A TEMPORAL AND SPATIAL ANALYSIS OF WEDGE-TAILED SHEARWATER (*ARDENNA PACIFICA*) FALLOUT ON O‘AHU

Jennifer L. Urmston

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Advisory Committee:

K. David Hyrenbach Chair
David B. Field
Susan Carstenn
Keith Swindle

ABSTRACT

Every year, hundreds of fledgling Wedge-tailed Shearwaters (*Ardenna pacifica*) are attracted to artificial light during their night-time voyage to sea, resulting in stranding and mortality from collisions and predation. I conducted a temporal and spatial analysis of fallout over an 8-year period during which highway streetlights were transitioned from unshielded high pressure sodium to shielded light-emitting diode lights. I used systematic road surveys at 3-day intervals to document road-killed shearwaters during November and December each year on southeast Oʻahu. I found that the change in highway lighting did not influence the magnitude of fallout, however an interaction between wind speed and moon illumination was a strong predictor. Likewise, the spatial distribution of fallout was not altered by the change in lighting, but the distance to the colony and maximum radiance were significant. My study showed no effect of the change in highway lighting on Wedge-tailed Shearwater fallout on southeast Oʻahu, suggesting that the new streetlights were neither better nor worse for the birds. The results of my study revealed that fallout occurs more frequently on nights with strong winds and low moon illumination and in brighter areas near the breeding colony. This new understanding of the timing and spatial distribution of fallout can be used to guide management of lighting and rescue efforts during the fallout season.

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Chapter 1

Seabird Attraction to Artificial Light:

A Review of Fallout Research

1. Introduction

Urban sprawl is threatening wildlife with loss of suitable habitat, noise, and light pollution. As the natural nightscape is altered by the addition of artificial (i.e., anthropogenic) lights from buildings, vehicle traffic, and street lamps, many species are impacted including sea turtles (Salmon, 2003), marine zooplankton (Longcore et al., 2004), and even humans (Zeiter et al., 2004). This review focuses on seabirds nesting near urbanized coastlines and the adverse impacts they face from artificial light at night during the fledging season.

Seabirds encompass some of the most endangered species of birds in the world, with 28% of seabird species listed as threatened under the IUCN (Croxall et al., 2012; Rodriguez et al., 2017a). Many threatened and endangered petrels (order Procellariiformes, including albatrosses, shearwaters, storm-petrels, diving petrels, and gadfly petrels) are inherently difficult to study due to their far-ranging movements and nocturnal habits in colonies. Conservation of migratory seabirds can be difficult since they span vast ranges, and only spend a portion of the year on land to breed. During the fledging season at least 56 species of petrels become grounded on land instead of flying out to sea due to attraction to light (Rodriguez et al., 2017a).

When fledgling seabirds leave their nest for the first time to fly out to sea, they rely on ambient moonlight to guide them (Telfer et al., 1987). However, artificial light can drive birds away from the ocean and towards these land-based light sources. Seabirds are drawn towards lit structures including streetlights, sports field lights, resort lights, and decorative lighting (Raine et al., 2007). This causes a phenomenon called fallout, whereby birds become disoriented by intense lights, fall from flight or collide with structures, and strand on the ground (Reed et al., 1985). Once stranded, chicks are often unable to regain flight, and face risks of vehicle collision and predation (Rodriguez et al., 2017a).

While it is clear that birds are attracted to onshore lights, little is known about how different types of lighting influence this attraction. As light-emitting diode (LED) light bulbs gain popularity for their energy-saving properties, municipalities are making a shift from sodium-based streetlights to LEDs (Soni and Devendra, 2008). Although this shift to LEDs is usually driven by eco-friendly intentions, it is hastily being implemented throughout the world without considering possible adverse effects. While it is known that seabirds are impacted by artificial light, the relative impacts of LED streetlights compared to sodium lights are unclear.

This review summarizes the current knowledge about the effects of environmental and anthropogenic factors influencing seabird fallout and identifies areas requiring further investigation. Moreover, this review evaluates the advantages and shortcomings of the methods used to study fallout. It is my intention to use this information to encourage more effective management of light-pollution to mitigate impacts on the affected seabird species.

2. The Fledging Process

Certain conditions must be met before seabirds can successfully fledge. First, chicks must reach the required stage of physical development for fledging. Once fit to fledge, the next step is departing from the nest. If the environmental conditions are favorable, with enough wind for the chick to take flight, then chicks can make their voyage out to sea. Whether fledglings are successful in flying out to sea or drawn toward land is largely dependent upon moon illumination and presence of land-based artificial lights.

2.1 Chick Development

Before a chick can leave the nest, it must have fully developed tail and wing feathers to

support flight. Wedge-tailed shearwaters (*Ardenna pacifica*) on O‘ahu reach a peak mass of approximately 480g before shedding weight in preparation for fledging (Hyrenbach, 2011). When chicks are ready to fledge, they appear virtually identical to adults externally, with the exception of some down feathers remaining (Whittow, 1997). A study by Rodriguez et al. (2012) suggests that underweight chicks will fledge later in the season and have reduced success.

Parental investment also plays a large role in the physical preparedness of the chick (Sprague and Breuner, 2010; Storey et al., 2017). Food delivery rates are a driver of chick growth and development. Many species of seabird chicks are eventually abandoned by their parents (Storey et al., 2017), with the point of abandonment playing a key role in whether they reach the required phase of development in time (Sprague and Breuner, 2010). Laysan Albatross (*Phoebastria immutabilis*) chicks whose parents abandoned them earlier were forced to fledge earlier to find food, while chicks that received extended parental care waited until they were fully prepared to fledge (Sprague and Breuner, 2010). Once fit to fledge, chicks may be more selective, waiting for the perfect environmental conditions to fledge.

2.2 Leaving the Nest

Once a chick decides to leave the nest, it embarks on its first voyage out to sea, during which it faces potential hazards. This initial flight is a major bottleneck event for seabird populations (Rodriguez et al., 2017; Troy et al., 2013). If a chick does not reach its fledging destination on the initial flight, its chances of survival are greatly reduced. Depending on location and environmental conditions, fledglings may face several obstacles during their flight (Rodriguez et al., 2014; Telfer et al., 1987). The most notable threats are artificial light pollution and onshore obstacles. While it is widely accepted that attraction to artificial light results in

seabird fledgling mortality, it is important to understand how variability in the environment influences fledging success.

2.3 Moonlight and Fledging

Seabird fallout is reduced when moon illumination is greater, suggesting that full moon conditions support successful fledging (Rodriguez et al., 2014; Telfer et al., 1987). However, where nocturnal avian predators are prevalent, moonlight may be a fledging deterrent for chicks, as it makes them more visible to predators (Syposz et al., 2018). Nonetheless, it is likely that many seabirds use the light from the moon to guide their navigation out to sea. A well-supported explanation for why a reduction in fallout occurs as moon illumination increases is that light pollution from streetlights is diluted by moonlight, thus reducing attraction to onshore lighting (Le Corre et al., 2002; Rodriguez et al., 2012; Rodriguez et al., 2014; Syposz et al., 2018; Telfer et al., 1987; Wilhelm et al., 2013).

2.4 Wind and Fledging

While the patterns associated with moonlight have been consistently reproduced, the effect of wind has only recently been explored and requires further examination. Ground-nesting birds with high wing loading, such as shearwaters, experience great difficulty taking flight without the presence of wind (Warham, 1977). High wind speeds have been correlated with increased fallout (Rodriguez et al., 2014; Syposz et al., 2018), however it is unclear whether high winds are causing fallout, or simply enabling more birds to fledge, some of which fail due to other factors. Nevertheless, it is unclear if an optimum wind speed exists for fledgling seabirds, and how it may vary across species.

In 1994, Work and Rameyer (1999) suggested that an unusual shift in wind direction was a driver of a mass fallout event for Wedge-tailed Shearwaters on O‘ahu. This result underscores the notion that fallout increases when onshore wind blows birds towards the artificial lights (Rodriguez et al., 2014; Syposz et al., 2018). Moreover, other meteorological variables (temperature, rainfall, atmospheric pressure) have not been linked to fledging success (Syposz et al., 2018).

3. Methodological Evaluation

Seabird fallout due to artificial light attraction has typically been examined in two ways. Most commonly, fallout data from rehabilitation centers, where grounded birds are delivered by the public, are used to characterize the timing and magnitude of fallout events. Another, more extensive way of researching seabird fallout is through systematic surveying. Below, I review the advantages and shortcomings of fallout data generated through public efforts and organized surveys (Table 1).

3.1 Public Efforts and Rehabilitation Centers

In regions with seasonal seabird fallout events, community members are often encouraged to rescue grounded birds by bringing them to local rehabilitation centers (Le Corre et al., 2002; Raine et al., 2007; Rodriguez and Rodgriguez 2009; Rodriguez et al., 2012; Rodriguez et al., 2015; Syposz et al., 2018; Telfer et al., 1987; Troy et al., 2013; Work and Rameyer, 1999). In several instances, televised campaigns, school visits, and social media are used to encourage community members to search for grounded birds (Le Corre et al., 2002; Rodriguez et al. 2012).

On Kauai, a program called “Save Our Shearwaters” set up stations across the island where grounded birds can be dropped off for rehabilitation (Telfer et al., 1987). Information on the number of birds, date and location of fallout is recorded and trends are examined over time. A study on the Balearic Islands combined data from three rehabilitation centers where birds were collected by the public and wildlife personnel (Rodriguez et al., 2015).

While community involvement is an effective way to raise awareness and enhance seabird survivorship, the data generated in this way are often biased because typically, only live birds are accounted for. In cases where dead birds were considered (Rodriguez et al., 2012; Syposz et al., 2018), the percentages of birds found dead were considerably low (7.8%, 6%), raising the suspicion that members of the public may be more inclined to rescue live birds, and may not be reporting dead birds. Furthermore, search effort may vary spatially and temporally (between and within seasons), depending on awareness, weather conditions, and convenience. Studies using rehabilitation center data provide useful information about the timing and number of birds rescued, however they can be misleading about the proportion of fatalities and rescue efforts are largely dependent on community involvement.

3.2 Fallout Surveys

Surveys along beaches, roads and obstacles (like wind energy installations) have been conducted to study trends in seabird fallout for four species of shearwater (*Ardenna pacifica*, *Ardenna tenuirostris*, *Puffinus newelli*, *Puffinus puffinus*), two petrel species (*Oceanodroma leucorhoa*, *Hydrobates pelagicus*) and one puffin species (*Fratercula arctica*). Survey methods varied amongst studies, with differences in time of survey, intervals between surveys, and means of searching (by car/on foot) (Table 2).

In Newfoundland, a community-based volunteer organization called “Puffin Patrol” conducted nightly searches to rescue stranded Atlantic Puffins (Wilhem et al., 2013). With 25-50 volunteers searching for birds by car or on foot each night, sampling of dead and alive birds was thorough, and sampling continued throughout the night (9:00PM-2:00AM). On St. Kilda, daily surveys were conducted on foot to search the perimeter of buildings for grounded Manx Shearwaters, Leach’s Storm Petrels, and European Storm Petrels (Miles et al., 2010). On Phillip Island, Australia, park rangers conducted road surveys by car twice in the morning and twice at night over a 15 year period, actively searching for grounded birds, both dead and alive (Rodriguez et al., 2014). The routine surveying method used in this study standardized observer effort, reducing variability. In a recent study in the British Isles, birds were collected through a combination of volunteer surveys and public involvement. Volunteers conducted daily surveys on foot, searching for dead and alive birds along a 2 km route where light pollution was known to affect shearwaters. Additionally, members of the community were encouraged to search for birds throughout the village (Syposz et al., 2018). Although most of the birds were found within the volunteer survey site, the observer effort in the rest of the village was not quantified.

While community-based rescue efforts likely achieve a closer estimate of absolute fallout, there are benefits to studying relative fallout by using consistent monitoring protocol. On O‘ahu, opportunistic road surveys for Wedge-tailed Shearwaters began in 2002 to document road mortality during the fledging season (Friswold et al., 2020). In 2012, methods were refined to obtain standardized effort, by conducting surveys along a prescribed route every 3 days at sunrise (Hyrenbach et al., In Progress).

To this point, the biggest challenges when conducting seabird surveys are standardizing observer effort and accounting for outside variables that may confound the data. The varying

approaches to surveys have resulted in a wide range of results regarding the proportions of live and dead birds observed, with a range of 3%-43% of birds found dead (Table 2). Surveys conducted solely by car yielded about 40% dead while surveys only by foot resulted in less than 10% dead birds, suggesting that vehicle-surveys may be biased towards dead birds. Foot-surveys may extend search efforts beyond the paved road, accounting for live birds that have been grounded, but not struck by vehicles. Most studies conducted nightly surveys, with only two adding additional morning surveys, and one surveying exclusively in the morning. While two studies including morning surveys found higher percentages of dead birds (Podolsky et al., 1998; Rodriguez et al. 2014), Miles et al. found only a mortality rate of <3%. However, this result may be related to their surveys being targeted around buildings rather than on roads. It is possible that morning road surveys may be biased towards dead birds since seabirds fledge during the night.

3.3 Underestimation

When using road surveys to estimate mortality, it is key to understand how long carcasses remain on the road to account for potential underestimation. Several studies have investigated carcass loss rate in various vertebrate species (Antworth et al., 2005; Degregorio et al., 2011; Ratton et al., 2014; Santos et al., 2011). Santos et al. (2011) examined 13 taxa of vertebrates that suffered road mortalities and quantified their duration on the road before being scavenged or dismembered by vehicles and weather. A key implication from this study was the determination of ideal sampling intervals for different species. For large birds, 2 or 3-day intervals were suggested, as most birds in this study remained on the road for over 48 hours. In several cases, scavenging was estimated by systematically placing chicken (Antworth et al., 2005; Ratton et al.,

2014) and snake (Antworth et al., 2005; Degregorio et al., 2011) carcasses on the road. Carcass removal was observed as early as 2 hours after death (Antworth et al., 2005), and at a loss rate of up to 89% after 24 hours (Ratton et al., 2014).

Despite the implications of carcass loss in road mortality surveys, only one seabird fallout study has accounted for this, estimating 17% carcass loss of Newell's Shearwaters on Kauai within the first 24 hours after death (Podolsky et al., 1998). This was done by using previously collected bird carcasses, intentionally placing them on the road, and resampling daily. In less than 24 hours, 17% of carcasses were removed by scavengers, and 60% remained longer than 4 days. Because scavenging likely differs regionally and between taxa, species and location specific assessments are required for road mortality studies.

4. Focus on Light

The reason for seabird attraction to artificial lights is uncertain, but several ideas have been suggested. Rodriguez et al. (2017a) outlined the three current explanations in a literature review. The first idea suggested is that birds consuming bioluminescent prey are mistakenly drawn to artificial lights when feeding (Imber 1975). Another idea is that seabirds mistake individual lights for the moon, which is their natural navigational beacon (Telfer et al., 1987) The third explanation is that the only source of light for burrow-nesting seabirds before fledging is the burrow entrance, where parents deliver them food. When chicks leave the nest to fledge for the first time, they may see light and mistake it for a food pathway (Rodriguez et al. 2017a). The argument that birds are mistaking light for the moon is supported by the fact that seabird fallout is typically greater with decreased illumination from the moon (Rodriguez et al., 2012; Rodriguez et al., 2014; Syposz et al., 2018; Telfer et al., 1987; Wilhelm et al., 2013).

As many streetlights are being replaced with white LED lights, it is important to understand how seabirds and other species are impacted by different wavelengths and intensities of light. Davies et al. (2013) classified 4 different types of streetlights: Low pressure sodium (LPS), high-pressure sodium (HPS), light-emitting diode (LED), and metal halide (MH). LPS lights are classified as narrow spectrum lamps, while HPS, LEDs, and MHs are classified as broad-spectrum lamps.

