WEDGE-TAILED SHEARWATER *ARDENNA PACIFICA* FALLOUT PATTERNS INFORM TARGETED MANAGEMENT

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ABSTRACT

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Seabird fledglings are often attracted to artificial, bright lights, leading to their grounding. This phenomenon is termed "fallout" and is associated with an increased risk of mortality from land-based threats. This study evaluated temporal trends and spatial factors, such as fallout clustering near lights and proximity to colonies, to inform targeted management actions. Standardized surveys were conducted from 2002 to 2010 for Wedge-tailed Shearwater *Ardenna pacifica* (WTSH) fallout on the island of O'ahu, Hawai'i, USA. First, yearly fallout counts along the transect showed a two-year cycle and identified 25 November as the date with the highest fallout across years. Second, artificial lights and utility lines were present in 94% and 83% of fallout locations, leading to significantly higher fallout rates at these locations compared to random points along the transect. Third, fallout decreased significantly as the distance from the colonies increased and was negligible farther than 5 km from the nearest colony. Overall, 60% of all fallout occurred along a 1.7 km section of the survey route, with 27% of this fallout occurring within 8 m of two light poles, highlighting the need for targeted management. Finally, the disposition outcomes of rescued shearwaters from non-fatal fallout were analyzed. Among grounded individuals that were recovered alive, 78% were admitted for rehabilitation with no injury and released. This suggests that rescue efforts during high-risk periods that are focused within 5 km of colonies, in fallout hot spots, are likely to enhance survival. Because little is known about the environmental drivers of WTSH fallout, our results specify when, where, and how targeted management could be used most effectively to reduce fallout on O'ahu. Our targeted approach may be applied in other regions where seabird fledging is heavily impacted by artificial lights.

Key words: fallout, light pollution, fledging, procellariiformes, targeted management, Wedge-tailed Shearwater, seabirds

INTRODUCTION

In the era of the Anthropocene, some innate behaviors, such as an attraction to light, reduce seabird survival in human-modified landscapes (Telfer *et al*. 1987, Le Corre *et al*. 2002, Rodriguez & Rodriguez 2009, Rodriguez *et al*. 2017b). The attraction to light often leads some seabird species toward human structures on land or at sea (see Imber 1975, Montevecchi 2006, Atchoi *et al.* 2020 for theories regarding light attraction in seabirds). This phenomenon is most prevalent when chicks take first flight from their natal colony, where some fly toward artificial lights onshore, rather than dispersing to the sea (Troy *et al*. 2011, Rodriguez *et al*. 2015b, 2017a). These individuals may eventually fall to the ground due to exhaustion or collisions with obstacles in an event referred to as "fallout" (Telfer *et al*. 1987).

Once grounded, car strikes and predation by introduced mammalian predators, including domesticated dogs and cats, are the main causes of injury and death. Grounded birds can also sustain injury from the initial impact and dehydration (Ainley *et al*. 2001, Smith *et al*. 2002, Rodriquez *et al.* 2014, Deppe *et al.* 2017). Additional land-based threats include strikes with physical structures such as utility lines, which may be more difficult to see in the evening (Cooper & Day 1998). High winds and weather events may increase the likelihood of light-induced fallout (Work & Rameyer 1999; Rodriguez *et al*. 2014, 2015b; Syposz *et al*. 2018), and the phase of the moon can also have an impact, with fallout increasing during moonless nights or nights with low lunar illumination (Telfer *et al*. 1987, Ainley *et al*. 2001, Le Corre *et al*. 2002, Rodriguez & Rodriguez 2009).

Seabirds are among the most endangered group of birds globally (Croxall *et al.* 2012, Dias *et al*. 2019). At least 56 species of seabirds in the order procellariiformes are subject to grounding from artificial lights, making them the group of seabirds most affected by this phenomenon (Rodriguez *et al.* 2017c). The vulnerability of highly threatened procellariiformes to light pollution requires novel approaches to reduce the magnitude of fallout and increase the survivorship of grounded birds. Several risk factors associated with coastal development can increase seabird fallout and mortality. The proximity of artificial lighting to colonies (Rodriguez *et al*. 2015a), particularly when lights are unshielded or generate certain wavelengths, can increase fallout (Reed *et al*. 1985, Rich & Longcore 2013, Rodriguez *et al*. 2017c, Longcore *et al*. 2018). However, seabirds fledging from "dark" colonies without a direct line of sight to artificial lighting may still be impacted if they encounter artificial lights post-fledging (Troy *et al*. 2011, 2013; Rodriguez *et al.* 2015b).

The Wedge-tailed Shearwater *Ardenna pacifica* (WTSH, ‘Ua‘u Kani) occurs throughout the Hawaiian archipelago (Hawai‘i Natural Heritage Program 2004). WTSH are one of the most abundant seabirds breeding in the Main Hawaiian Islands with an estimated 87 825 pairs (Pyle & Pyle 2017). On O‘ahu, they nest on islets offshore and less abundantly along the shoreline, with many of their current colonies protected from predators (USFWS 2005). They play an important role in coastal ecosystems in Hawai‘i, as their guano is a source of nutrients for coastal vegetation and coral reefs (Honig & Mahoney 2016). Because WTSH nest near developed areas on the island of O‘ahu, Hawai‘i, which has one of the highest light intensity values on the entire planet (Troy *et al*. 2013), they are an ideal model species for examining the relative impact of different factors on fallout, and how targeted management of light pollution, coastal structures, and rescue campaigns could mitigate mortality. WTSH chicks fledge from the Hawaiian Islands in early November to late December (Whittow 1997), when hundreds of birds become grounded on O‘ahu (Work & Rameyer 1999). WTSH represented 96% of all seabirds delivered to the Sea Life Park (SLP) rehabilitation center during the period 1999–2003 (unpublished data), likely due to their high relative abundance.

