewed from the major portion of a watershed that led into one or more ocean regions from which light could also be viewed, a total weighted value >1 was produced, which inflated the value of shearwater site area within that watershed. However, these weights were used to calculate a proportion of the island-wide total fallout for all fallout sectors and, thus, were ultimately relative. Therefore, watersheds with weighted values >1 were appropriately weighted because birds from those watersheds who could view light from both the watershed and its associated ocean regions were hypothesized to be more likely affected by light (and attracted to a particular fallout sector) than birds traveling through more space from which light could not be viewed.

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Supplement 2. Methods for development of GIS layers for pixel summaries and calculation of expected numbers from the hypothetical models

Overview

Layers containing polygons (representing the 2-dimensional boundaries of Newell's shearwater activity sites, watersheds, and regions of ocean) were used and developed in this study so that pixel summaries within the boundaries of these polygon features could be performed. The values generated from these pixel summaries were then used to weight calculations of expected numbers within fallout sectors under different hypothetical models.

Newell's shearwater activity sites

The Kauai Endangered Seabird Recovery Project provided a shapefile containing polygons of Newell's shearwater (hereafter simply 'shearwater') sites of activity on Kauai. After deletion of redundant polygons, 59 shearwater site polygons were available for analysis. We used the 'Add AREA/PERIMETER Fields to Table' tool in Hawth's Analysis Tools (Beyer 2004) to calculate the 2-dimensional surface area of each site polygon, and these values were used as the basis for calculating expected numbers in our stationary, island movement, and ocean movement models.

Viewshed layer development

A shapefile of Kauai fallout sectors was obtained from the Save Our Shearwaters program (Hawaii Division of Forestry and Wildlife). A copy of the fallout sector shapefile was clipped by a shapefile of Kauai representing areas with no artificial light cover from 2009, so that the area of the clipped fallout sectors matched that of artificial light cover within the sector. The original large pixel size of the night light layer (911.25 × 911.25 m) resulted in some light-clipped fallout sectors containing small sector sections very near the coastline that were separated from the main fallout sector polygon. Because these polygons overlapped with regions of no light, they were trimmed from the main fallout sector polygon. Small regions of the main fallout sector polygon not in overlap with light (because of the manner in which the layer was clipped) were not trimmed and remained as part of the main polygon; contributions of these small regions to viewsheds were likely negligible.

To aid in estimating how shearwater fledglings may have arrived in particular fallout sectors (i.e. from what locations fledglings are attracted by light such that birds are downed in particular sectors), viewshed analyses were conducted from the perimeter of each light-clipped fallout sector to establish which locations on the island could be viewed from the lighted portion of each sector. Conducting viewsheds in this manner therefore results in an estimation of the locations on this island from which lights in particular fallout sectors could be viewed. A previous study estimated that adult shearwaters on Kauai flew at a mean height of 125 m (with a range of 8 to 750 m) above ground level with considerable variation among sites (Day & Cooper 1995). Therefore, each light-clipped fallout sector polygon was converted to a polyline outlining the light-clipped fallout sector perimeter, and this polyline was raised to 100 m above ground level (a general approximation of 125 m). A viewshed was then conducted from each raised perimeter to simulate birds viewing light emanating from each fallout sector from a realistic flight height.

The resulting output viewshed layers for each fallout sector, which were composed of pixels, were reclassified using the 'Reclassify' tool such that all pixels viewable from the light-clipped fallout sector perimeter had a value of 1 and all pixels not viewable had a value of 0. A digital elevation model (DEM) of Kauai extended to 10 km past the coastline was used as input for the viewshed analyses so that regions of ocean within 10 km of the coastline viewable from each fallout sector were highlighted; see the Appendix in Troy et al. (2011) for details concerning the development of such an extended DEM. Curvature of the earth was accounted for in viewshed analyses with a refractory coefficient of 0.13.

Watersheds redefined by elevation for the island movement model

A copy of the extended 10 km DEM of Kauai was reclassified such that, within watersheds containing known shearwater activity sites, pixels higher in elevation than the highest elevation pixel within activity sites were converted to values of 0, while all elevation values equal to or lower in elevation than that highest elevation pixel were converted to values of 1. Elevation pixels within watersheds containing no activity sites were all reclassified to values of 1. To reclassify the DEM in this watershed-specific manner, each individual watershed was first saved as a shapefile. The DEM was then reclassified once for each watershed containing one or more known shearwater activity sites (n = 14), masking the reclassification by the watershed of interest. This masking resulted in individual DEMs for each of these 14 watersheds. For each of these DEMs, values of 0 were converted to shapefiles; these shapefiles were pasted into a new shapefile containing no features, and all of these polygons were joined into a single polygon. This joined polygon was then used to clip a copy of the original watershed layer. This clipped (redefined) watershed layer was then used in summaries of pixels for the island movement model and ocean movement models. Redefining watershed boundaries by elevation in this manner corresponds to an assumption that fledglings fly least-cost downhill paths (following topographical depressions such as watersheds) to the ocean (Telfer et al. 1987, Podolsky et al. 1998, Troy et al. 2011), ensuring that areas within watersheds higher in elevation than known shearwater activity sites did not factor into calculations of the proportion of watersheds viewable from lighted portions of fallout sectors or mean 2-dimensional distance from those viewable areas to those sectors.