Although Davies et al. (2013) suggest that the navigational abilities of some species will improve with broad-spectrum lamps, seabirds have exhibited sensitivity to the wavelengths of LED and MH lights, suggesting an opposite response (Hart, 2004). An experiment comparing attraction of Short-tailed Shearwaters to LED, MH, and HPS lights in a non-light polluted colony, revealed lowest attraction levels to HPS lights (Rodriguez et al., 2017b). The problem associated with broad-spectrum lights, particularly LED streetlights, is the increase in light scatter throughout the atmosphere (Mehmedinovic and Heffernan, 2018).

4.1 The Bright Side of LEDs

While conservation biologists have expressed valid concerns regarding LED lighting, a 2018 review by Longcore addresses how new variations of LEDs may hold potential benefits for humans and wildlife. A survey of lighting professionals and light pollution experts concludes that LED lighting can both decrease or increase overall light pollution depending on how it is implemented (Schulte-Römer et al., 2019). It is a common misconception that LED lights can only emit white or blue light, however the spectral possibilities are quite broad (Longcore, 2018; Longcore et al., 2018). A recent study compares lamps of a broad range of spectral intensities to assess their impacts on insects, sea turtles, Newell's Shearwaters, and juvenile salmon finding

that combinations of yellow, green, and amber filtered LED lights may provide the best compromise between wildlife safety and human use (Longcore et al., 2018).

Furthermore, new technology allows LED streetlights to be adjustable in terms of direction, duration and intensity (Longcore, 2018; Schulte-Römer et al., 2019). The use of microlens arrays in LED streetlights directs light downward, reducing horizontal light scatter. Additionally, the ability to turn lamps on or off without requiring substantial energy is exclusive to LEDs. An added benefit of LEDs is that they can easily be dimmed to reduce light intensity. However, it is a natural temptation for users to increase the brightness of these lights since the cost of doing so is cheaper than previous light-types. While there is potential benefit in the future of LED lights, it will require the cooperation of wildlife managers and governing agencies to implement these lighting systems in a way that will balance energy-efficiency and wildlife protection.

5. Mitigation

The overarching goal of seabird fallout research is to reduce mortality caused by light pollution. Arguably the most effective method of mortality reduction is the continuation and enhancement of rescue programs (Le Corre et al., 2002; Rodriguez et al., 2012; Rodriguez et al., 2015). By focusing rescue efforts at times and in locations when fallout is historically the highest, mortality mitigation will be maximized. However, when considering the root of the problem, turning lights off during fledging season is the ideal solution, but it is not always practical (Le Corre et al., 2002; Rodriguez et al., 2014; Rodriguez et al., 2017; Troy et al., 2013). Where restricting light use is not feasible, shielding can be used to reduce scatter, directing light only in the downward direction (Le Corre et al., 2002; Raine et al., 2007;

Rodriguez et al., 2017; Telfer et al., 1987; Troy et al., 2013). Motion sensors can be used to restrict light use to only when necessary (Raine et al., 2007). In high traffic regions, lowering speed limits and increasing public awareness of downed seabirds can help reduce fatalities from vehicle collisions (Rodriguez et al. 2014). Switching light sources to less intense bulb types or dimming lights can potentially mitigate the problem; however further research is required to determine specific responses to varying types of light (Rodriguez et al., 2017b; Troy et al., 2013).

6. Summary and Unresolved Issues

It is imperative to understand how shifting from HPS to LED streetlights influences fallout in seabirds. If LED lights are in fact increasing attraction, it will be useful for municipalities to consider this information before making the investment in LEDs. The effectiveness of light mitigation (shielding, dimming, turning off, spectral modification) should be examined to determine the best possible management practices, taking into consideration the safety of both humans and wildlife. Future seabird road-mortality surveys must include a correction factor for carcass loss rate to address underestimation caused by scavenging and washout.

Sources of inter-annual variability in seabird fallout, in addition to moon phase and wind speed, should be examined to develop predictive models. Wildlife rehabilitation centers will benefit from predictive modeling by preparing for mass fallout events based on meteorological conditions. This information can also be disseminated to encourage citizens to be on the lookout for grounded birds during high-fallout risk periods.

As the impacts of light pollution on seabirds are elucidated, management plans should be proactive. Unlike other sources of pollution that are extremely difficult to manage, light pollution is reversible and reverting to natural, dark skies can have immediate positive effects on wildlife and humans.

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Table 1. Pros and cons table for fallout methodology

	Pros	Cons
Surveys	Standardized search effort Location (can be) recorded Target specific regions where fallout occurs	Time/resource consuming Limited search area
Rescue Data	Closer to absolute fallout Not time/resource consuming Wider search area	Variable search effort Location usually not recorded

Table 2. Survey methods of previous seabird fallout studies. Timing, sampling intervals and percentage of birds found dead.

Author	Year	Species	Sampling Interval	Sampling Hours	Survey method	% birds found dead
Miles et al.	2010	*Puffinus puffinus, Oceanodrama leucorhoa, Hydrobates pelagicus*	Daily	Within hour after dawn	Foot	<3%
Podolsky et al.	1985	*Puffinus newelli*	Varied (up to 3 times per day)	19:00-01:00 (night), before 12:00 (morning)	Car	43%
Rodriguez et al.	2014	*Ardenna tenuirostris*	Twice nightly, once daily	17:00-22:30 (night), 5:30-7:00 (morning)	Car	39%
Wilhelm et al.	2017	*Fratercula arctica*	Nightly	21:00-2:00 (night)	Car/foot	17.60%
Syposz et al.	2018	*Puffinus puffinus*	Nightly	22:00 (night)	Foot	7.80%

Chapter 2

Timing and Magnitude of Wedge-tailed Shearwater (*Ardenna pacifica*) Fallout on Southeast Oʻahu, Hawaiʻi: A Dynamic Interaction Between Moon and Wind

Abstract

Attraction to artificial light poses a threat to many fledgling seabirds leaving their nests for the first time. Fledgling Wedge-tailed Shearwaters disoriented by lights can collide with obstacles and become grounded, where they face the threats of predation and vehicle collision. While the timing and magnitude of shearwater fallout varies from year to year, little is known about how changing lighting and environmental conditions influence the risk of stranding for this species. We used 8 years (2012-2019) of observations of road-killed shearwaters along the Kalanianaʻole Highway on Oʻahu, Hawaiʻi to quantify the timing and magnitude of fallout during fledging season (Nov – Dec). The main goal was to compare shearwater fallout before (2012-15) and after (2016-19) a transition in highway lighting from unshielded high-pressure sodium to full-cutoff light-emitting diode streetlights. To detect the fallout response to the lighting regime, we also accounted

for several other potential environmental drivers of year-to-year variability: moon illumination, wind speed, and wind direction. The effects of these environmental drivers varied across years, with moon illumination, wind speed and wind direction significantly affecting fallout in at least one year. Altogether, the interaction between moon illumination and wind speed was the most important predictor, suggesting that fallout increases during nights with low moon and strong winds

1. Introduction

Light pollution is a concern for burrow-nesting seabirds globally, with documented studies impacting over 50 species of shearwaters, petrels, and puffins (Rodríguez et al., 2017a). While coastal light pollution can disrupt adult seabirds provisioning their chicks on colonies (Telfer et al., 1987), fledglings consistently account for the majority (68% - 99%) of the grounded specimens (Rodriguez et al., 2017a). Fledgling seabird "fallout" occurs when chicks leaving their nests are attracted to onshore lighting and become stranded on land instead of flying out to sea (Rodriguez et al., 2017a). The magnitude of fallout is likely influenced by the number of chicks fledging, by the prevailing environmental conditions, and attractiveness of the human lights, which varies as a function of bulb type (Rodriguez et al., 2017b) and by celestial conditions (Telfer et al., 1987). To gauge the effectiveness of light pollution mitigation measures, wildlife managers need to understand the influence of these biological and environmental drivers on the timing and magnitude of fallout (Ainley et al., 2001).

A conceptual model to explain fallout involves fledging seabirds being drawn towards well-lit coastal areas, especially in the absence of moonlight (Ainley et al., 2001; Le Corre et al., 2002; Rodriguez and Rodriguez, 2009; Rodriguez et al., 2014; Syposz et al., 2018; Telfer et al., 1987, Wilhelm et al., 2013), and when strong winds are directed toward shore (Rodriguez et al., 2014; Syposz et al., 2018). Nearing land, birds are attracted to bright light sources including streetlights (Rodriguez et al., 2014), sports fields (Rodriguez et al., 2017a), and urbanized areas (Raine et al., 2007; Reed et al., 1985; Rodriguez and Rodriguez 2009; Telfer et al., 1987). Collisions with these structures and surrounding powerlines (Podolsky et al., 1998) can lead to injury and

grounding. While our understanding of the environmental drivers of fallout is growing, the influence of specific design features of anthropogenic light sources remains understudied. In particular, lamp color and directionality are two key streetlight features that can affect seabird attraction (Reed et al., 1985; Rodriguez et al., 2017).

Spurred by efforts to improve energetic efficiency, many regions are replacing yellow high-pressure sodium (HPS) lightbulbs commonly used in streetlights with white light-emitting diode (LED) bulbs (Longcore, 2018; Longcore et al., 2018; Shulte-Romer et al., 2019; Soni and Devendra, 2008). Although LED bulbs decrease electricity consumption and maintenance costs, these benefits may be costly to wildlife because there is evidence that seabirds may be more sensitive to LEDs (Davies et al., 2013). A study on the visual perception of Wedge-tailed Shearwaters (*Ardenna pacifica – previously Puffinus pacificus)* showed that they experience maximum light absorption of the wavelengths emitted by white LED lights (between 406-566 nm) and have lower absorption of the wavelengths emitted by HPS lights (between 560-620 nm) (Hart, 2004). Moreover, a field-based experiment in Australia showed that Short-tailed Shearwaters (*Ardenna tenuirostris*) have increased attraction to LED lights over HPS lights, although the difference was not statistically significant (Rodriguez et al., 2017a).

Mitigation measures often target light directionality, whereby shielding directs light downwards to reduce scatter. This approach, when applied to HPS lights, reduced Newell's Shearwater (*Puffinus newelli*) fallout on Kauai (Hawai‘i) (Reed, 1985). In addition to using optimized LEDs (broad spectra and high CCT (>2700 K)), streetlights are commonly shielded through the use of a "full-cutoff" design which precludes light from being emitted above the horizontal plane of the fixture. While shielding alone is

beneficial for seabirds, the effectiveness of shielding coupled with the use of optimized LEDs is unclear.

On the island of Oʻahu, Hawaiʻi, Wedge-tailed Shearwaters (hereafter referred to as WTSH) experience fallout during the annual fledging season (November-December) (Friswold et al., 2020; Work and Rameyer, 1999). A three-year study in the early 1990s, revealed that hundreds of chicks become grounded on Oʻahu every fledging season, with the number varying widely from year to year (Work and Rameyer, 1999). Starting in 2002, USFWS initiated a program of opportunistic road surveys of the SE section of Oʻahu during the fledging season (November – December), which documented fallout hotspot in the town of Waimānalo, within 5 km from two WTSH colonies located on offshore islets. That study also found smaller-scale spatial patterns, with fallout being highly clumped, and closely associated (<8 m) with unshielded HPS light fixtures (Friswold et al., 2020).

While there is evidence of interannual variability in WTSH fallout, little is known about the influence of biological (breeding population size and chick production) and environmental (weather and oceanographic conditions) drivers. Friswold et al. (2020) documented an increasing trend in annual fallout numbers between 2003 and 2010, and a two-year cycle of alternating years of high and low fallout. These results are suggestive of a potential influence of the breeding population size and the annual reproductive success on fallout. To date, only one study has investigated the environmental drivers of WTSH fallout, by comparing a "wreck" year of unusually high fallout (1994) where WTSH groundings increased ten-fold from the two "normal" years

prior (Work & Rameyer 1999). This study suggested that anomalous southerly winds likely carried fledglings inland rather than out to sea and scattered them throughout the windward coast of Oʻahu (Work & Rameyer 1999). While the southerly winds help explain why birds were found inland, it is unclear if this was the driving force of the increase in the number of birds observed that year.

In 2012, we began conducting systematic road surveys along a 17.3-km section of the Kalanianaʻole Highway to document WTSH fallout. In 2016, the Oʻahu Department of Transportation changed the streetlights on Oʻahu's major roads from unshielded, 2200 K yellow-orange HPS lights to shielded, 3000 – 4000 K white LED lights. The shift in lights halfway through the study period provided a unique opportunity to compare WTSH fallout under different lighting conditions. To this end, we continued conducting surveys following the established protocol through 2019 and analyzed an 8-year time series of standardized surveys, with four years before (2012-15) and four years after (2016-19) the change in highway lighting. This is the first study to compare seabird attraction to HPS and LED streetlights in the natural course of the fledging season.

The goal of this study is to describe the temporal patterns and magnitude of WTSH fallout under two contrasting highway lighting regimes, to inform future coastal development and management of light pollution. Although shielding of the LED streetlights may reduce initial WTSH attraction, we predicted that disorientation caused by high intensity/shorter wavelength lights would outweigh the benefits of shielding. Thus, we expected an increase in fallout after the installation of LED streetlights (2016 – 2019). To detect this fallout response to the lighting regime, we also accounted for other potential environmental drivers: moon illumination, wind speed, and wind direction. In

both lighting regimes we predicted higher fallout during nights of low moon illumination (<50% lunar disk illuminated) and strong northeasterly trade winds (>8 mph).

2. Methods

2.1 Study Area

This study focuses on the southeast section of Oʻahu, where a two-lane coastal highway runs through a rural and developed landscape (Figure 1). The survey route was illuminated with HPS streetlights until 2016, when the Hawaiʻi Department of Transportation (HDOT) transitioned to LED streetlights. The Correlated Color Temperature (CCT) of the LED streetlights is 3000 ^{o} K on sections of the highway directly adjacent to the ocean, whereas lights inland lights are 4000 ^{o} K.

The WTSH breeding colonies of Mānana Island and Kāohikaipu Island, where approximately 25,000 and 800 chicks were counted in 2019, are located 1.3 and 0.7 km offshore of our study area on Oʻahu, respectively (DOFAW, 2020). Three additional WTSH colonies on offshore islets (Mokulua Nui, Mokulua Iki, and Popoiʻa) lie approximately 6 km north of the study area (Figure 1), with 2019 chick count estimates of 3,500, 5,000, and 900, respectively (DOFAW, 2020).

Weather patterns on windward Oʻahu are dominated by the northeast trade winds, which typically persist for 1 to 2 weeks at a time, interspersed with no-wind periods or Kona (southerly) storms. Peak wind speeds occur in the afternoon, with lower wind speeds at night (Leopold, 1948).

2.2 Intake Records

Sea Life Park (SLP), a marine life center located along our survey route, in Waimānalo, hosts a seabird rescue and rehabilitation program. Members of the public rescue WTSH and deliver them to SLP. We used the intake records, involving the daily number of rescued WTSH chicks, to provide a broader context of the timing and the number of grounded WTSH affected by fallout annually. Previously, these intake records have been used to document the temporal variability in WTSH fallout during the fledging season (Friswold et al., 2020).

2.3 Road Surveys

We used a time series of standardized road surveys along a 17.3-km stretch of the Kalaniana‘ole Highway, starting at the Olomana Golf Club, running through Waimānalo, and ending at the Koko Marina Center (Figure 1). While this survey route is a subset of the area surveyed by USFWS from 2002-2010, it encompasses the main location of WTSH fallout in Waimānalo (Friswold et al., 2020). We conducted morning surveys by car, every 3 days, throughout the WTSH fledging season (Nov. 6 – Dec. 21). We began surveys at sunrise (6:15-7:15 AM) and drove the route once in each direction at speeds between 25-35 mph while visually searching for birds in each lane and along the shoulder. All birds sighted while driving were included in the surveys, even if they were found on the shoulder, the median, or off the road.