This study evaluated WTSH fallout in southeast O‘ahu. Nine years (2002–2010) of systematic surveys along a coastal highway near several WTSH colonies were analyzed to evaluate the spatial distribution of fallout (compared against random points). Results were modeled to ascertain the potential influence of proximity to colonies and the aggregation of urban light poles and utility lines on spatial fallout patterns. Records of grounded and rescued WTSH from a local rehabilitation center were also analyzed that included the relative condition of fallout birds and their potential for release. Based on previous studies, we predicted that fallout locations would be more abundant near colonies and would be significantly associated with light poles and utility lines. Finally, we used our findings to make recommendations for targeted management actions to reduce fallout and increase the survival of grounded WTSH in Hawai‘i.

METHODS

Study area

The majority of WTSH nesting colonies on O‘ahu occur at small islets located off the southeast coastline of the island (Fig. 1A); five colonies occur within our study area: Manana (32 930 nesting pairs, np), Kaohikaipu (649 np), Popoia (669 np), Mokulua Nui and Mokulua Iki (8968 combined np), and Freeman Seabird Preserve (mainland O‘ahu; 313 np). These abundance estimates are based on systematic surveys conducted by the Hawai‘i Division of Forestry and Wildlife (DOFAW), Pacific Rim Conservation, Hawai‘i Audubon Society, and Pyle & Pyle (2017; Fig. 1A).

The south-central region of O‘ahu is highly developed, with high-density residential, commercial, and street lights (Fig. 1A). The study area, spanning the windward and leeward shores of the southeastern region of the island, encompassed a mixture of urbanized and residential areas with light poles along a coastal highway. Included is a beach park with a sports field containing stadium lights, and an entertainment park with flood and stadium lighting (Fig. 1A, B). Throughout this paper, the term “light poles” refers predominantly to street lights affixed to utility poles and includes a small number (< 1%) of beach park and bathroom lights using halogen bulbs, and two stadium floodlights in a sports field (not consistently illuminated). Not all locations along the transect that contained light poles also contained utility lines and vice versa, and there were stretches of roadway that contained neither. The streetlights were fully unshielded (not full cut off) and emitted light in an omnidirectional pattern for 360 degrees in the horizontal plane. They also emitted light above the horizontal plane (i.e., were visible above the elevation of the light bulb). The street lights used high-pressure sodium bulbs that produced light at a characteristic wavelength near 589 nm, a correlated color temperature of ~2200 Kelvin, and a color rendering index of ~25 (Iwai *et al*. 1977).

Road surveys for fallout detection

Systematic road surveys were conducted from a vehicle to map fallout along a 25.7-km transect of the Kalaniana‘ole Highway

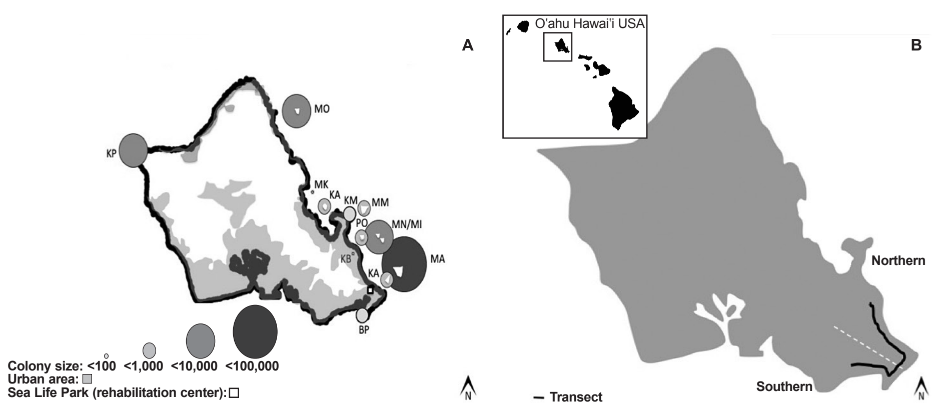

Fig. 1. (A) Wedge-tailed Shearwater (WTSH) colony sizes across O‘ahu. Colony size based on nest surveys of the number of occupied burrows obtained from the Division of Forestry and Wildlife (2018 survey), Freeman Seabird Preserve (2019 survey), Kāne‘ohe Marine Corps Base (2018 survey), Pacific Rim Conservation (2018 survey), and Pyle & Pyle (2017). Colony ID’s; KP: Ka‘ena Point; PO: Popoia; MN/MI: Mokulua Nui and Mokolua Iki; MA: Manana; BP: Black Point; KB: Kailua Beach Park; KM: Kāne‘ohe Marine Corps Base; MM: Moku Manu; MO: Moku‘aia; KA: Kapapa; MK: Mokoli‘i. Urbanized area projections were obtained from NOAA (2009) and are indicated with grey shading. The location of Sea Life Park (WTSH rehabilitation center) is indicated with a black square. (B) Survey route with transect across southeastern O‘ahu, Hawai‘i, USA designating the northern and southern regions of the transect. Transect length = 25.7 km.