Ocean region polygons for the ocean movement models

Our ocean movement models incorporated regions of ocean 0–1, 1–5, and 5–10 km past the coastline to the island movement model. Ocean polygons actually developed for these distances were generated as 0–1, 0–5, and 0–10 km, and pixel summaries from these polygons were then used to calculate summary values for the 0–1, 1–5, and 5–10 km distance categories. To develop these ocean polygons, a copy of the watershed shapefile was generated, and all individual watershed polygons within that layer were dissolved so that only 1 polygon (that of the island boundary) remained. This polygon layer was then converted to a polyline layer representing the coastline of Kauai. Each individual watershed from the original watershed layer was then exported as an individual layer, and each watershed was used to clip the coastline layer. This resulted in individual polyline coastline layers for each watershed. These watershed coastlines were then merged into a single layer containing each watershed coastline using the 'Merge (Data Management)' tool. A buffer layer for each ocean distance category (0–1, 0–5, and 0–10 km) was then produced using the 'Buffer' tool with the new watershed coastline layer as input. This resulted in a layer containing a buffer of 0–1, 0–5, or 0–10 km from the coastline of each watershed. Because buffers are generated out to a specified distance in all directions from a feature, these buffers not only extended out to the ocean, but extended inland as well. Therefore, the buffers were clipped by the polygon of the boundary of Kauai (the layer produced by merging the watersheds) so that the buffers only covered regions of ocean. All buffers from the same distance category were then joined into a single layer (resulting in 3 ocean buffer layers). These buffers were used to calculate the proportion of ocean viewable from the lighted portion of each fallout sector on the island, as well as the mean 2-dimensional distance from the viewable pixels within each ocean buffer to the lighted portion of each of those sectors.

Distance from viewable pixels to lighted portions of fallout sectors

Artificial light varied among fallout sectors in proportion of the sector covered. The 'Euclidean Distance' tool was used to calculate the 2-dimensional distance from the lighted portion of each fallout sector (i.e. from each light-clipped fallout sector polygon) to every 10 x 10 m DEM pixel on the island, as well as those extending to 10 km past the coastline. This was accomplished by expanding the output extent of the 'Euclidean Distance' tool to the boundary of a 10 km extended DEM of Kauai. A polygon layer was developed from the 10 km extended DEM (using the 'Raster to Polygon' tool with the 'Simplify Polygon' box left unchecked) so that the 10 km boundary could be used to clip the Euclidean distance outputs from each of the fallout sectors. Values of mean Euclidean distance were calculated only for pixels viewable from each light-clipped fallout sector, and these distances were used to weight values of shearwater activity site area. Because weighting involved dividing values of shearwater area by values of mean distance, values of 0 from the Euclidean distance layers were converted to values of 1 using a 'Con' statement in the 'Raster Calculator.' Each fallout sector distance layer was then multiplied by its corresponding reclassified fallout sector viewshed layer (composed of values of either 0 or 1) so that pixels not viewable from the fallout sector had distance values of 0 and only those pixels that were viewable from the fallout sector retained their original distance values.

Pixel summaries for hypothetical models

The proportion of pixels within each redefined watershed and ocean region viewable from the lighted portion of each fallout sector was calculated using output from the 'Thematic Raster Summary' tool (Beyer 2004), a tool that provides a total count of pixels with discrete values (e.g. viewable and non-viewable) within the boundaries of a polygon. A combination of techniques was used to calculate the mean distance from only the viewable pixels within watersheds and ocean regions to the lighted portion of each fallout sector. First, the value of total distance (i.e. the sum of all distance pixels) within each redefined watershed and ocean region polygon was obtained using the 'Zonal Statistics ++' tool (Beyer 2004). Second, this value was divided by the count of viewable pixels obtained from the thematic raster summary. Three types of ocean regions (0–1, 0–5, and 0–10 km from each watershed coastline) were developed and used in pixel summaries. For ocean regions, values for only 0–1, 1–5, and 5–10 km past the coastline were obtained by subtracting values obtained for the region closer to the coastline from those of the region farther from the coastline (e.g. values for the 0–1 km region were subtracted from values for the 0–5 km region). Values equal to these could also have been achieved using ocean regions that were clipped to those preferred sizes before pixel summaries were generated (i.e. using ocean buffers 0–1, 1–5, and 5–10 km in size for pixel summaries).

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