Upon encountering a carcass, we recorded its position on the road, location (GPS coordinates), nearest street address, and nearest utility pole, showing the unique pole id

tag. We also documented the fallout locations by taking photos of the carcass, showing diagnostic identification features (head and feet).

2.4 Environmental Variables

To ensure the wide use of our predictive models, we related WTSH fallout to publicly-available environmental datasets: (i) wind speed (knots) and wind direction (degrees) provided by PacIOOS (www.pacioos.org), which is a part of the U.S. Integrated Ocean Observing System (IOOS).

Because WTSH fledge during the night, we averaged the night-time hourly data (18:00 – 6:00 local time) daily. We related the number of WTSH documented during a road survey to the average wind speed (knots), wind direction (degrees), and lunar disk illumination (%) from the three nights prior.

2.5 Data Analysis

To explain trends in fallout within and across years, we developed generalized linear models (GLM) using R version 3.5.1 and the stats and MASS packages (R Core Team 2019). We fitted nine models: eight separate yearly models explored interannual variation in environmental influences, and a full model involving all study years provided an overview of fallout drivers, including the highway light regimes. We used the full model to assess interannual variability, and the yearly models to visualize the interannual differences documented by the full model.

We ran models using both Poisson and negative binomial distributions to assess the fit for individual years and the full 8-year study period. While the Poisson distribution is appropriate for ecological count data, it relies on the assumption that the variance equals the mean. In cases where this assumption is violated due to overdispersion, the negative binomial distribution is more appropriate (Ver Hoef and Boveng, 2007; Zuur et al., 2010).

In every model, the dependent variable was the number of new WTSH observed on the road during a given survey of the entire study area (every three days). For each year, we tested the effects of four explanatory variables: moon illumination (% lunar disk illuminated), average wind speed (knots), average wind direction (degrees), and Julian date (the number of days since the beginning of the year). We calculated pseudo R-squared values based on the standard error using the 'rsq' package (R Core Team, 2019).

For the full 8-year model, we also predicted the number of new grounded birds observed on the road during a given survey of the entire study area (every three days), and used multi-model inference to test all possible combinations of explanatory variables. We considered six explanatory variables: year, Julian date, wind speed, wind direction, moon illumination, and light regime (HPS / LED). Whenever two of three potentially interacting variables were present in the model, we also included their interaction ('moon*date', 'moon*wind speed', and 'wind speed*date').

To determine the better fitting model distribution for each year, we used the Akaike Information Criterion, corrected for small sample size (AICc) (Burnham and Anderson, 2004). We used the AICmodavg package (R Core Team 2019) to conduct a model fit assessment with AICc, which prevents over-fitting by penalizing models for

each additional variable. AICc will assign a value to each model using the formula**, AICc = *-2log(L)+2K+(2K(K+1)/(n-K-1))***, where *K* is the number of parameters, *n* is the sample size, and *L* is the maximum likelihood of obtaining the given results with *K* parameters. We used the Akaike weights to calculate the likelihood of each model as follows:

$$\omega_i = \frac{exp\left(\frac{-\Delta_i}{2}\right)}{\Sigma_{r=1}^{R} exp\left(\frac{-\Delta_r}{2}\right)}$$

where w_i is the Akaike weight, the numerator is the model likelihood with Δ_i showing the change from the lowest AICc model to the given model, and the denominator is the sum of all relative weights, as determined by Δ_r, the change in each contending model from the lowest AICc model. The lowest AICc value indicates the model that best describes the patterns in the observed data without over-fitting (Burnham and Anderson, 2004; Michael et al., 2014).

To test the influence of light regimes, in the context of interannual variability, we built two complementary sets of models that included "light regime" (comparing two groups of years: 2012-15 vs 2016-19) or individual "years". This resulted in a total of 106 models; 36 included "light regimes" and 36 included "years", and 34 included neither. Individual models ranged from having one to eight predictors (five variables and three interactions) (Table S1.). We report the importance of each variable in terms of the scaled average weight, calculated using the models where those variables were included, following methods used by Michael et al. (2014).

2.6 Reproductive Success and ENSO

Finally, to address the observed interannual variability in fallout magnitude and timing, we explored potential predictive metrics using WTSH chick productivity, and oceanographic drivers. The former predictors provide a direct mechanistic link between fallout and reproductive phenology / success, with little lead time (e.g., weeks) for managers. The latter predictors provide an indirect empirical link between fallout and oceanographic conditions, with a longer lead time for managers (e.g., months). Finally, to evaluate the influence of the WTSH productivity on fallout, after controlling the influence of the oceanographic variability on the reproductive success metrics, we calculated semi-partial correlations with package ppcor v 1.1 in R.

We used four chick productivity metrics which captured yearly variability in the phenology (timing) and magnitude of chick survival (fledging success): median hatch date, median peak mass (g), median peak mass date, and nest success (%). Hatch date and peak mass date were used to indicate the timing of chick development, whereas peak mass is indicative of the condition of the chicks each year (Hyrenbach, 2011; Hyrenbach and Hester, 2020). The demographic data are from the Freeman Seabird Preserve, a nearby WTSH colony located on the southern shore of O‘ahu, where breeding phenology and chick growth have been monitored and protected from predation since 2009 (Hyrenbach, 2011; Hyrenbach and Hester, 2020). Nest success was measured by calculating the percentage of occupied nests on July 14 that successfully hatched chicks by September 14. This metric indicated changes in chick survival by assuming that lower nest success would translate into fewer chicks fledging.

We also used the multivariate El Niño Southern Oscillation (ENSO) index (MEI) to test the effect of oceanographic conditions on fallout (Wolter et al., 2011). This multivariate metric integrating sea level pressure and sea surface temperature in the tropical Pacific Ocean, is often associated with reduced prey availability for many marine species, which can lead to lower reproductive success, particularly in seabirds. At the Freeman Seabird Preserve, MEI was significantly linked to peak mass and hatch date (Hyrenbach, 2011). Increased frequency of ENSO conditions have been associated with a decrease in Sooty Shearwater (*Ardenna grisea*) populations in New Zealand (Lyver et al., 1999). We used the mean MEI values during pre-breeding (from December to-May), and breeding (from June to November), to test whether oceanographic conditions during these two broad time periods influence the magnitude and timing of fallout.

We performed a series of Pearson cross-correlations and used two criteria to assess meaningful pair-wise relationships: (i) correlation coefficients ($|r| \geq 0.5$) were considered evidence of strong relationships (explaining at least 25% of the shared variance, r^2), and (ii) statistically significant correlations at alpha = 0.05 ($|r| \geq 0.632$, given our small sample size, n = 8 years). Overall, we estimated a matrix of eight cross-correlations, involving two fallout metrics, four breeding metrics, and two oceanographic metrics. This analysis aimed to use the observed covariation in these parameters to predict the yearly magnitude and timing of fallout.

3. Results

First, to interpret the WTSH fallout numbers from our road surveys in a broader context, we compared the number of road-killed WTSH with the SLP intake records,

which provided a larger-scale measure of fallout timing and magnitude. The SLP intake records of fledging chicks spanned from November 2 to January 5, and the observations of grounded shearwaters along the Kalaniana‘ole Highway spanned from November 6 to December 21 (Table 1). Overall, only 2.3% of the SLP intake records fell outside of our road survey period (November 6 – December 21), with yearly proportions ranging from 1.3 to 6.3 (Table 1).

The total number of rescued WTSH brought into SLP yearly across the 8-year study varied by nearly an order of magnitude, ranging from 74 to 525 birds per year, with an average of 226.1 +/- 170.6 S.D. (median = 159.5) (Table 1). The number of WTSH carcasses observed on the survey route per year also varied widely, ranging from 7 to 60 birds, with an average of 24.1 +/- 18.7 S.D. (median = 17.5) (Table 1). There was a strong correlation between the yearly number of road-killed birds (our surveys) and rescued birds (SLP records), with 2012 and 2016 standing out as high-fallout years (r^2=0.85, df = 6, $p < 0.01$) (Figure 2). There were 469 rescued birds in 2012 and 525 in 2016, with both years exceeding the median by over 300 birds. Likewise, there were 60 road-killed birds in 2012 and 45 in 2016, compared to the median of 17.5 birds. The lowest numbers of rescued and road-killed birds occurred in 2018, with 74 and 7 birds respectively.

3.1 Fallout Modeling

3.1.1 Yearly Models

The number of WTSH observed per survey ranged from 0 to 10 with an average of 1.5 +/- 2.2 S.D. (median = 1) (Figure 3). There was substantial variability in the temporal aggregation of the fallout, as evidenced by the wide range of dispersion parameters (variance to mean ratio, VMR) observed (1.02 – 4.03) (Table 2) and a large proportion (46%) of absences (0 WTSH detected during a road survey) . While in most years, fallout counts followed a Poisson distribution (1< VMR < 2), the counts were highly aggregated in 2016 (VMR = 3.89) and 2019 (VMR = 4.03) (Table 2). All yearly models displayed better fit with a Poisson distribution, except for 2019, when the negative binomial model yielded a lower AICc value.

Overall, the yearly GLMs explained a wide range of the variation in fallout (quantified using the pseudo R^2) throughout the fledging season, from 18% (2017) to 64% (2014). Moreover, different variables were significant in different years (Table 2). Surprisingly, moon illumination was not consistent across years, with a significant effect in three years: it was negative twice (2013 and 2019), and it was positive once (2015). Wind speed had a significant positive effect in three years (2013, 2014, and 2016), whereby higher wind speeds led to more fallout. Wind direction had a significant positive effect once (2013), whereby winds coming from a higher degree angle (southwest) led to more fallout. Julian date was never significant as the yearly timing of fallout was fairly consistent throughout the study period. Overall, while fallout was explained well (pseudo $R^2 \geq 0.5$) by wind speed alone in 2014 and 2016, it was moderately explained (pseudo $R^2 \geq 0.3$) by moon alone in 2015 and 2019. In 2013, about half of the fallout variation was explained by a combination of wind speed, wind direction and moon. In three years (2012, 2017, and 2018), fallout was not significantly explained by any of the predictors.

Two WTSH wreck years (2012 and 2016) showed significantly higher fallout compared to the other study years (Figure 3) and together accounted for 55% of the bird carcasses found during road surveys. Those same years were responsible for 55% of all rescued birds brought to SLP throughout this study. While none of the predictor variables were statistically significant in 2012, moon and date were marginally significant ($0.10 < p\ 0.05$) (Table 2). The highest yearly fallout occurred in 2012, when 60 WTSH were grounded during two separate new moon periods: an early one (Julian days: 317 – 326, November 12-21), and a later one (Julian days: 344 – 353, December 11-18) (Figure 4). Yet, a substantial number of WTSH were also grounded during periods of higher moon illumination in 2012. However, the new moon periods were accompanied by relatively high windspeeds (Figure 5) (aside from a decline in wind speed around Julian day 325) (Figure 6). In 2016, a single new moon occurred in the middle of fledging season, leading to a single peak in fallout (Figure 4), which coincided with a period of high wind speeds (> 12 knots), increasing the number of birds fledging at this time (Figure 6).

3.1.2 Full Model

Nine models were required to achieve AICc weight of 0.90. Of the 9 variables tested, only the interaction between moon illumination and wind speed (moon*wind speed) achieved a scaled average weight above 1 (thus deeming it an "important" variable) (Table 3). Moon, wind speed, and year all had weights equal to 1, contributing an average amount to each model's weight. Date, wind direction, (moon*date), and (wind speed*date) had weights below 1, contributing less than the average variable to each

model's weight. Light regime had a weight of 0, appearing in none of the models required to achieve AICc weight of 0.90.

The overall best-fitting model had a weight of 0.37 and included four explanatory variables: moon, wind speed, year, and the interaction of moon and wind speed (moon*wind speed) (Table 4). All variables in this model were significant, except for wind speed and year 2016 (not significantly different from 2012). The negative coefficient for the moon variable in this model (-2.9) indicates that across the 8 year period, fewer birds were grounded when a greater percentage of the lunar disk was illuminated. All years except for 2016 were significantly different from the reference year (2012). The interaction between wind speed and moon had a positive coefficient (+0.23) suggesting that fallout was higher during periods of lower lunar illumination and higher wind speed (Figure 5).

3.2 Reproductive Success and ENSO

Seven of the 28 possible pair-wise correlations were meaningful ($|r| > 0.5$), but only three were statistically significant ($p < 0.05$). Because peak fallout date and median fallout date were highly correlated ($r = +0.922$, $df = 6$, $p = 0.001$), we only used median fallout date (MFD) for all subsequent analyses. Moreover, because fallout abundance and median fallout date were not correlated ($r = -0.035$, $df = 6$, $p = 0.993$), we considered these two variables separately, as uncorrelated metrics of the magnitude and timing of WTSH fallout.

Only one of the six pair-wise cross correlations between the four WTSH demographic variables yielded a strong (yet not significant) negative correlation, between the median chick peak mass (MPM) and the median hatch date (MHD). When we considered the correlations between the two fallout metrics (magnitude and timing) and the four WTSH demographic metrics, two variables were meaningful, and one was significant. The median fallout date was positively correlated with nest success (NS%), with later fallout in years with higher nest success. The log10-transformed number of grounded WTSH (L10F) was positively correlated to the median chick peak mass (MPM) and negatively correlated with the median hatch date (MHD), such that fallout was higher in years of earlier hatch date and in years when chicks reached a higher peak mass. Only the correlation between MHD and L10F was statistically significant.

When we considered the influence of the MEI before (December – May) and during (June – November) the breeding season, we documented one significant pattern of co-variability. The MEI before the breeding season was correlated ($|r| > 0.5$) with two WTSH productivity parameters: negatively with the median hatch date (MHD) and negatively with the nest success (NS%), suggesting that in warm-phase ENSO years, chicks hatched earlier, and a higher proportion of nests failed between July and September. Yet only the correlation with the nest success was significant ($p<0.05$). On the other hand, the MEI during the breeding season was not correlated to any of the WTSH productivity parameters. Overall, the MEI before the breeding season was negatively correlated with the median fallout date (MFD).

4. Discussion

The strong correlation between the yearly numbers of grounded WTSH found during our road surveys and rescued WTSH brought to SLP suggests that our surveys reflect larger scale fallout trends on O‘ahu. Both the rescue data and the survey data documented WTSH wrecks in 2012 and 2016, and the lowest fallout in 2018. Only 2.3% of the WTSH brought to Sea Life Park during the fledging season between 2012-2019 fell outside our study period (Nov. 6 – Dec. 21), suggesting that our survey window captures most of the fledging season fallout.

4.1 Model Interpretations

4.1.1 Yearly Models

While most previous studies have found strong negative relationships between moon illumination and fallout, our yearly models only showed this pattern in 2 years (Le Corre et al., 2002; Rodriguez et al., 2012; Rodriguez et al., 2014; Syposz et al., 2018; Telfer et al., 1987; Wilhelm et al., 2013). One possible explanation for this result could be a mismatch between moonrise / moonset times and WTSH fledging. We used an average lunar disk illumination for the three nights prior to each survey, assuming that this would be representative of visible moonlight while WTSH were fledging. However, if most birds fledge within an hour after sunset, before the moon rises during waning moon phases, conditions will resemble a new moon. Similarly, if island topography obscures a rising moon from a given natal colony, then navigational benefits provided by the lunar disk could be compromised until the moon rises over any obscuring landscape

features. We did not assess whether this occurs at the several colonies near our study area. The peak fledging times of WTSH are unknown but could be useful to improve our understanding of the influence of moonrise / moonset times on fallout. Furthermore, the lack of strong lunar trends in the yearly models could be due to small sample sizes, as each year only included 16 surveys.