(State Route 72). Vehicle surveys were conducted approximately every three days during the fledging season (mid/early November to late December) 2002–2010. Each survey was initiated at about dawn and consisted of an out-and-back trip along the controlled intersection of Ainakoa Avenue, Waikui Street, Lunalilo (H1) Freeway, and Kalaniana'ole Highway in Honolulu. The eastern terminus of the Ko'olau Mountains divides the northern and southern portions of the transect (Fig. 1B), where 98% of all surveys were conducted by the same observer (K. Swindle). On several surveys, one additional observer was present, primarily as a note-taker. Posted speed limits along the route were 20–45 mph, however, survey speeds typically ranged 25–35 mph.

The survey was limited to the roadway and areas immediately adjacent (≤ 4 m), such as paved or graveled road shoulders, sidewalks (when present), and mowed areas between the road and vehicular guardrails (when present), with the inclusion of one beach park parking lot. Visual barriers such as unmanaged tall vegetation, walls, fences, or structures associated with housing bounded the majority of the survey route. WTSH, being relatively large, are easily observed on or adjacent to paved roadways, including days-old carcasses flattened by repeated traffic, sometimes represented by single contour feathers stuck to the roadway. Fallout that was not visible from the road was not detected; therefore, the number of fallout birds documented by these surveys did not represent the totality of fallout likely to have occurred along the survey route. The WTSH that were collected included live grounded birds (11%) and carcasses (89%) (Table 1). All grounded WTSH were assumed to be the result of fallout. Carcasses were removed after each survey and living birds were transported to a nearby rehabilitation center. Only surveys with at least one fallout detection were used in this analysis. The latitude and longitude of each bird found were recorded with a Garmin GPS III Plus or Garmin GPS 76; digital photographs of locations, surroundings, and grounded specimens were taken.

Fallout survey data and random point generation

The relative proximity of fallout locations (n = 376) versus randomly generated points (n = 250) to light poles and utility lines were compared by plotting their GPS locations along the digitized transect using ArcGIS (ArcMap 10.4, ESRI) and by measuring distances to light poles using Google Earth (2018), and photogrammetry from digital images taken at fallout locations. To match the survey constraints of fallout locations, the random points were similarly constrained to be ≤ 4 m from the roadway by using a constraining extant parameter. Using these methods, we determined if light poles or utility lines were present within 8 m of the observed fallout locations and the random points. The occurrence (presence/absence) of light poles and utility lines adjacent to the fallout locations and random points were compared independently using chi-squared tests (Pearson 1900) three categories: light poles present, utility lines present, or none present.

Data analysis

All data summaries and analyses were performed using R version 3.3.2 (R Core Team 2016) and R Studio (R Studio Team 2015) with significance assessed using α = 0.05. All GIS analyses and maps were created using ArcGIS®, ArcGIS Pro®, and ArcMap™ software by ESRI Version 10.4.

TABLE 1
Summary of systematic road surveys for Wedge-tailed Shearwater (WTSH) fallout detection

Year[a]	# Surveys with fallout	# Fallout discovered	# Birds alive, (%)	Earliest date of discovery	Latest date of discovery
2002	4	35	1 (2.8)	04 Dec	24 Dec
2003	8	42	4 (9.5)	17 Nov	04 Dec
2004	11	25	1 (4.0)	17 Nov	24 Dec
2005	14	55	0 (0)	14 Nov	22 Dec
2006	6	9	0 (0)	14 Nov	14 Dec
2007	15	76	9 (11.8)	07 Nov	17 Dec
2008	10	34	4 (11.8)	16 Nov	04 Dec
2009	14	91	24 (26.4)	18 Nov	28 Dec
2010	5	29	0 (0)	14 Nov	12 Dec
Total	**87**	**396**	**43 (10.9)**	**07 Nov**	**28 Dec**

[a] The 2002 start date began later in the fallout season than in subsequent years.

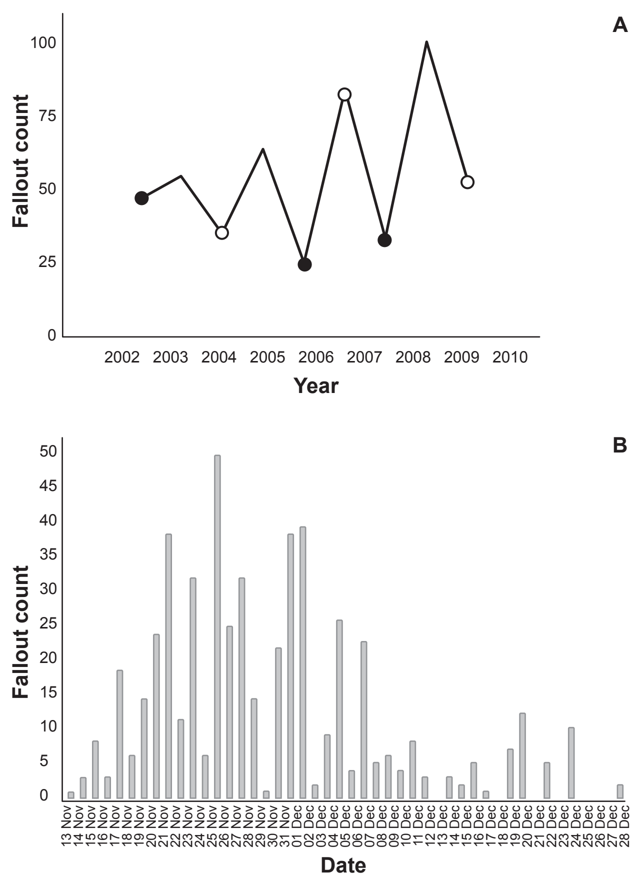

Fig. 2. (A) Count of Wedge-tailed Shearwater (WTSH) fallout along the survey transect from 2002–2010. Open circles indicate years where peak fallout coincided with a full moon (± three days), and closed circles indicate years where peak fallout coincided with a new moon (± three days) (Byrd *et al*. 1983, Rodriguez *et al*. 2012b). (B) Count of WTSH fallout for survey dates pooled for all survey years (2002–2010).

Temporal analysis

The temporal analyses considered two scales: the magnitude of fallout across years and the timing of fallout within years. The yearly totals (WTSH discovered during our road surveys) showed a two-year cycle, with sequentially high and low fallout counts (Fig. 2A). Because we detected a significant negative autocorrelation, we modeled yearly totals as a function of the total from the previous year using simple linear regression. This approach allowed us to test for a one-year lagged response and a linear trend using eight yearly values from 2003 to 2010. To characterize fallout during the fledging season (November–December), fallout observations were pooled across the study period (2002–2010) to depict total counts for each date (Fig. 2B).

Distance tests

The distances from each fallout location and random point to the closest light pole and WTSH colony were calculated using the "near" tool in ArcPro. Binomial generalized linear models (GLM) with a logit link function were employed to compare fallout locations (coded as "1", n = 250) and random points (coded as "0", n = 250) as a function of the distances to the nearest colony (m) and light pole (m). For the GLM's, a subset of 250 of the total 376 fallout locations were randomly chosen to match the sample size of 250 random points; other analyses that were conducted used all 376 fallout locations. Akaike's Information Criterion (AIC) values were used to compare the fit of models with different parameters (Burnham & Anderson 1998).

Hot spot analysis

An optimized hot spot analysis was conducted in ArcGIS Pro using fallout location and light poles as incident points to generate two maps of statistically significant hot spots. The Hot Spot Analysis tool calculates a Getis-Ord Gi* statistic (Getis & Ord. 1992) for every feature in the dataset, and a resulting Z score displays where features with high values cluster spatially. The larger the Z score, the more intense the clustering of high values (hot spot), which is indicated by color. The point data are automatically aggregated using the appropriate scale of analysis while correcting for multiple testing and spatial dependence. Hot spots were generated with 99% confidence.

Clustering analysis

To determine whether WTSH fallout clustered around specific poles, the number of fallout locations within 8 m of each light pole (n = 633) was counted using geoprocessing tools in ArcGIS. A Spatially Constrained Multivariate Clustering analysis was conducted in ArcPro using fallout location as the feature attribute looking for spatially contiguous clusters. Because this spatial analysis is defined by the variable distance, it is constrained using a spatial weights matrix. Additionally, a cluster limit of seven points was selected for the analysis by assessing clustering effectiveness with the Calinski-Harabasz pseudo F-statistic (the ratio of between-cluster variance to within-cluster variance) (Calinski & Harabasz 1974). All values were standardized with a z-transformation. The algorithm uses a connectivity graph of a minimum spanning tree (Kruskal 1956) and the method "skater" to determine natural clusters in the data and to ascertain regions of clustering and of cluster membership likelihood (probability of belonging to a cluster) for the fallout points along the transect. The number of features per cluster was generated with fallout locations using Trimmed Delauney Triangulation (Watson 1981); this approach uses a non-intersecting network of triangles in which each feature (fallout location) is a triangle node, with nodes that share edges considered "natural" neighbors. This ensures that a feature will only be included in a cluster if at least one other cluster member is a "natural" neighbor. Finally, multivariate clustering boxplot analyses were generated to show the calculated distance from location point to the nearest light pole, and the calculated distance from location point to nearest neighbor point (fallout location to fallout location or random point to random point), using standardized values.

Rescue center intake data analysis

Five years of available intake data from a seabird rehabilitation center within the study area (Sea Life Park: 2010, 2012, 2014, 2017, 2018; Fig. 1A) were analyzed to quantify injuries upon intake and the disposition outcomes (euthanized, died, released, transferred).

RESULTS

Road surveys for fallout detection

In total, 396 incidences of WTSH fallout (both live and dead) were documented along the survey transect during the survey period and 376 were analyzed (Table 1; 20 not analyzed due to incomplete documentation). When considering the northern (303 light poles) and southern (309 light poles) regions of the study area (Fig. 1B), the transect had similar levels of light pollution shown by the number of light poles (Fig. 3A). However, 94% of fallout occurred

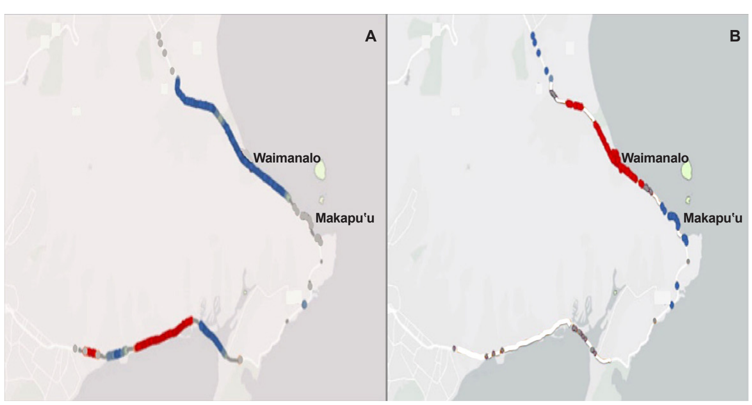

Fig. 3. (A) Light pole counts along the transect, with the density increasing from grey to blue to red with 99% confidence. A light pole hot spot is indicated by the red cluster in the southern region of the transect (n = 663). (B) Fallout counts along the transect, with density increasing from grey to blue to red with 99% confidence. A fallout hot spot is indicated by the red cluster in the northern region of the transect (n = 376).

in the northern region, which contains several offshore nesting islet colonies (~41 900 np). In contrast, there is only one small (~313 np) onshore colony in the southern region (Fig. 1A). Within the northern region, 70% of all fallout was concentrated in two areas: the town of Waimanalo (60%) and Makapu'u (10%) (Fig. 3B). The town of Waimanalo contains numerous light poles and stadium/beach park lighting near large offshore islet colonies.