The influence of the predictor variables wind speed, wind direction, moon, and date were not consistent across all 8 years. Contrary to Rodriguez et al. (2014), who found a significant date effect, with increasing fallout as the fledging season progressed, we found no effect of date. However, the likelihood of finding an effect of date depends partly on the timing and the duration of the study period. While opportunistic studies using intake records and citizen-science programs sample a wider temporal window, spanning before and after the fledging season, our surveys spanned a narrow temporal window during the WTSH fledging season. In summary, our results suggest that, due to interannual variability in the timing and magnitude of fallout, on average it is distributed evenly throughout this period (Nov. 6 – Dec. 21). Fledging primarily occurs during this 6-week period, and is likely modulated by a variety of factors, including breeding phenology, chick development, and environmental conditions (Hyrenbach et al., 2011; Rodriguez et al., 2012; Rodriguez et al., 2014).

The positive relationship between wind speed and fallout is likely related to the fledglings relying on wind to take flight and using this environmental cue for fledging. One possible explanation for why we observed more fallout with higher windspeeds is that intermediate wind speeds enable WTSH fledging, but strong onshore winds blow the

birds toward land and, thus into our study area, where they are susceptible to artificial lights and obstacles.

Although the model results suggest that wind speed is more important than wind direction, an exception to this general pattern was observed in 2013, when peak fledging coincided with a period of moderate to weak southerly winds (Figure S1). A previous study on O‘ahu found that winds from the southeast were more common during a year of very high fallout compared to the two years prior, and hypothesized that birds were advected to the northwest and deposited along the entire windward coast of the island (Work and Rameyer, 1999). The lack of significance of wind direction may be related to the prevailing wind patterns on windward O‘ahu, which rarely switch from the northeast direction, thus limiting the comparison of different wind directions. Furthermore, because south-westerly winds during the study are characterized by lower speeds, any potential influence of direction is not independent from the wind speed effect discussed previously (Figure S2).

Previous studies show an increase in fallout when prevailing winds are directed toward brightly lit coastal areas (Rodriguez et al., 2014; Syposz et al., 2018). Yet, the influence of wind direction is difficult to interpret since headings are circular (0-360 degrees) and should be carefully considered on a case-by-case basis. Because the prevailing winds in our study area are the northeasterly trade winds or southern (Kona) storms, these bi-directional wind headings facilitated the analysis and simplified the interpretation (Figure S2). With the exception of 2013, peak fallout occurred during trade winds (Figure 6).

Although our study did not show a significant effect of Julian date on fallout, previous road survey records from O‘ahu spanning from 2002 to 2010, revealed that November 25 was the peak fallout date, with 67% of the carcasses found during a one-week period (21-27 November) (Friswold et al., 2020). Whether the moon is closer to the full or new phase during this peak time could explain why the trends between moon illumination and fallout vary across years.

In 2015, the full moon occurred around November 28, whereas in 2013 and 2019 the moon phase was closer to a new moon on that date. It appears that when peak fledging coincides with a new moon, a single fallout peak occurs, thus showing a negative influence of moon illumination. However, if peak fledging coincides with a full moon, the unimodal pattern breaks down, resulting in two smaller fallout peaks. Previous work shows a quadratic relationship between the timing of the full moon and the number of Newell’s shearwater (*Puffinus newelli*) groundings, with fewer total groundings when the full moon occurs during the middle of the month (Ainley et al., 2001). However, our results showed no linear trend ($R^2 = 0.009$, p=0.82, df=1,6, $F_{1,6}=0.056$) (Figure 7), despite having normally distributed regression residuals (W= 0.913, p-value = 0.3758). We also tested a quadratic fit and found no significance ($R^2 = 0.038$, p=0.39, df=2,5, $F_{2,5}=1.140$) despite having normally distributed residuals (W= 0.95, p-value = 0.69). Given these weak model fits, the timing of the moon does not seem to be the main driver of the annual magnitude of fallout.

These disparate yearly effects of moon and wind speed, and the lack of a pervasive “date” effect underscore the high variability in yearly fallout patterns. Moreover, it is critical to consider that the high degree of aggregation of the fallout

counts, in years of high (2012, 2016) and low (2019) fallout, is inherently difficult to model. Therefore, the full (multi-year) model including “date*moon” and “date*wind” interactions, and the dummy variable “year” should be given the most consideration.

4.1.2 Full Models

The higher than average variable weight of the interaction between moon and wind speed suggests that fallout is a dynamic process, driven by the synergy of low moon illumination and strong winds, more so than by moon or wind alone (Figure 5). While previous studies have identified the importance of moon and wind, this is the first time their interaction has been considered.

This significant interaction underscores a conceptual model, whereby wind speed determines the magnitude of fledging birds departing their colonies, and the moon illumination determines the attraction of those fledglings toward onshore lighting. This conceptual model can explain why years like 2016, where the peak of the fledging season coincided with a new moon and high wind speeds, have greater fallout (Figure S3).

While the interaction of the lunar illumination and the wind speed was important, the timing of these variables, captured using their interactions with date, were less important. Together, these results suggest that within the time frame of our study, fallout is most dependent on the temporal overlap of low moon illumination and high winds, rather than on their specific timing.

Our hypothesis that the LED streetlights would increase shearwater attraction due to higher sensitivity to shorter wavelengths was not supported, as the light regime was

not present as a predictor variable in any of the top models. It is possible that shearwater visual perception of LED lights was in fact greater, but shielding reduced initial attraction, thus balancing out overall groundings. However, even if this were the case, it is impossible to distinguish these two factors in our analysis, because the changes in bulb type and shielding were not independent. Furthermore, it is possible that, even if there is an effect of light type, it may be marginal compared to the environmental effects discussed previously. Nonetheless, the findings have useful implications for resource managers since this streetlight model is a common replacement for HPS lights in Hawai‘i and elsewhere. While we encourage managers to seek lighting adjustments that will mitigate fallout, our study shows that the change to the shielded LED streetlights was not further exacerbating the problem.

A recent survey of lighting experts suggests that while LEDs can be adjusted to reduce light pollution and minimize wildlife impacts, yet municipalities rarely capitalize on those benefits (Shulte-Romer et al., 2019). For instance, while new-technology LED streetlights can filter out lower wavelengths (Longcore, 2018), full spectrum white LED lights maximize brightness, and are commonly chosen to replace HPS streetlights. Furthermore, LEDs come in a variety of correlated color temperatures (CCT), with options as low as 2200 º K, well below the expert recommendation of 2700 º K temperature for wildlife (Shulte-Romer et al., 2019). However, municipalities commonly implement 3000 -5000 º K LED streetlights because of their efficiency for human use (Shulte-Romer et al., 2019).

4.2 Reproductive Success and ENSO

The strong negative correlation between the median chick peak mass (MPM) and the median hatch date (MHD) suggests that chicks attained a lower peak mass in years when they hatched later, reinforcing previous findings from a study comparing chick development at this colony during a warm-water year (2009) and a "normal" year (2010) (Hyrenbach 2011). Overall, MEI conditions before the breeding season were cross-correlated with the timing of fallout (MFD), and this relationship was mediated by the cross-correlations between MEI and two WTSH productivity metrics (median hatch date, and nesting success). Once we removed the influence of MEI on WTSH productivity using semi-partial correlations, only the timing of hatching (MHD) had a strong correlation with the magnitude of WTSH fallout (Figure 8) indicating that years when chicks hatched earlier (lower median hatch date) the magnitude of fallout was greater. A possible explanation for this co-variation is that breeding occurs earlier when there are more pairs nesting, so the higher magnitude of fallout in these years is reflective of a higher fledgling population. However, this is not entirely clear. Given the negative relationship between pre-breeding MEI and nest success, we would expect to see lower fledgling populations in years with high MEI.

While we observed a relationship between median hatch date at the Freeman Seabird Preserve and annual fallout magnitude, we suspect that trends would be clearer if the productivity data came from a larger colony. Unfortunately, we lack complete monitoring records for Mānana and Kāohikaipu, the islets nearest to our survey area, which account for 73.6% of the WTSH population on southeast windward Oʻahu (Figure S4). For this reason, we cannot discount the notion that the magnitude of fallout varies with fluctuations in population. Consistent population monitoring at the larger colonies is

necessary to address this. Monitoring chick phenology at larger colonies would provide useful insight regarding productivity and fallout on a larger scale.

5. Conclusion

Our results are encouraging because they suggest that the shielded LED streetlights are not increasing fallout, as we hypothesized. However, the new lights did not reduce fallout either. Modifications to existing streetlights near breeding colonies, such as dimming, wavelength alteration or motion sensors should be explored as possible mitigation methods (Raine et al., 2007; Shulte-Romer et al., 2019). While it may be unfeasible to reduce light in all areas where fallout occurs, fallout hotspots could be targeted for localized management. In addition to diminishing light pollution during the fledging season, we encourage the continuation of community-based rescue efforts on Oʻahu and recommend active searches for WTSH on nights with low moon illumination and strong winds. Further studies to document fallout locations on other areas of Oʻahu would help guide lighting management and rescue efforts throughout the island. Finally, predictive fallout models are limited by the lack of comprehensive annual population estimates, which might have explained some of the interannual variation in the number of grounded birds. Future efforts to document annual population estimates for WTSH in Hawaiʻi would likely improve our understanding of fallout trends.

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Table 1. Comparison of annual WTSH fallout magnitude (total numbers of birds) and timing (date ranges) between Sea Life Park and this study. Because this study involved 16 standardized surveys spanning November 6 to December 21, summary statistics (mean, median, and range of birds per survey), are reported for each year.

	Sea Life Park			Road Surveys					
Year	Total	First intake	Last intake	Total	First sighting	Last sighting	Mean	Median	Range
2012	469	2-Nov	4-Jan	60	9-Nov	21-Dec	3.75	3.50	0-9
2013	172	22-Oct	5-Jan	11	24-Nov	9-Dec	0.69	0.00	0-3
2014	160	14-Nov	23-Dec	13	18-Nov	18-Dec	0.81	0.50	0-2
2015	124	22-Oct	23-Dec	19	15-Nov	21-Dec	1.19	1.00	0-3
2016	525	30-Oct	27-Dec	45	6-Nov	27-Nov	2.81	1.00	0-10
2017	159	2-Nov	21-Dec	16	6-Nov	12-Dec	1.00	1.00	0-4
2018	74	23-Oct	31-Dec	7	19-Nov	9-Dec	0.44	0.00	0-2
2019	126	6-Nov	2-Jan	21	19-Nov	4-Dec	1.31	0.00	0-7

Table 2. GLM output of annual fallout models, based on 16 surveys (Nov. 6 – Dec 21) (p =

Poisson distribution, nb = negative binomial distribution, * indicates significant at alpha=0.05).

Year	Dis.	VMR	Pseudo Adj. R^2	Estimate					p-value				
				Int.	WS	WD	Moon	Date	Int.	WS	WD	Moon	Date
2012	p	2.11	0.41	-29.293	-0.744	-0.032	-0.065	0.137	0.096	0.236	0.408	0.071	0.054
2013	p	1.50	0.51	-28.120	0.684	0.029	-4.944	0.065	0.146	0.028*	0.016*	0.006*	0.211
2014	p	1.02	0.64	3.055	0.393	0.003	-1.659	-0.020	0.751	0.045*	0.782	0.144	0.456
2015	p	1.14	0.33	-3.680	0.03	-0.001	1.993	0.008	0.575	0.818	0.902	0.006*	0.720
2016	p	3.89	0.50	-0.169	0.268	0.002	0.439	-0.006	0.979	0.034*	0.816	0.507	0.777
2017	p	1.20	0.18	8.690	0.099	-0.002	-0.854	-0.027	0.291	0.273	0.638	0.291	0.309
2018	p	1.20	0.57	-20.160	-0.190	-0.001	-1.592	0.064	0.183	0.546	0.959	0.261	0.178
2019	nb	4.03	0.26	42.940	-0.100	-0.022	-3.305	-0.115	0.056	0.543	0.196	0.004*	0.055

Table 3. Scaled average variable weights. (>1 values indicate greater than average weight when variable was included in model; weights = 1 are average, weights <1 less than average).

Explanatory variable	Scaled avg. weight
(WS*Moon)	1.088
WS	1.000
Moon	1.000
Year	1.000
Date	0.643
(Moon*Date)	0.643
WD	0.626
(WS*Date)	0.527
Light	0.000

Table 4. Output from best-fit multi-year model. Reference year = 2012.

(* significant at alpha=0.01, ** significant at alpha=0.001).

Explanatory variable	Estimate	S.E.	Z-value	p-value
Intercept	2.136	0.580	3.709	<0.001**
WS	-0.027	0.046	-0.576	0.565
Moon	-2.884	0.827	-3.485	<0.001**
Year2013	-1.711	0.447	-3.825	<0.001**
Year2014	-1.685	0.406	-4.148	<0.001**
Year2015	-1.490	0.365	-4.082	<0.001**
Year2016	-0.373	0.324	-1.148	0.251
Year2017	-1.661	0.391	-4.247	<0.001**
Year2018	-2.492	0.483	-5.153	<0.001**
Year2019	-1.034	0.366	-2.824	0.005*
WS*Moon	0.225	0.083	2.710	0.007*

Table 5. Pearson correlation coefficients (r) and associated significance (p value) of WTSH fallout with demographic and oceanographic variables. (MFD=median fledging date, FL10=Fallout (log_{10}), MHD=median hatch date, MPMD=median peak mass date, MPM=median peak mass, NS%=nest success (% remaining from July to September), MEI-PB= average MEI pre breeding, MEI-BR=average MEI during breeding). =Bold font denotes significant at alpha=0.05. Grey shaded area shows the correlations between the four demographic variables.

r / p	MFD	L10F	MHD	MPMD	MPM	NS%	MEI-PB	MEI-BR
MFD	-	0.933	0.253	0.489	0.972	0.173	0.091	0.634
L10F	-0.035	-	**0.028**	0.302	0.096	0.839	0.225	0.814
MHD	+0.458	***-0.761***	-	0.720	0.178	0.607	0.143	0.882
MPMD	+0.287	+0.418	+0.151	-	0.214	0.743	0.958	0.961
MPM	-0.015	*+0.627*	*-0.529*	0.493	-	0.411	0.511	0.646
NS%	*+0.534*	-0.086	+0.216	-0.139	-0.339	-	**0.040**	0.283
MEI-PB	***-0.635***	+0.482	*-0.566*	+0.022	+0.274	***-0.729***	-	0.591
MEI-BR	+0.200	-0.099	+0.063	+0.021	+0.193	-0.433	+0.226	-