Analytical results

Temporal analysis

The linear regression model of yearly fallout between 2003 and 2010 revealed two significant drivers: (1) there was a two-year cycle (Fig. 2A), evident as a significant (t = -4.203, P = 0.00847) lagged influence of the preceding year's fallout (coefficient = -0.9976 ± 0.2374 standard error (SE)); and (2) a significant (t = 3.191, P = 0.02424) longer-term increase (estimate = 8.3443 ± 2.6149 SE). Overall, this best-fit model was significant ($F_{2,5}$ = 9.644, P = 0.01923) and captured 71.18% (adjusted R^2) of the variance in the data. Moreover, the regression residuals were normally distributed (Shapiro-Wilk test, W = 0.95608, P = 0.7721) and not autocorrelated ($|r|$ < 0.25, P > 0.05). The fallout events documented along the survey transect spanned 46 days (range: 13 November–28 December) with a peak on 25 November, and most fallout (83%) was concentrated within three weeks, from 17 November to 07 December (Fig. 2B). With narrower focus, two-week (19 November–2 December), and one-week (21 November–27 November), temporal windows contained 67% and 36% of all fallout events, respectively.

Fallout survey data and random point generation

Chi-squared tests compared counts of WTSH fallout locations and random points along the transect that fell within 8 m of light poles and utility lines and found a significant difference between the two (X^2 = 18.42, df = 2, P < 0.0001). Subsequent chi-squared tests were used to assess the response to individual parameters, and all three comparisons were significant: (1) light poles (fallout = 94%, random = 24%, X^2 = 10.83, df = 1, $P \leq 0.05$); (2) utility lines (fallout = 83%, random = 34%, X^2 = 9.55, df = 1, $P \leq 0.05$); (3) no light poles or utility lines (fallout = 1%, random = 40%, X^2 = 15.37, df = 1, $P \leq 0.0005$). Overall, fallout locations occurred most often within 8 m of light poles or utility lines, with the opposite true of random points. The presence of light poles and utility lines across the transect was slightly varied and the majority of random points were not within 8 m of utility lines or light poles. While the chi-squared tests used counts, percentages were used to depict these data graphically (Fig. 4).

Distance tests

Multivariate box plot analyses showed that fallout locations were significantly closer to light poles and each other compared to

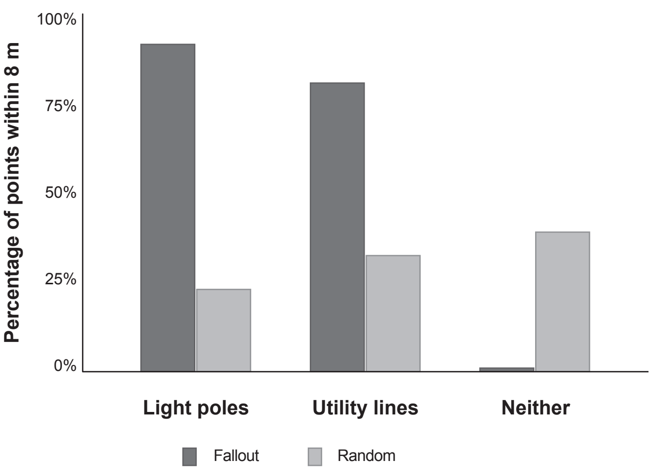

Fig. 4. Percentage of Wedge-tailed Shearwater (WTSH) fallout locations (dark grey, n = 376) and randomly selected points (light grey; n = 250) along the survey transect within 8 m of (1) light poles, (2) utility lines, (3) neither.

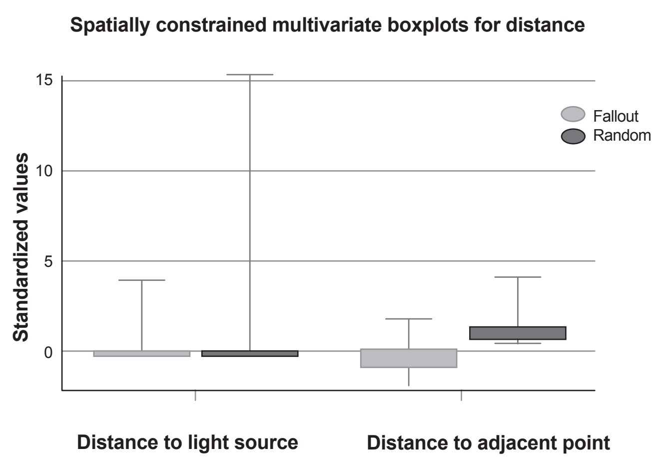

Fig. 5. Spatially constrained multivariate box plots showing standardized distances between adjacent fallout locations and light poles (light grey, n = 376), and distances between adjacent randomized points and light poles (dark grey, n = 250).

TABLE 2
Binomial generalized linear model (GLM) results using the logit link function for the distances between fallout (n = 250) and randomized points (n = 250) for colony, light poles, and colony + light poles

Distance (fallout vs. random)[a]	Estimate	Standard Error (SE)	df	t	P	AIC[b]	ΔAIC
Light + Colony	3.236	0.351	498	9.207	< 0.001	489	0
Light	-4.19E-04	7.30E-05	499	-5.747	< 0.001	663.4	174.4
Colony	4.81E-05	1.40E-05	499	3.43	< 0.001	685.5	196.5

[a] The response variable is a "1" (fallout) or a "0" (random).
[b] AIC values and ΔAIC values show the Akaike's information criterion (AIC) and the distance between the best fit model.

random points (Fig. 5). Most fallout occurred within 2400 and 5000 m of a colony (fallout distance to colony range: 636–8619 m, $\bar{x}$ = 3184.5 m, $\tilde{x}$ = 3029.3 m; Fig. 6A). The GLM also showed significant differences between the fallout locations and random points for distance to light poles ($P < 0.001$; Table 2; fallout distance to light pole range: 1.59 m–1728 m, $\bar{x}$ = 176.8 m, $\tilde{x}$ = 20.3 m; Fig. 6B). In contrast to the random points, fallout locations were negligible beyond 5000 m from the nearest colony, with 96% of fallout locations within 5000 m. The GLM also showed significant differences between the fallout and random points for distance to colony ($P < 0.001$). While the AIC values were comparable for the two models with a single predictor—light source distance (AIC = 685.5) and colony distance (AIC = 663.4)—the model including both variables (colony distance + light pole distance) had the best fit (AIC = 489; Table 2).

Hot spot analysis

A 99% confidence fallout hot spot was identified in the town of Waimanalo along the northern region of the transect (Fig. 3B). Conversely, a 99% confidence light pole hot spot was identified in the southern region of the transect where little fallout occurred (Fig. 3A).

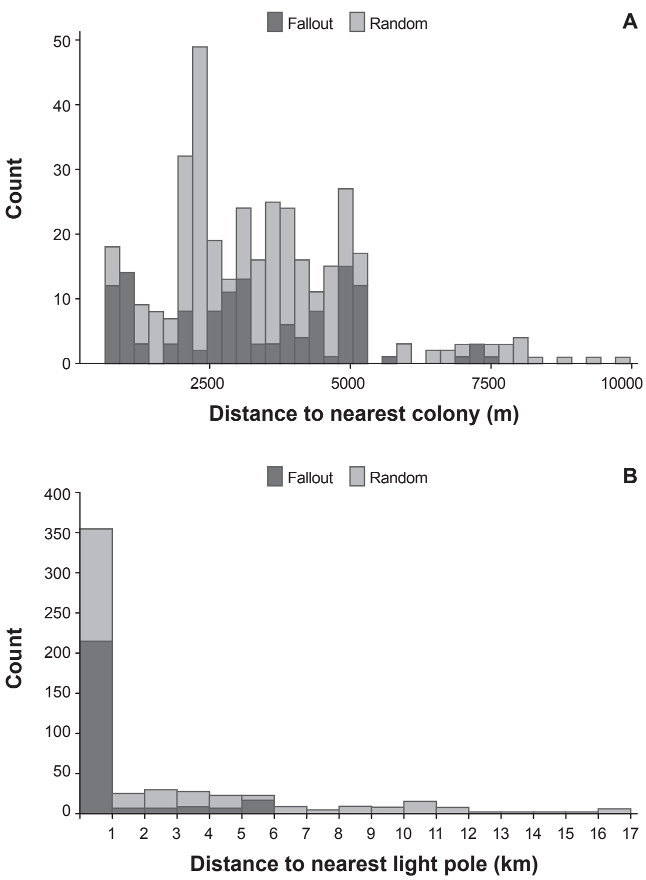

Fig. 6. (A) Stacked histogram depicting the relative frequency of distance from fallout locations and random points to the nearest colony (m) (n = 376 and n = 250, respectively). (B) Stacked histogram depicting the relative frequency of distance from fallout locations and random points to the nearest light poles (km) (n = 376 and n = 250, respectively).

Clustering analysis

Spatial multivariate clustering analysis showed high clustering of fallout locations near specific light poles. High clustering occurred within the largest fallout hot spot in the town of Waimanalo (Fig. 3B), with most clusters containing seven or more fallout locations. Fallout locations showed high membership probability, indicating that single fallout locations did not typically occur and that the majority (83%) occurred in cluster groups. In fact, 27% of all fallout was clustered among two specific light poles along the transect (Fig. 7).

Rescue center fallout data

The SLP rehabilitation center intake data (n = 1883 records) showed that 30% of the WTSH admitted were found in the town of Waimanalo (fallout hot spot) and that the majority (78%) of the admitted WTSH were released with "no apparent injury."

DISCUSSION

This study examined spatial and temporal factors associated with fallout of WTSH on the southeast shore of Oʻahu, with the intent of developing targeted management recommendations to reduce fallout and increase the probability of fledgling survival by identifying when and where management actions should be implemented. Our results are consistent with the literature regarding the negative impact of artificial lights and coastal structures on procellariiform birds inducing fallout on Oʻahu and elsewhere, e.g., Reunion Islands (Le Corre *et al*. 2002), New Zealand (Deppe *et al*. 2017), Kauaʻi (Reed *et al*. 1985, Telfer *et al*. 1987, Ainley *et al*. 1997, Podolsky et al. 1998), Canary Islands (Rodríguez & Rodríguez 2009), and the Outer Hebrides (Miles *et a*l. 2010).