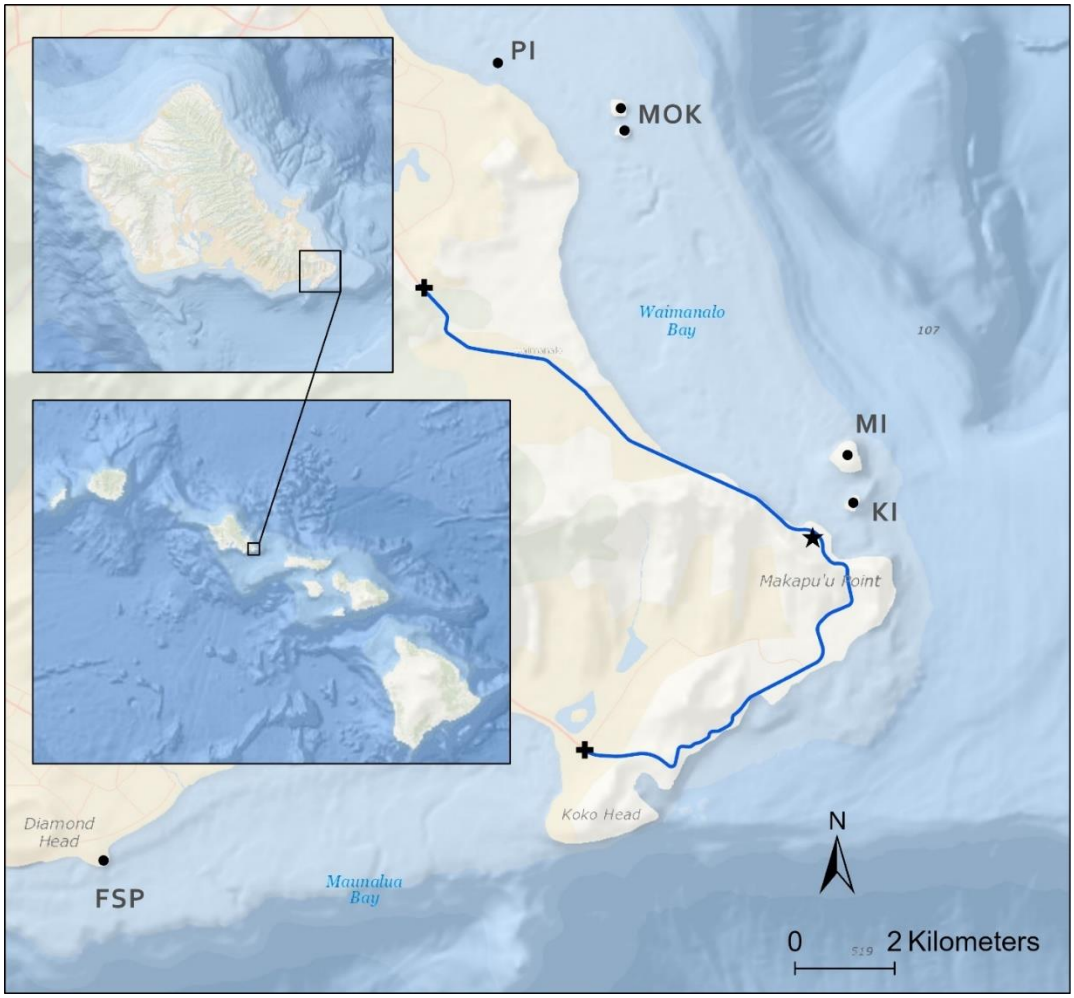

Figure 1. Map of the study area, in southeast Oʻahu. Blue line indicates survey route, crosses indicate start and end points. Black dots indicate breeding colonies. (PI = Popoiʻa Island, MOK = Mokulua Islands, MI = Mānana Island, KI = Kāohikaipu Island, FSP = Freeman Seabird Preserve). Star indicates Sea Life Park seabird rehabilitation center. Inset maps show the island of Oʻahu, and the main Hawaiian island chain.

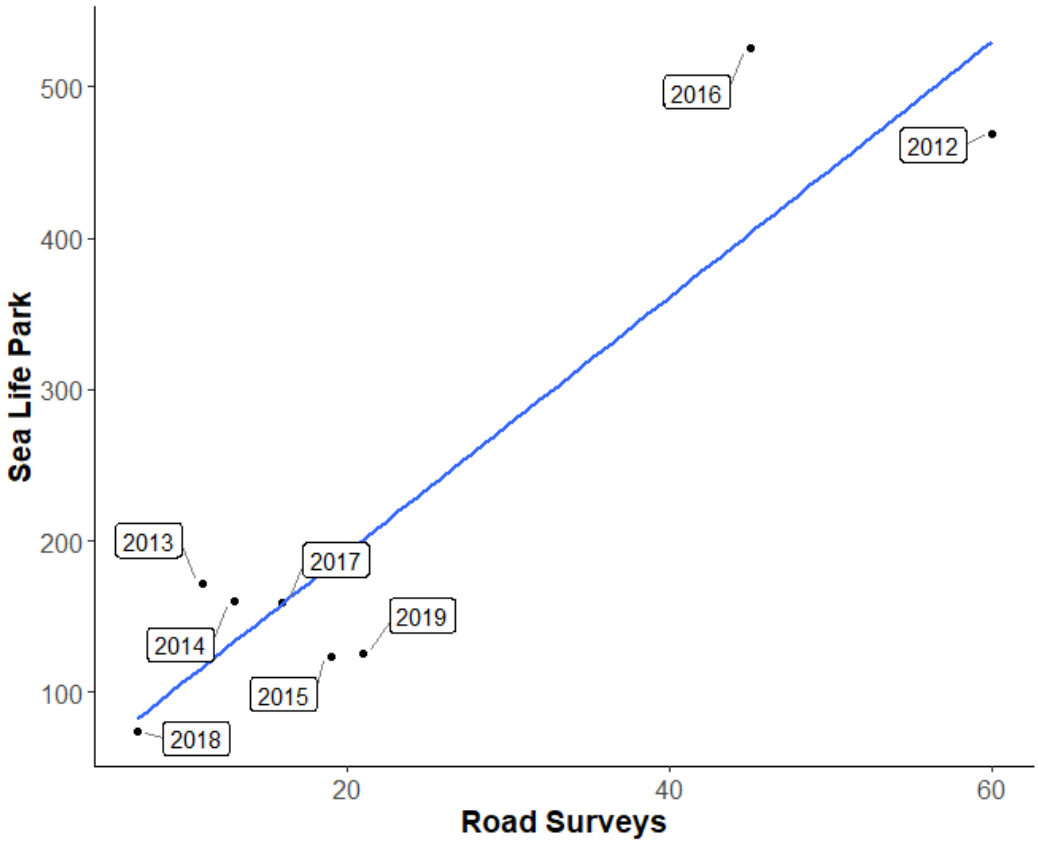

Figure 2. Scatterplot showing the total rescued WTSH per year from Sea Life Park intake records versus total WTSH carcasses documented per year during road surveys (r^2 = 0.85).

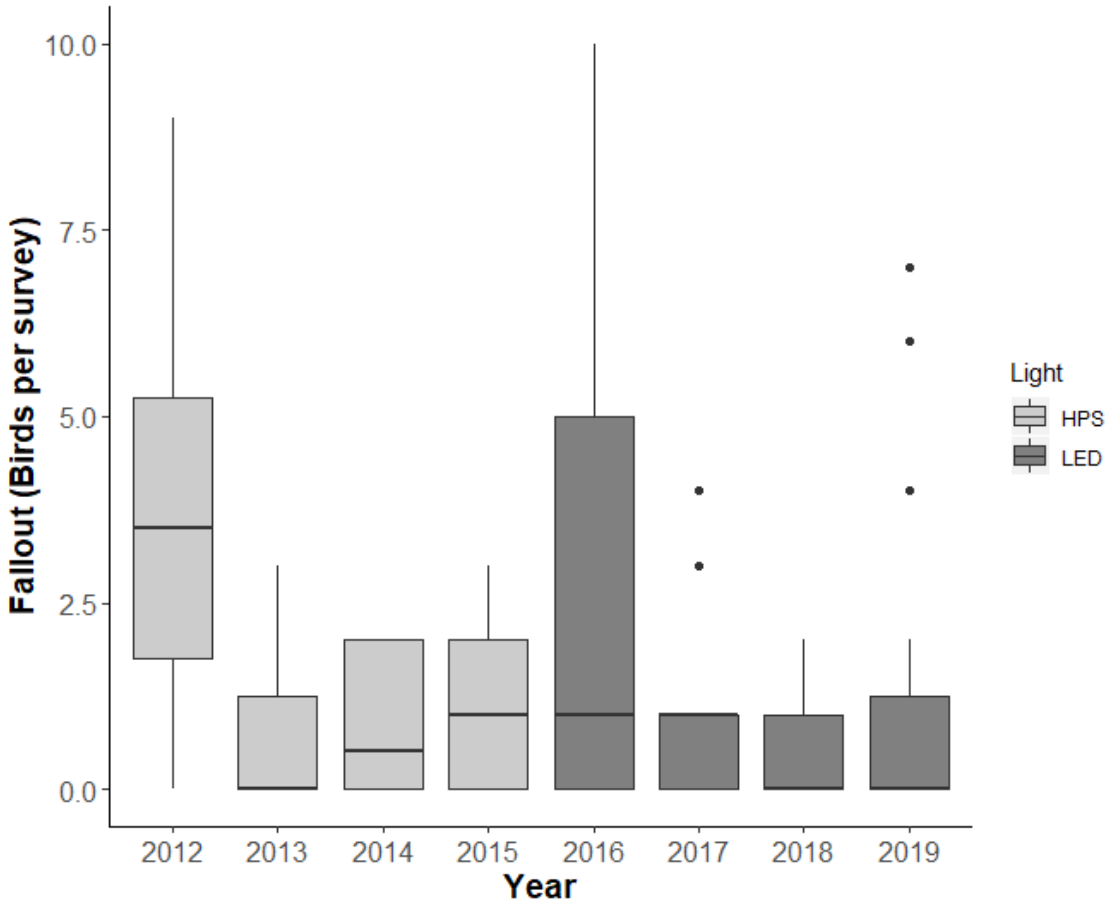

Figure 3. Box and whisker plot of the number of grounded WTSH observed per survey during annual road surveys. Black dots indicate outliers.

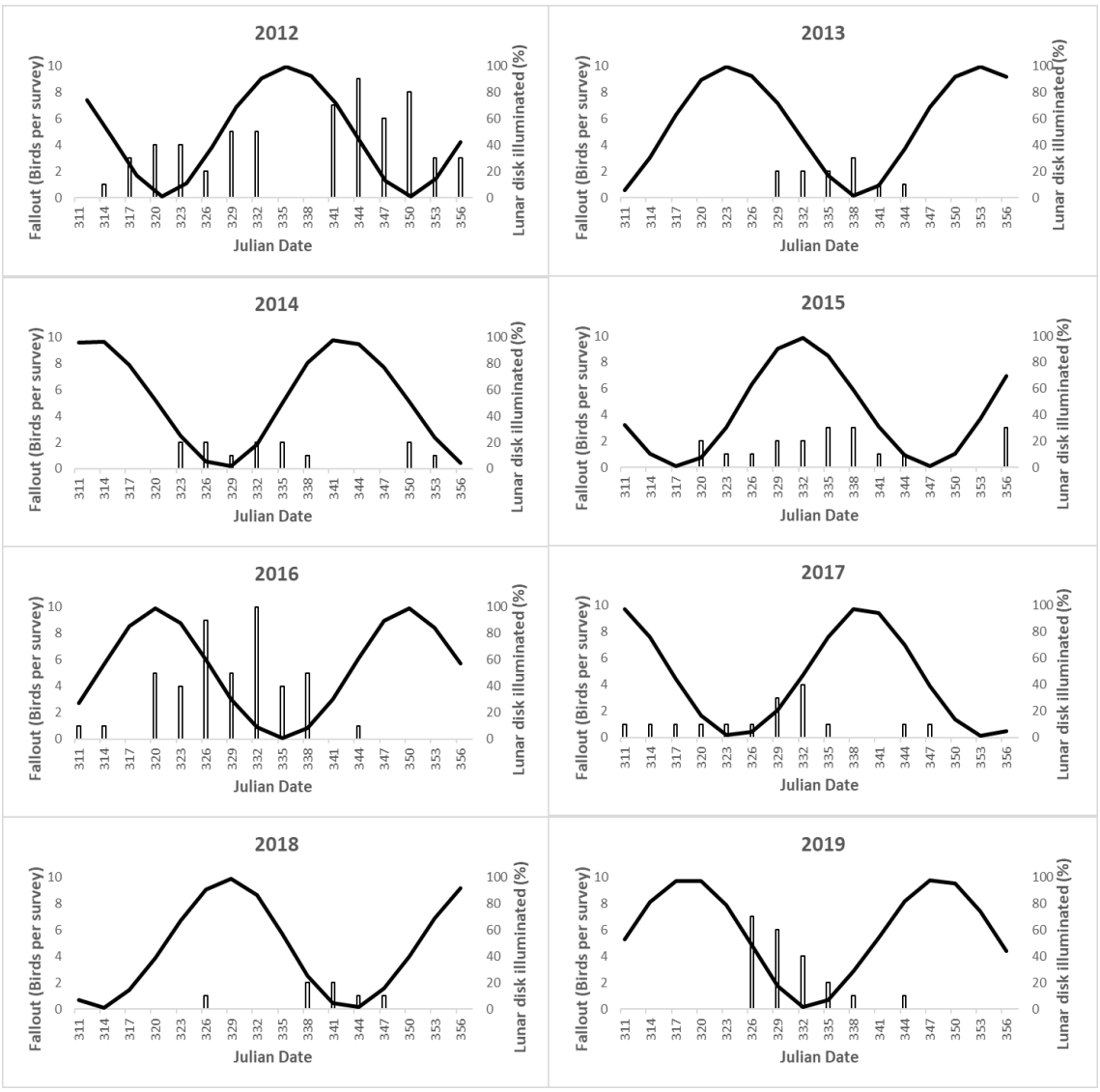

Figure 4. Time series of the number of new WTSH carcasses observed per survey (white bars) and nightly lunar illumination (back lines). Dates on x-axes are days that a survey was conducted, the absence of a white bar indicates that zero birds were observed during that survey.

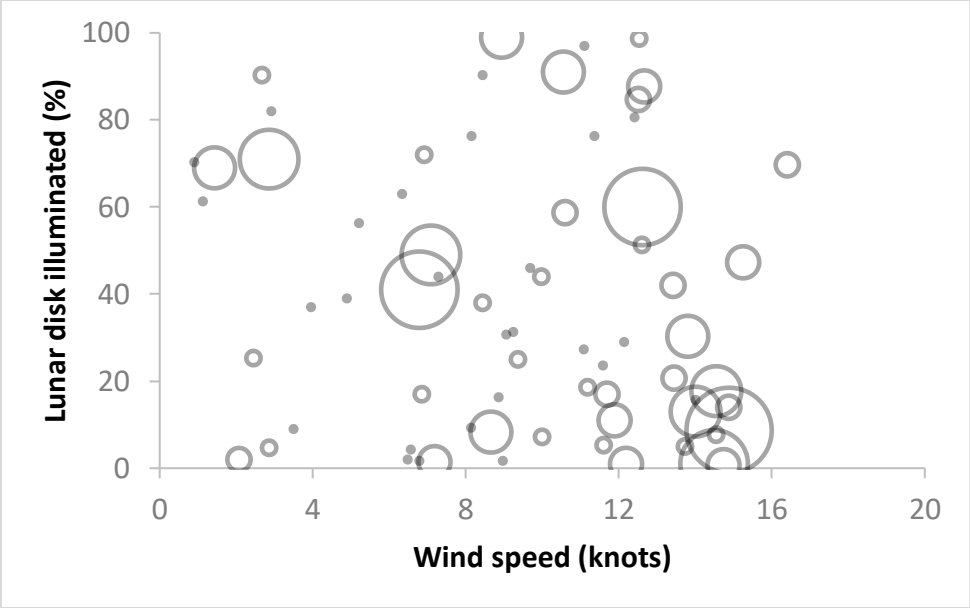

Figure 5. Scatterplot of the number of WTSH found during road surveys, in relation to wind speed, and moon illumination. Birds represented by gray circles of increasing radius, ranging from 0 to 10.

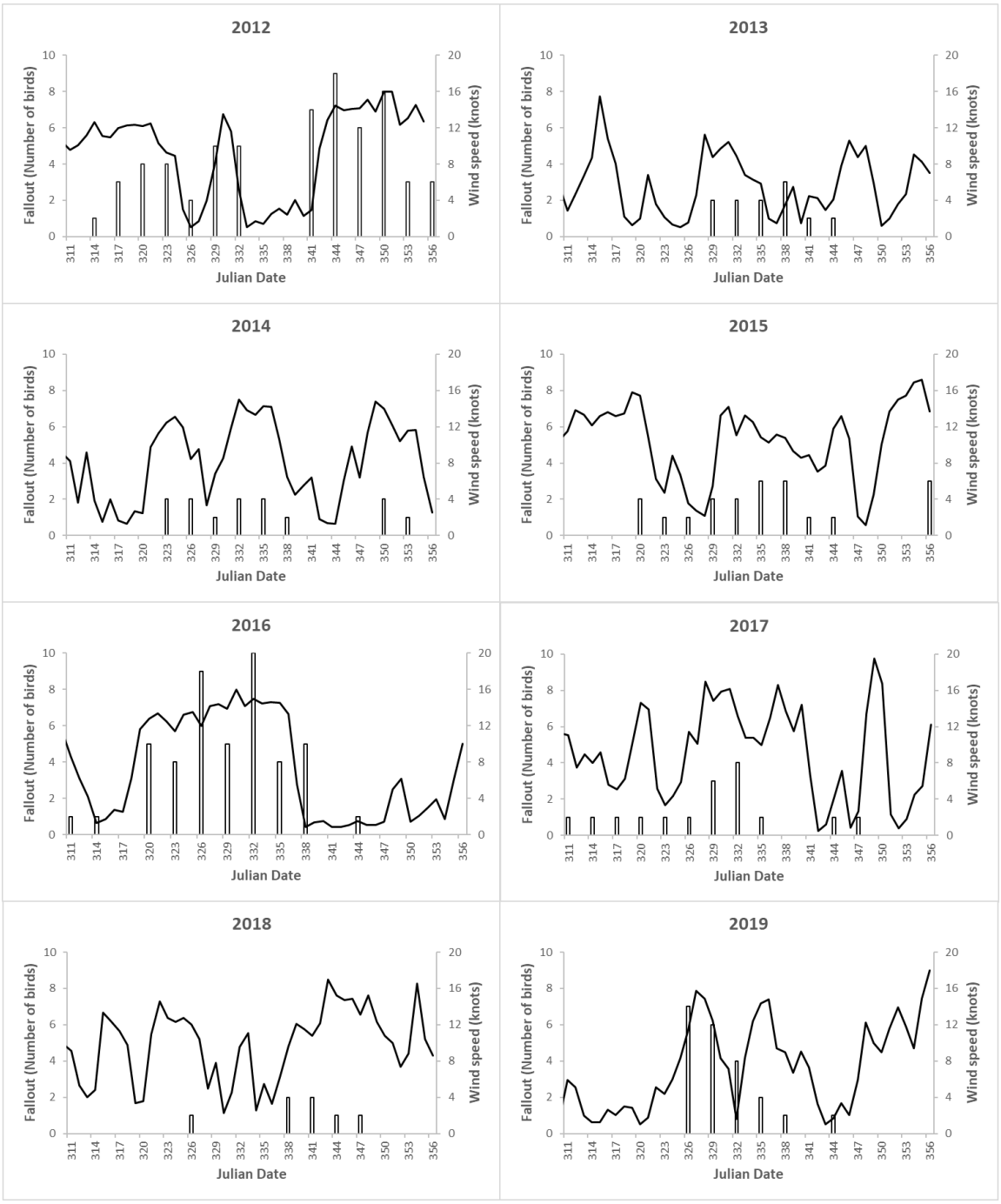

Figure 6. Time series of the number of new WTSH carcasses observed per survey (white bars) and nightly wind speed (back lines). Dates on x-axes are days that a survey was conducted, the absence of a white bar indicates that zero birds were observed during that survey.

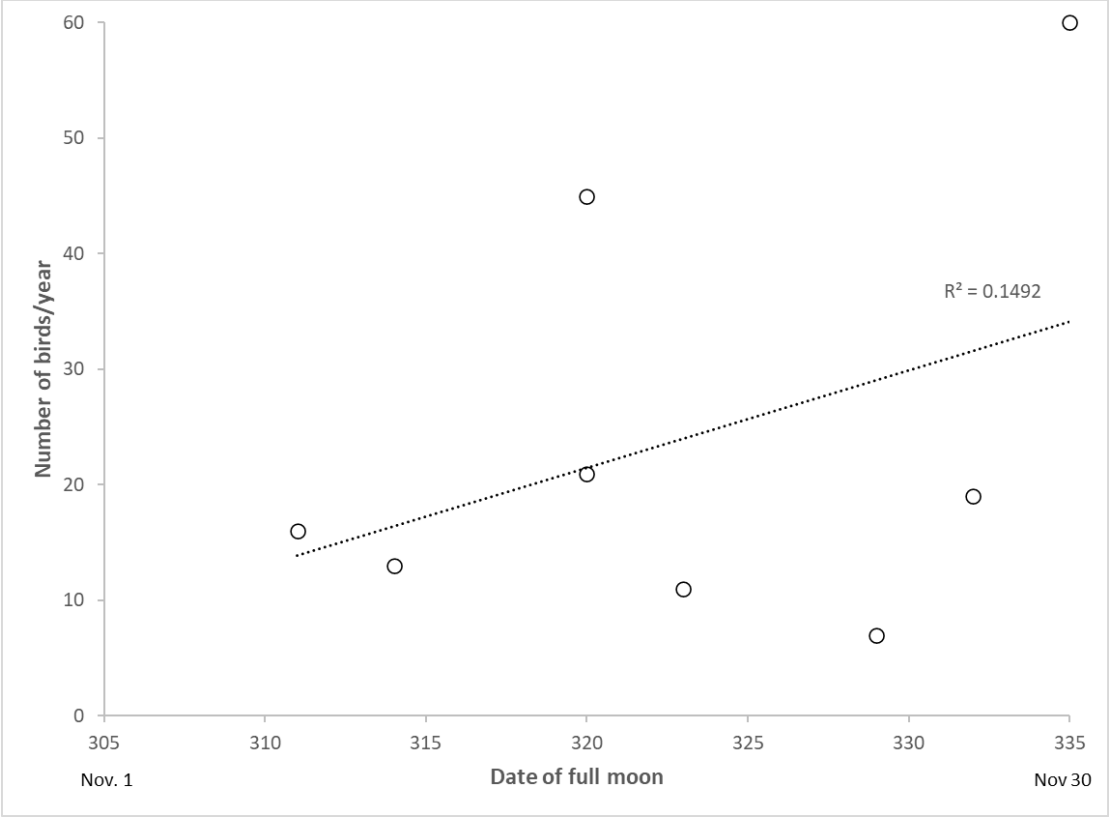

Figure 7. Scatterplot showing the relationship between the date of the first full moon in November and the number of birds found each year ($R^2 = 0.15$).

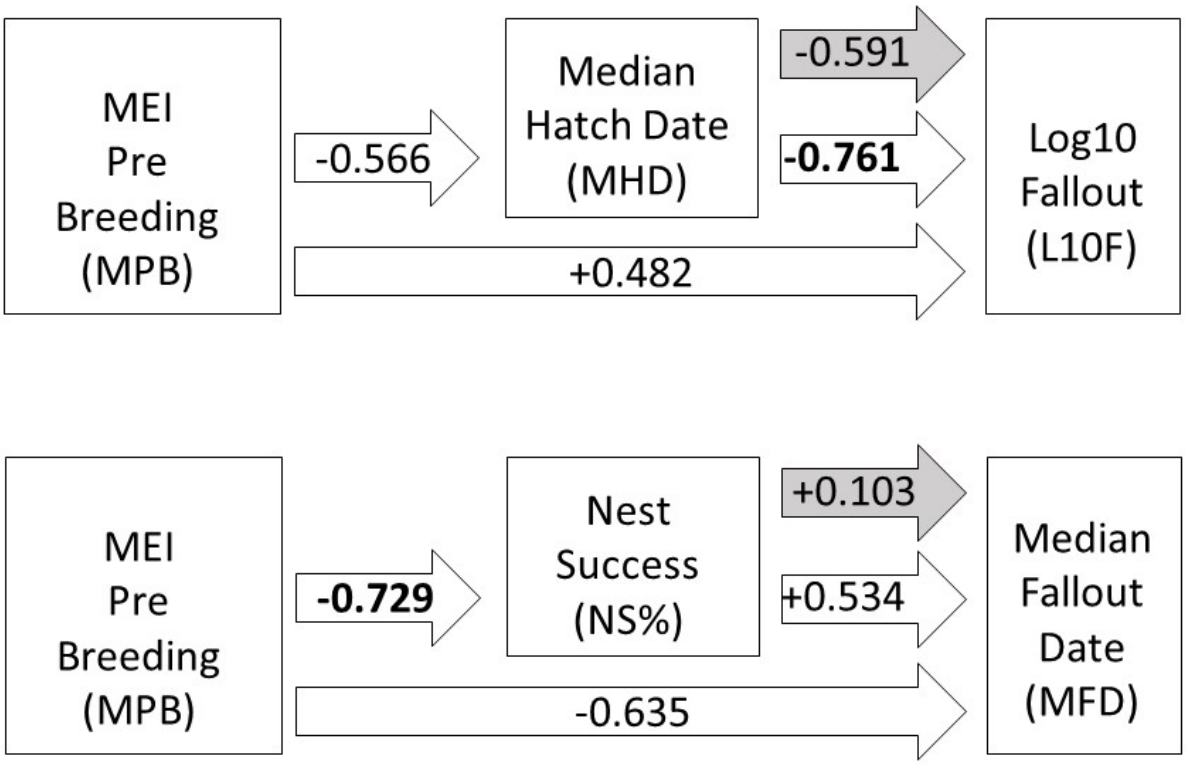

Figure 8. Path diagram, showing the correlations between two fallout metrics, two WTSH demographic metrics, and MEI conditions. Statistically significant Pearson correlations are shown in bold font. Semi-partial correlations, accounting for the influence of MEI on the WTSH demographic metrics are shaded grey.

Supplementary Materials

Table S1. Model combinations used in full 8-year model AIC analysis. (WS=Wind speed, WD=Wind direction, Date=Julian date, Moon=% Lunar disk illuminated, Light=HPS or LED regime, Year=2012-2019). Total=106 models.

Birds per survey ~		
Models with neither "Light" nor "Year"	*Models with "Light"*	*Models with "Year"*
Moon	Light	Year
WS	Moon+Light	Moon+Year
WD	Date+Light	Year+Date
Date	WS + Light	WS + Year
WS+WD	WD + Light	WD + Year
Moon+Date	WS+WD+Light	WS+WD+Year
WS + Moon	WD+Date+Light	Moon+Year+Date
WS + Date	WS+Date+Light	WD+Date+Year
WD + Moon	WD+Moon+Light	WS+Date+Year
WD + Date	WS+Moon+Light	WD+Year+Moon
WS+WD+Moon	Light+WD+Moon	WS+Year+Moon
WS+WD+Date	WS+WD+Moon+Light	WS+WD+Moon+Year
WD+Date+Moon	Moon+Date+Light+(Moon*Date)	Moon+Date+Year+(Moon*Date)
WS+Date+Moon	WS+Moon+Date+Light	WS+Moon+Date+Year
Moon+Date+(Moon*Date)	WD+Moon+Date+Light	WD+Moon+Date+Year
WS+Date+(WS*Date)	WS+WD+Date+Light	WS+WD+Year+Date
Moon+WS+(WS*Moon)	WS+Light+Date+(WS*Date)	WS+Year+Date+(WS*Date)
WS+WD+Moon+Date	WS+Moon+Light+(WS*Moon)	WS+Moon+Year+(WS*Moon)
WS+WD+Moon+(WS*Moon)	WS+WD+Moon+Date+Light	WS+WD+Moon+Date+Year
WS+WD+Date+(WS*Date)	WS+WD+Moon+Light+(WS*Moon)	WS+WD+Moon+Year+(WS*Moon)
WS+Moon+Date+(Moon*Date)	WS+WD+Date+Light+(WS*Date)	WS+WD+Date+Year+(WS*Date)
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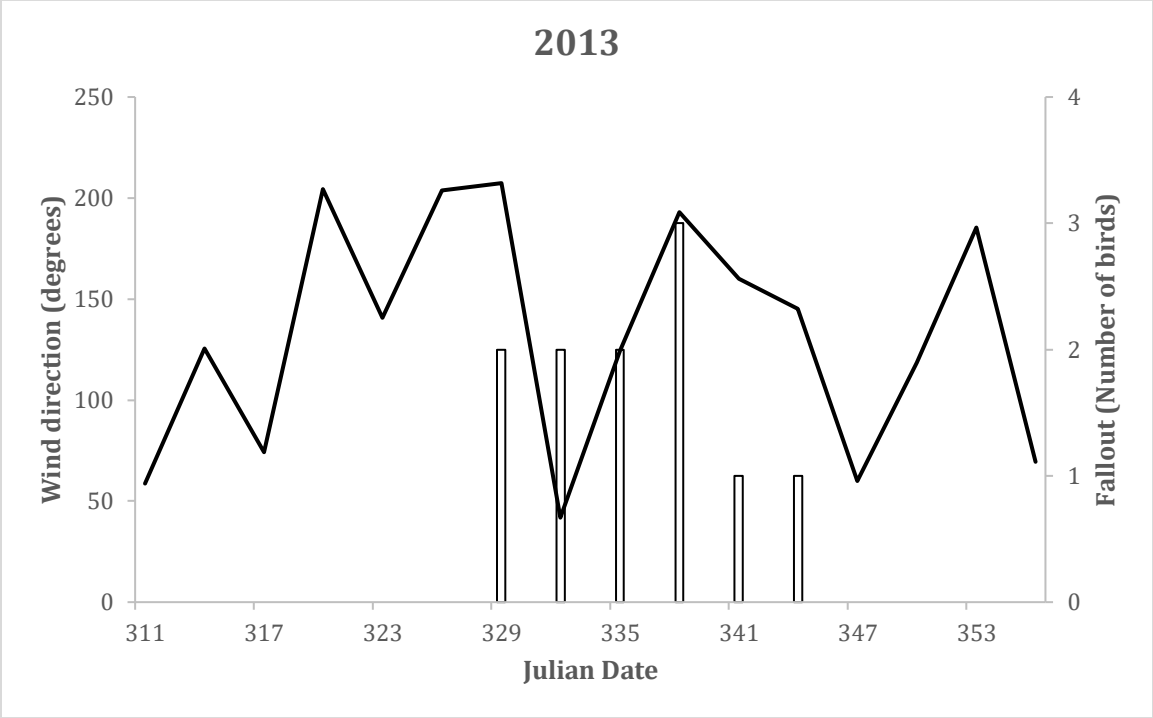

Figure S1. Wind direction and fallout during the 2013 fledging season. Black line is wind direction and white bars are number of birds per survey.