Temporal management

Targeted management efforts could be used through temporal measures to mitigate light attraction, reduce fallout, and enhance search efforts for the rescue of grounded seabirds (Telfer *et al*. 1987). Our results indicate substantial inter-annual oscillations in fallout of WTSH on Oʻahu, with an overall increase across the study period,

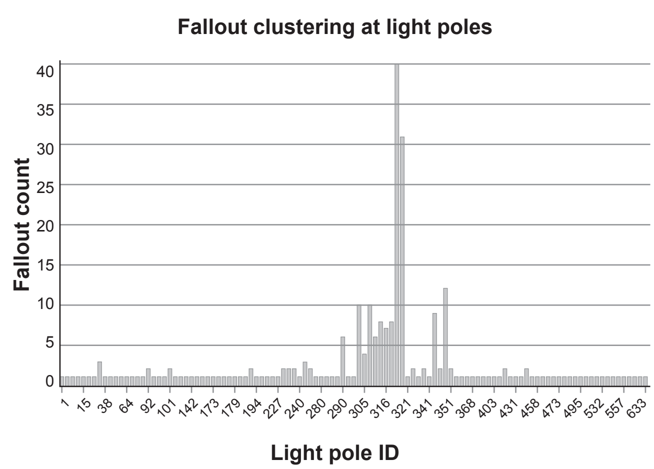

Fig. 7. Fallout count clustering discovered within 8 m of light poles along the transect (n = 663). The light pole number corresponds to specific light pole locations along the transect.

and we document significant autocorrelation, with the total fallout on a given year being negatively related to the total fallout in the preceding year. This pattern may be due to oscillations in annual reproductive success, as has been described in other shearwater species (Ainley *et al.* 2001, Rodriguez *et al*. 2012b), warranting further research to determine the underlying causes for the two-year cycle. Although the driver is currently unknown, this oscillating pattern could inform targeted management actions on an annual scale, with light mitigation and rescue efforts increasing during years predicted to have high fallout (i.e., odd years). If fallout seems to be low in a given year, managers and rehabilitators might safely assume that the following year may require additional staffing and resources. Identification of 25 November as the peak fallout date across the 6.5-week survey period allows identification of a narrower time window for targeted management that includes light mitigation and rescue efforts. This enhanced management period could span three weeks (17 November to 07 December, encompassing 83% of all fallout), two weeks (19 November to 02 December, 67% of all fallout), or one week (21 November to 27 November, 36% of all fallout).

Spatial management

We recognize that live grounded birds could have moved from their original fallout location, and that fallout may not have occurred as a direct result of the offending light fixture; however, the significant clustering and spatial patterns offer a distinct management opportunity. Although the mechanisms driving fallout warrant further research, the documented spatial and temporal patterns have clear management implications. WTSH fallout occurred near light poles and utility lines at a much higher rate compared to random points, with the majority of the fallout locations occurring within 8 m of a light pole (94%) or a utility line (83%). Conversely, very few fallout locations occurred where light poles or utility lines were absent (1%) compared to random points (40%). By using a conservative distance of 8 m around a light pole, we can determine a relatively high light intensity visible to seabirds (90–100% of original). This small buffer also ensures visibility by seabirds regardless of differences in light intensity that are dependent on positioning and light fixture structure. An interaction between light poles and utility lines is possible, but due to limitations in the data set, we were unable to test for independence. We can, however, see a variation in the detection of light poles and utility lines among fallout locations and random points. Random points occurred at a high rate near no light poles or utility lines, indicating that fallout that occurs on the roadway is not automatically within 8 m of light poles or utility lines; in fact, the opposite was true. Moreover, two adjacent light poles (representing 0.3% of all light poles in the study area) were associated with disproportionately high fallout (27%), identifying the highest priority sites for targeted spatial management.

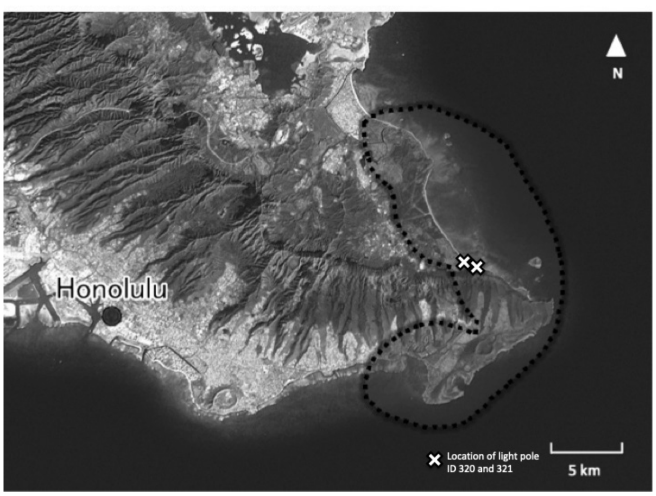

Fig. 8. Map of southeast O‘ahu (survey area) showing the recommended area for targeted management, depicted by a 5-km buffer around Wedge-tailed Shearwater nesting colonies in the study area (dashed line). The two ×’s indicate the location of light poles (ID 320 and 321) where a disproportionately high proportion of fallout occurred (see Fig. 7).

On O‘ahu, light poles and utility lines within 5 km of a colony present an increased fallout risk for fledglings and should be given increased priority for targeted management (Fig. 8). Fallout locations were negligible at a distance > 5 km from a colony, with ~95% of fallout occurring within 2.4–5.0 km ($\bar{x}$ = 3.4 km). This provides a good indication of the distance around a colony that targeted management through light pole and utility line mitigation and rescue campaigns would be most beneficial. Certain light pole hot spots along the survey transect located outside of the 5 km colony buffer were associated with very few instances of fallout. Additionally, the majority of light poles in the southern (low fallout) portion of the transect were > 5 km from a colony, whereas in the northern (high fallout) portion, the majority of light poles occurred within 5 km of a colony (Fig. 1A, B). While our analysis assumed that fallout involved fledglings from the nearest colony, we were not able to determine the source colonies of grounded WTSH. These results are, however, similar to a previous study from the Balearic Islands, where shearwaters and petrels were rescued at a mean distance of 4.8 km from the nearest colony, with outliers occurring as far away as 20 km (Rodriguez *et al*. 2015a).