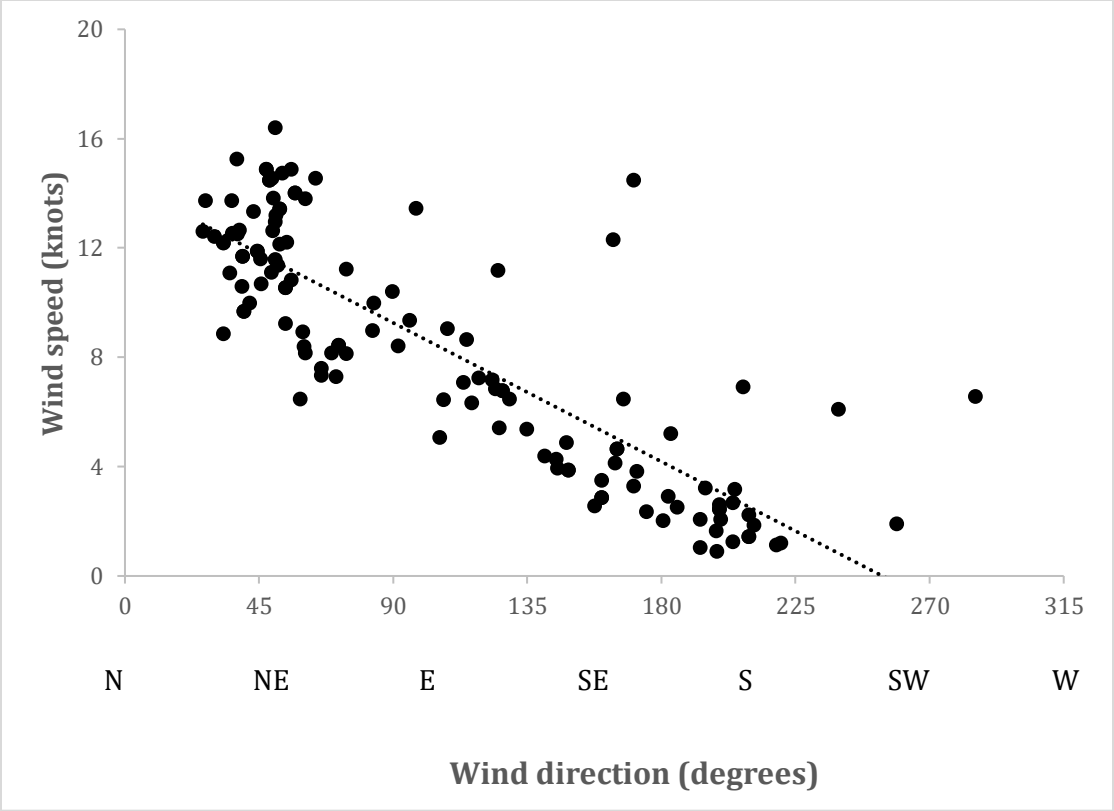

Figure S2. Scatterplot of wind speed and wind direction during the fledging seasons 2012-2019 (R^2 =0.71).

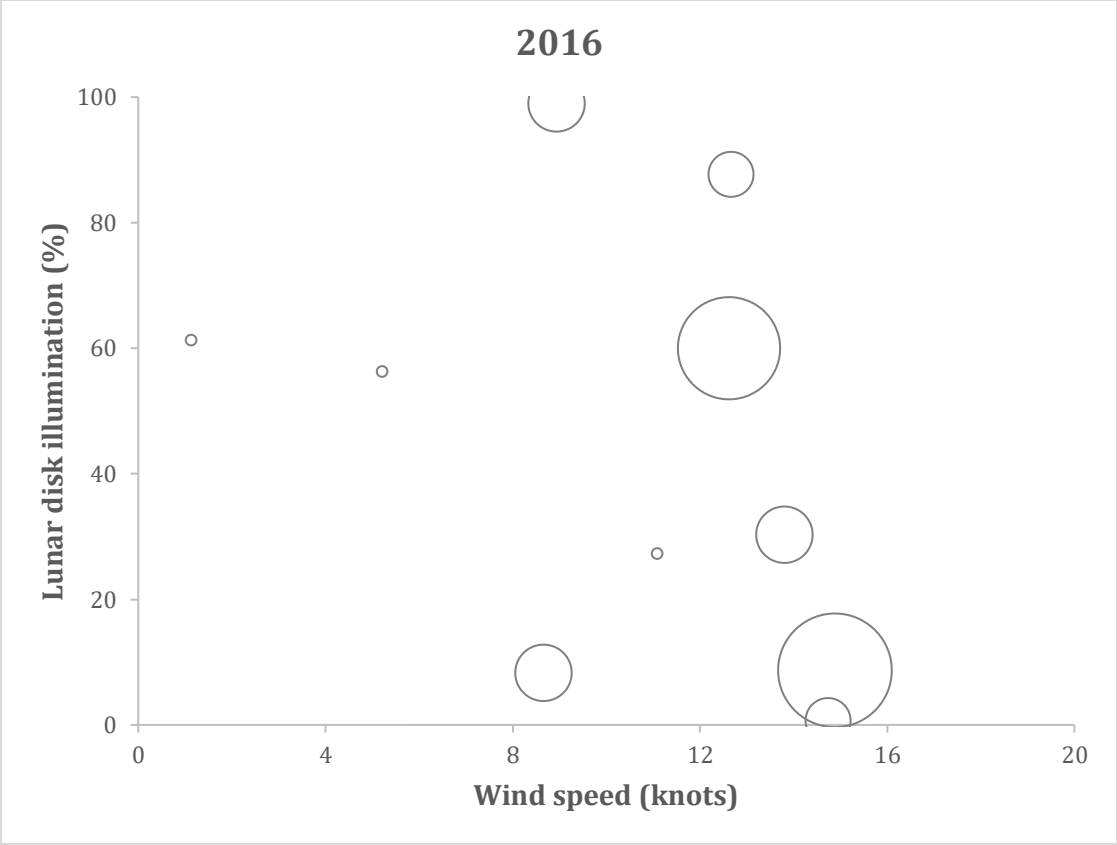

Figure S3. The number of birds found during road surveys in 2016, in relation to wind speed, and moon illumination. Birds represented by gray circles of increasing radius, ranging from 0 to 10.

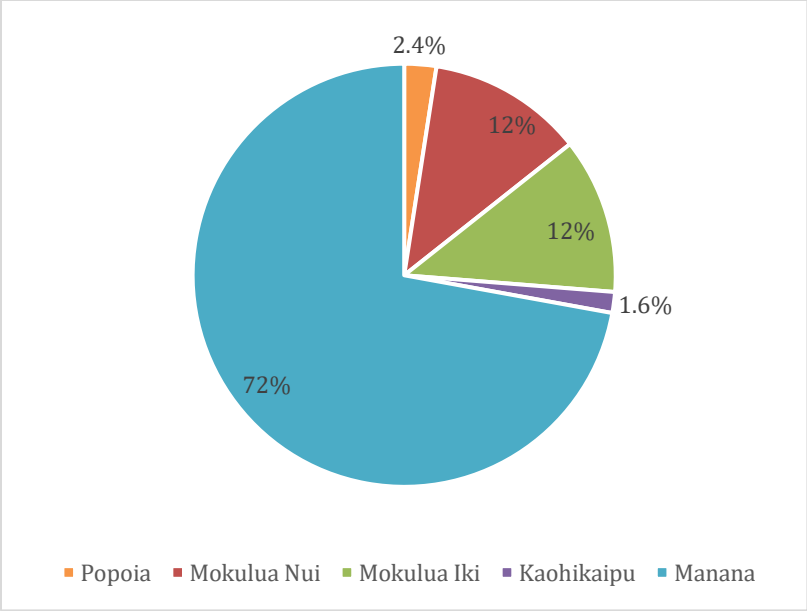

Figure S4. Relative WTSH colony sizes on southeast, windward O‘ahu. Figures are based on averages of chick counts conducted by DOFAW from 2012-2019.

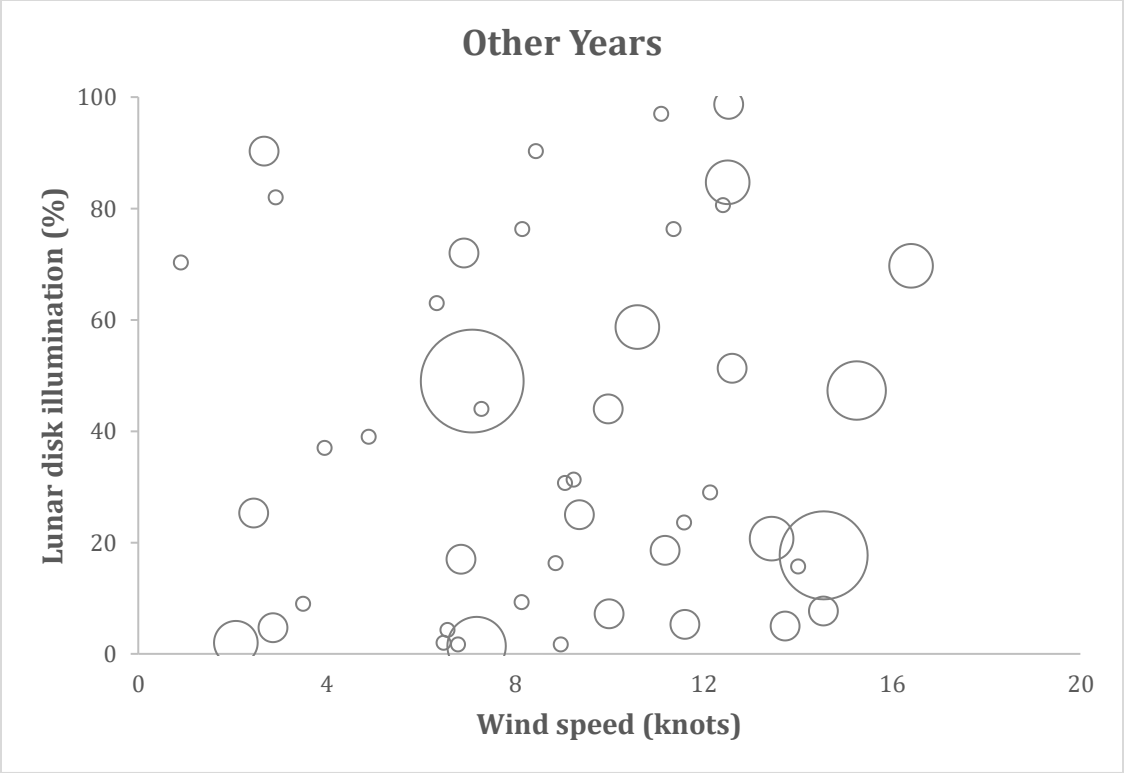

Figure S5. The number of birds found during road surveys in 2013-2015 and 2017-2019, in relation to wind speed, and moon illumination. Birds represented by gray circles of increasing radius, ranging from 0 to 7.

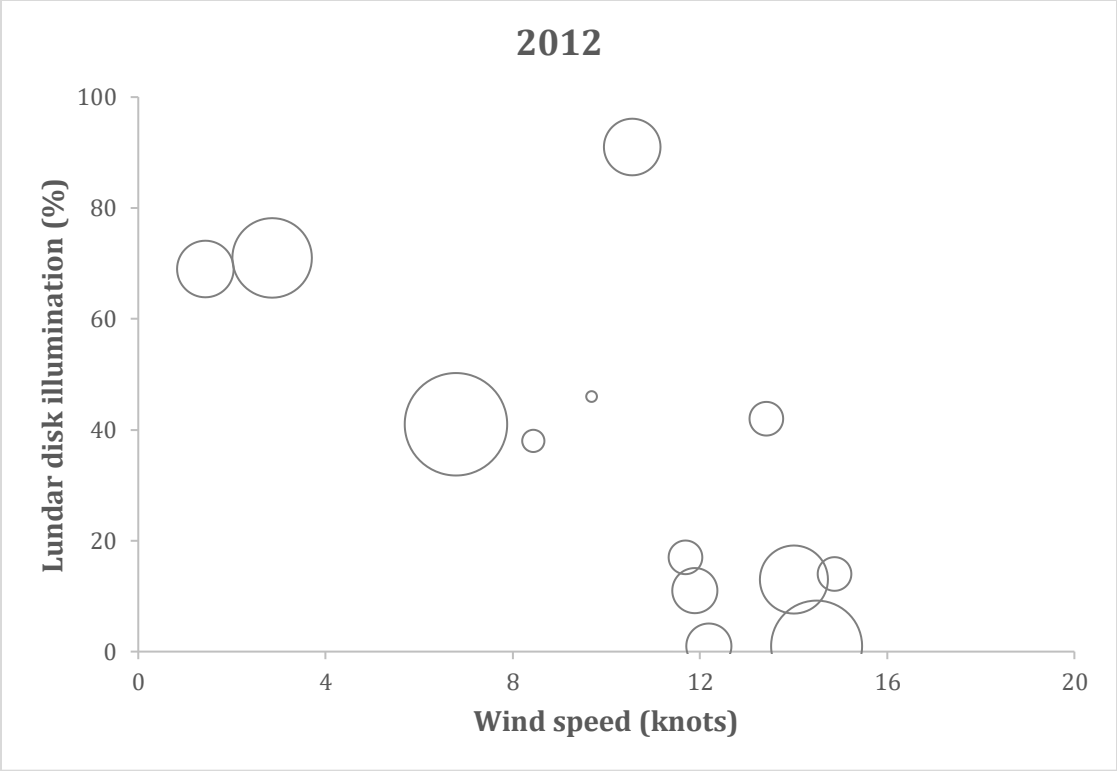

Figure S6. The number of birds found during road surveys in 2012, in relation to wind speed, and moon illumination. Birds represented by gray circles of increasing radius, ranging from 0 to 9.

Chapter 3

Spatial Analysis of Wedge-tailed Shearwater Fallout on Southeast Oʻahu, Hawaiʻi

Abstract

Attraction to artificial light at night causes hundreds of fledgling Wedge-tailed Shearwaters (*Ardenna pacifica*) to strand on land every year. Fallout hotspots have been identified near brightly lit structures, like sports fields and resorts. In this study, we explored the spatial distribution of grounded shearwaters to quantify the drivers of fallout hotspots. We used an 8-year time series of road surveys, spanning a change in highway lighting, to document the timing and GPS location of road-killed shearwaters along a coastal highway on southeast Oʻahu, during which a change in highway lighting occurred. We compared fallout distribution during four years (2012-2015) with high pressure sodium (HPS) streetlights and during four years (2016-2019) with light-emitting diode (LED) streetlights, and did not find a spatial difference between these two lighting regimes. We also compared the spatial distribution of fallout across three wind regimes, north-northeast trade winds (NNE), east-northeast trade winds (ENE), and light variable winds (LV), finding no difference across regimes. Using a fishnet grid to divide our survey route into sections co-registered with remotely-sensed light imagery from NASA, we modelled the effect of physical structures and geographical features on the number of carcasses found within each cell. Distance to the colony, night-time radiance, and road length were significant predictors, with more WTSH carcasses found in grid cells with

longer road sections, higher radiance values, and shorter distance to the colony. We identified three fallout hotspots which were associated with proximity to the primary breeding colony on Mānana Island, an unobstructed view of highway lights from the colony, and the presence of unshielded bright lights in relatively darker regions. Our findings suggest that management should target brighter areas in close proximity (<6 km) to the colony.

1. Introduction

Seabird attraction to artificial light affects burrow-nesting seabirds in many regions of the world including Hawai‘i, Australia, Canada, and Europe (Rodríguez et al., 2017a). Fallout occurs when juvenile birds leaving their nests for the first time are attracted towards onshore light pollution and strand on land, rather than flying out to sea. While birds can be rescued and safely released, many are killed by collisions with vehicles or predated by cats and dogs, resulting in high fledgling mortality (Miles et al., 2010; Podolsky et al., 1985; Rodriguez et al., 2014; Syposz et al., 2018; Wilhelm et al., 2017). Previous studies have quantified the temporal variability (timing and magnitude) of fallout (Friswold et al., 2020;; Miles et al., 2010; Rodríguez et al., 2014; Syposz et al., 2018; Wilhelm et al., 2013), and the spatial distribution of fallout (Friswold et al., 2020; Rodrigues et al., 2012; Rodríguez et al., 2015; Work and Rameyer, 1999).

In general, anthropogenic structures can obstruct the flight of fledgling seabirds from their colony to the open ocean through direct collision or disorientation by light pollution. The presence of powerlines has been significantly linked to increased fallout of Newell’s Shearwaters (*Puffinus newelli*) as they commute from their upland nesting sites to the ocean (Ainley et al., 2001; Podolsky et al., 1998; Telfer et al., 1987). Seabirds can also become disoriented by and collide with brightly lit structures, like hotels (Reed et al., 1985). A recent study on O‘ahu identified streetlights and utility wires as features associated with Wedge-tailed Shearwater (*Ardenna pacifica*, hereafter WTSH) clusters of fallout (Friswold et al., 2020).