Fallout hot spots are an important consideration when determining light management regimes. If light mitigation efforts are focused in the hot spot regions identified in this study, 70% of all fallout in the study area (Waimanalo, 60%; Makapu‘u, 10%) could be reduced by management actions along a small section of the road (~1.7 km linear distance). Because our transect was selected to include the highest density of suspected fallout along a public roadway, and also because of its proximity to nesting colonies, management in this study area could reduce a substantial percentage of the total fallout on the island of O‘ahu.

The most productive WTSH colony on O‘ahu, Manana (~30 000 np), is near the region’s greatest fallout hot spot, suggesting that colony size may also influence fallout rates. The distance between lights and breeding colonies will likely vary across species depending on their nesting habitat. In Hawai‘i, WTSH colonies occur near coastlines, placing fledglings near artificial light sources associated with coastal development. Because higher intensity lights may increase the distance from a colony where fallout is likely to occur, we caution that the distance of impact is likely to vary based on light intensity and species (Rodriguez *et al*. 2015b). WTSH are a close relative of the Manx Shearwater *Puffinus puffinus*. Manx Shearwater have nocturnally adapted eyes (Martin & Brooke 1991) that are capable of amplifying light sources, making even low-intensity light a potential threat. WTSH have also exhibited a stronger response to ultraviolet and long-wavelength light compared to some other procellariiform species based on their retinal response to flashing LED lights, with adults showing slightly less sensitivity than juveniles (Moon 2020).

Next steps

Some of the most pressing actions to mitigate light-induced mortality of WTSH on Oʻahu involve estimating the effects of fallout on populations, determining safe distances from light sources and colonies, improving targeted rescue campaigns to recover grounded birds, and documenting the fate of rescued birds (Rodriguez *et al*. 2017c). Some areas in Hawaiʻi have already adopted targeted light mitigation strategies (e.g., on Kauaʻi, turning off stadium lights in autumn). The outcomes of this study could be used to implement a strategic plan for reducing fallout and increasing fledgling survival of WTSH on Oʻahu and may apply to other regions experiencing high fallout and fallout-induced mortality due to light pollution. A strategic plan that emphasizes rescue campaigns, coastal structure mitigation in the fallout hot spots, and colony buffers, particularly during the high-risk periods identified in this study, could minimize fallout and maximize fallout recovery with minimal resource use.

Light poles in the targeted management areas can be eliminated, altered, or managed (permanently or temporarily), and various options exist for threat reduction if certain alterations or extinguishment is not possible due to human safety, lack of funding, resources, or ability (although targeted management may mitigate these issues). Some studies suggest that a modification of light color may reduce attraction in seabirds (Rodriguez *et al*. 2017c). Artificial lights may also be modified with shields or oriented downwards or towards the object of focus to avoid skyward light spill, an approach that has been shown to deter light spread and reduce seabird attraction; however, this may not deter light attraction from birds at sea (Reed *et al*. 1985). Lights can also be placed on timers or motion sensors. Utility lines in targeted management areas can be modified by increasing their visibility or rewired underground (Cooper & Day 1998, Silva *et al*. 2013).

"Lights out" initiatives for seabirds and sea turtles have proven successful in various regions. In highly industrialized and populated areas like Oʻahu, "lights out" programs, where all lights are extinguished across a broad area during the fledging season, have had limited adoption due to concerns about human safety, mobilizing citizens to action, recreation, lack of political will, and limited funding. Targeted management actions in smaller areas and time scales can increase the likelihood of adoption by reducing these concerns. Beginning with accessible targeted management programs can increase the likelihood of eventual large-scale adoption.

Rescue campaigns hold the ability to minimize mortality risk for thousands of seabirds a year (Rodriguez *et al*. 2017b, Le Corre *et al.* 2002), and WTSH populations may benefit from a targeted management approach that focuses on the high-risk areas (i.e., fallout hot spots and 5-km buffer) and periods (17 November to 07 December) identified. WTSH are predominately admitted for rehabilitation with no injury and have a high likelihood of release; therefore, rescue campaigns that recover grounded seabirds before mortality events occur can increase survival. Conducting surveys in the evening and morning could also increase the detection of downed birds (Rodriguez *et al.* 2014, and observed during this study). Knowledge of high-risk time periods and regions may prepare rehabilitation centers for high-intake events and direct local awareness campaigns, media, and education.

The effects of artificial light pollution and coastal structures hold multiple tangible solutions with the potential for rapid reversal and adoption. Targeted management can reduce stress on populations experiencing human-caused mortality by artificial light and coastal structures (Troy *et al.* 2011, Rodriguez *et al.* 2017c). Mitigating these stressors is a proactive approach to lessening human-wildlife conflict and pressure on seabird populations and encourages the growth of a native seabird population in Hawaiʻi. Anthropogenic effects such as fisheries conflict, plastic ingestion, climate change, and depleting fish stocks are large-scale and inherently difficult to manage. Conversely, mitigating the impacts of light pollution using targeted management to identify areas and times of greatest threat is a tractable approach to diminish seabird mortality and to raise public awareness for the plight of seabirds in urbanized landscapes.

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