Satellite imagery of night-time light has been used to model patterns in seabird fallout. Several studies use data from the Defense Meteorological Satellite Program

(DMSP), which provide annual composites of light intensity, expressed in relative units (Rodrigues et al., 2012; Troy et al., 2011). A 2011 study that modeled the visibility of light from the perspective of seabirds in their colonies and along their flight paths found few paths in which Newell's Shearwaters on Kauai could avoid light entirely (Troy et al., 2011). A subsequent study that divided Kauai into "fallout sectors" and examined light intensity levels within each sector found more fallout occurring in brighter sectors, with the exception of one moderately bright sector that contained a large proportion of the breeding population (Troy et al., 2013). Several studies suggest that seabirds can be attracted towards land by artificial light even after successfully flying out to sea (Podolsky et al., 1998; Rodriguez et al., 2015; Troy et al., 2013). Researchers on the Azores Archipelago used satellite imagery of night-time light to determine that Cory's Shearwaters were stranding in areas brighter than the colonies they fledged from (Rodrigues et al., 2012). In 2012, NASA's Visible Infrared Imagery Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP) began producing higher resolution monthly and annual composites of night-time light, expressed in units of radiance ($nw/cm^2/sr$) (Elvidge et al., 2013). A tracking study on Cory's Shearwaters in the Canary Islands used the VIIRS data to show that most fledglings that stranded from light attraction were found in brightly lit areas with radiances greater than 18 $nw/cm^2/sr$ and 50% were within 3 km of the colony (Rodriguez et al., 2015). Although several studies have used the VIIRS data to display light pollution around seabird colonies (Rodríguez et al., 2014; Rodríguez et al., 2017a; Syposz et al., 2018) no other studies have included these data to model seabird fallout.

Wedge-tailed Shearwater fallout on Oʻahu was first described by Work and Rameyer (1999), where they compared a wreck fallout year (1994) to the two years prior. Stranded juvenile shearwaters were most frequently found on the windward side of the island, in Waimānalo and Kailua. A study on WTSH fallout from 2002-2010 focused on documenting fallout on the windward side of Oʻahu, identifying a fallout hotspot in Waimānalo town, specifically associated with proximity to streetlights and utility lines within 5 km of the nearest colony (Friswold et al., 2020). This study revealed that certain streetlights were associated with clusters of fallout and suggested the targeted management of problematic light sources to reduce fallout. One particularly problematic area was the sports field with bright, unshielded lights at the Waimānalo Beach Park. After 2011, these sports field lights were turned off during the WTSH fledging season, and fallout in this location was greatly reduced (Hyrenbach et al., In Progress).

In 2016, the major highway streetlights on Oʻahu were transitioned from unshielded High Pressure Sodium (HPS) bulbs to shielded Light Emitting Diode (LED) bulbs to reduce costs and improve energy efficiency. A study on the timing and magnitude of wedge-tailed shearwater fallout on Oʻahu from 2012-2019 showed no difference in the magnitude of fallout during the two lighting regimes, but that the environmental variables moon illumination and wind speed were the most important drivers of fallout (Reference Ch. 2). Although wind direction was not a significant predictor across all years, it was significant in one annual model. Work and Rameyer (1999) suggest that in 1994, southeast winds caused birds to strand inland along the leeward coast, and in northwest regions of the island, dispersing the geographic range of fallout more than in other years. While we clarified the influence of light regime and

wind conditions on the magnitude of WTSH fallout, with no difference between light regimes and more fallout with stronger winds (Reference Ch. 2), these analyses did not address the small-scale spatial distribution of grounded birds. Understanding if these factors influenced the spatial distribution of fallout is critical for targeting mitigation and rescue efforts.

In this study, we used the same 8-year time series of standardized road surveys analyzed in Chapter 2 to examine the spatial distribution of WTSH fallout. We compared fallout distribution during two 4-year periods of different lighting conditions (HPS and LED regimes) to determine if the aggregations of fallout changed after the implementation of shielded LED streetlights. We also compared fallout locations across three prominent wind conditions to investigate if the strength and direction of the wind influences where WTSH ground. Finally, we modelled fallout along the survey route as a function of night-time radiance, using the satellite-determined grid cells, and included other covariates (number of utility poles, number of bus stops, distance to the main breeding colony, and the length of the road, a measure of survey effort in each grid cell). We expected fallout to increase in areas with higher night-time radiance values, more utility poles, more bus stops, shorter distance to the colony, and longer stretches of road. The results of these analyses aimed to quantify the spatial distribution and drivers of fallout hotspots to inform management actions.

2. Methods

2.1 Study Area

Our study area included a 10.17 km section of the Kalaniana‘ole Highway on Southeast O‘ahu, between the Olomana Golf Course (157.734° W, 21.359° N) to the north and the Makapu‘u lookout (157.657° W, 21.306° N) to the south. We selected this portion of the survey because it contained 95% of the fallout density across the 8 year period analyzed previously (Reference Ch. 2). The study area is located on the windward side of O‘ahu, influenced by the northeast trades, with occasional shifts to variable south or west Kona winds. A large WTSH colony on Mānana Island (30,000 breeding pairs) is located within the study area, and the Mokulua Islands (10,000 breeding pairs) is located approximately 5 km from the northernmost point of the study area.

The surrounding area is rural but developed, and primarily residential with interspersed businesses. The maximum radiance value in this area is 11 nw/cm^2/sr (Figure 2), 95% lower than the highest radiance value on O‘ahu of 196 nw/cm^2/sr in Honolulu. Despite these low levels of light pollution, WTSH from large breeding colonies on nearby offshore islets are attracted and grounded every fledging season. Prevailing winds on O‘ahu are dominated by northeast trade winds, with occasional shifts to southwest Kona winds.

2.2 Data Layers

The GPS coordinates of road-killed WTSH were recorded during annual road surveys on southeast O‘ahu during November and December of eight years (2012-2019)

(See Thesis Chapter 2) and imported these as XY points into ArcGIS Pro 2.5.0 for spatial analysis. We divided these points into separate groups based on wind regime and lighting regime to identify changes in fallout hotspots.

We also added point files for utility poles and bus stops along the highway, because shearwaters may have collided with these anthropogenic structures (http://planning.Hawai‘i.gov/gis/download-gis-data/). Last, we used raster monthly imagery of VIIRS night-time radiance from the NASA Suomi NPP Satellite (https://eogdata.mines.edu/download_dnb_composites.html). The VIIRS data have a higher spatial resolution (742 m x 742 m cells), compared with the DMSP imagery previously used to monitor light pollution (5 km x 5 km cells) (Elvidge et al., 2013). We created a fishnet grid, containing 31 cells, co-registered to the (742 m x742 m) VIIRS raster cells, that overlapped the 10.17 km survey route (Figure 1). We used these 31 cells as our sample to build a generalized linear model (GLM) and to test for differences in fallout distribution across lighting regimes and wind conditions.

2.3 Lighting Regimes

To understand how light pollution changed in our study area, we first compared the radiance values between the HPS and LED regimes. We used the mosaic function in ArcGIS Pro to create two 4-year composites of the maximum radiance values in our study area during the fledging season (November – December). The two composites consisted of images during the years before and after the shift in highway lighting, involving a “before” period, (2012-2015) with unshielded, HPS lights, and an “after”

period (2016-2019) with shielded, LED lights. To facilitate temporal comparisons, the same grid cells were used for analysis during both time periods.

The distribution of radiance values in our study area did not follow a normal distribution (SW= 0.86, p= <0.0001), so we used non-parametric analyses. A Wilcoxon paired rank test, comparing the maximum radiance values within the cells along the survey route during the "before" and "after" periods revealed that radiance values were significantly lower during 2016-2019 (V=210, p=<0.0001, n=31). The reduction in radiance per cell ranged from 0 nw/cm^2/sr to 6 nw/cm^2/sr, with an average of 2 nw/cm^2/sr and a median of 1 nw/cm^2/sr.

Since there was a significant difference in overall night-time radiance between the two lighting regimes, we used a Spearman rank correlation to determine if the reduction in radiance was consistent across the study area or if a few individual cells were responsible for the observed changes. We also used a Spearman rank correlation to determine if the proportions of all grounded WTSH found per grid cell during the two lighting regimes were. To visualize the spatial distribution of fallout during each regime, we used kernel density estimation. We divided the fallout points into two files based on whether the point was collected in the HPS regime (2012-2015) or the LED regime (2016-2019), and then created kernel maps for each regime to compare fallout hotspots (Figure 3).

2.4 Wind Regimes

Because we previously showed that stronger winds were a significant driver of fallout, now we are assessing the effect of wind conditions on fallout spatial distributions. We downloaded wind speed and direction data provided by PacIOOS (www.pacioos.org), which is a part of the U.S. Integrated Ocean Observing System (IOOS®).

We divided wind conditions into 3 regimes that dominate windward Oʻahu, NNE trade winds, ENE trade winds, and "other" winds (Figure S1). We defined NNE winds as those coming from 15-45 degrees, with speeds => 8 knots. ENE winds ranged from 46-75 degrees, with speeds => 8 knots. Other winds included anything < 8 knots (all directions), and all other winds (=> 8 knots) from 76-360 degrees, and 0-15 degrees. The sample size in each wind regime varied, with 42.1% of all birds under the other wind condition, 41.1% under East-northeast trade winds, and 16.8% under North-northeast trade winds. With a total of 136 survey days, 54% had light variable winds, 24% had ENE winds, and 18% had NNE winds.

To analyze the influence of wind conditions on fallout, we reclassified the fallout points into three categories based on the dominant winds during the three nights prior to when the carcass was found. We used a Spearman's rank correlation between the percentages of points from each wind condition in each grid cell to determine if the spatial distributions were correlated across wind conditions. We then created three kernel density maps, showing the fallout hotspots for birds that were grounded under NNE trade winds, ENE trade winds, and other winds (Figure 4).

2.5 Model Variables

The disance to Mānana Island was determined using a spatial join of the midpoints of each grid cell to the midpoint of the colony. Additionally, we added distance to the Mokulua Islands, another potential source colony northwest of Mānana, suspecting that some of the birds we observed originated from there. However, because these colonies are on opposite ends of the survey route, there was a strong negative correlation between the distance of the grid cells to the Mokulua Islands and to Mānana ($r=-0.89$, $n = 29$, $p= <0.0001$). Therefore, we only included the distance to Mānana in our analysis but acknowledge that this variable is negatively cross-correlated with the distance to the Mokulua Islands.

We imported a point layer for bus stops, suspecting that these areas may be prone to fallout because they are often well-lit and busses are less capable of swerving or stopping for grounded birds in the road (http://planning.Hawai‘i.gov/gis/download-gis-data/). We created a point file for utility poles by documenting the coordinates of streetlights, telephone poles, traffic lights, speed limit signs, sirens, stadium lights, crosswalk posts, and overpasses. More than 90% of the poles in our layer are telephone poles or streetlights, and these poles have utility wires attached to them, so we did not use a separate layer to model utility wires.

Since each grid cell contained a different length of road, we accounted for survey effort bias due to road length. We calculated the length of road within each cell by clipping the survey route line file to each grid cell and extracting the road length from individual cells. We used road length as a co-variate in our analysis to account for the disparity in the survey effort across the grid cells so we could model the discrete counts using a Poisson and negative binomial distributions.

We used a GLM to describe the spatial distribution of WTSH fallout along our survey route. Since our previous study found no significant difference in the timing and magnitude of fallout between light regimes (See Thesis Chapter 2) we analyzed all 8 years of survey data collectively. The dependent variable (total number of birds within each grid cell over the entire study period) was related to five independent variables: night-time radiance ($nw/cm^2/sr$), number of utility poles, number of bus stops, distance to Mānana Island, and length of road. Due to a high frequency of zeros in the data, we assessed both Poisson and negative binomial distributions for fit. We tested multiple model combinations and used Akaike Information Criterion (AIC) to determine the best fitting model (Reference Ch.2).

First, we related the number of birds per cell in response to each predictor individually using five single-predictor models. Road distance, number of bus stops, and number of utility poles were each significant predictors. Because road distance, the correction for varying survey effort across grid cells, was the most significant variable, we included it in every subsequent model we built. In total, we tested 15 models containing 2 to 5 predictors (Table S1), and used AIC to determine the best fitting model, across all combinations of predictor variables.

3. Results

We observed no difference in the spatial distribution of fallout across lighting regimes, with a strong positive correlation between the number of birds per cell between the HPS and LED periods (r_s=0.71, df = 29, p= <0.0001) (Figure 5), whereby the grid cells with high fallout in the early period also had high fallout in the later period. Two

cells deviated strongly from this pattern, with more fallout in cell 14 during the HPS regime, and more fallout in cell 21 during the LED regime (Figure 5). The kernel maps show similar distributions of fallout across the two lighting regimes, with 95% of all fallout occurring across almost the entire survey route (Figure 3). However, the area containing 5% of total fallout differed in that the HPS regime had one concentrated area in the middle of the survey route, and the LED regime required three clusters, toward the middle and south, to account for 5% of fallout.

Although there was an overall decrease in radiance between the lighting regimes, there was a strong correlation between the radiance values in each cell during both time periods (Figure 6). For 13 of the 33 (39.4%) cells, there was no change in radiance, therefore having a 1:1 linear relationship. While there was a decline in radiance within the remaining 20 (60.6%) cells, their relative brightness remained unchanged, as evidenced by the little change in their ranked brightness values (r_s=0.92, df = 29, p=<0.001). Because of this strong correlation, we used the overall maximum value, (which happened to be the HPS maximum), in our GLM.

The numbers of birds in each cell across the three wind conditions were significantly correlated, with several cells consistently containing more fallout than others, despite the wind condition. (Table 1). However, there were four outlier cells with disproportionate fallout density between wind conditions (Figures 7A-C). In particular, cells 14 and 15 had highest fallout density in the NNE wind condition and fairly high density in the other wind condition. Cells 18 and 21 had higher fallout density during ENE winds compared to NNE and other. Although there were no statistical differences at the scale of the grid cells, the kernels show small-scale differences in fallout distribution (Figure 4). The

north-northeast wind condition shows that 95% of fallout was concentrated toward the middle of the route, with very little fallout on either the north or south ends, and a single area in the middle of the route accounted for 5% of fallout. On the contrary, the east-northeast condition shows most fallout occurring from the middle to the north end of the survey route, with a single area accounting for 5% of fallout toward the north end. The other wind condition shows a broad distribution of fallout, and two clusters, across from the colonies and just north of the colonies.

There were 4 sets of significant correlations between predictor variables: night-time radiance and colony distance, night-time radiance and length of road, night-time radiance and bus stops, night-time radiance and utility poles, and utility poles and bus stops (Table 2). However, the variance inflation factor (VIF) which tests for collinearity amongst predictor variables in a model, was below the collinearity threshold of 5 for all models, indicating that the variables are not highly collinear. The model with the lowest AIC value, thus deeming it the best fit (See Thesis Chapter 2), followed a negative binomial distribution and included the predictors night-time radiance, distance to colony, and road distance (AIC=177.09) (Table 3). Night-time radiance and road distance had positive coefficients, and resulted in increased fallout, while distance to the colony exhibited a negative relationship, decreasing fallout in cells further from the colony. We did not observe a significant effect of utility poles or bus stops, however both predictor variables were highly correlated with night-time radiance (Table 2). When we calculated the distance from individual WTSH carcass points to the colony (rather than the cell midpoint), 50% were located within 3.7 km of Mānana Island, and 95% were within 6.9 km (Figure 8).

We identified fallout hotspots as the cells that accounted for 50% of overall fallout density, and fallout coldspots were cells were cells in which a WTSH carcass was never documented. We divided the number of birds in each cell by the road length to calculate fallout density per cell and values ranged from 0 to 69 (Figure S2.). Six cells accounted for 50% of the fallout density, while 7 cells contained zero birds (Table 4). The NTR values ranged from 2 to 6 in the hotspot cells and 1 to 4 in the coldspot cells (Table 4). While the distance to the colony for the hotspot cells ranged from 1.5 km to 5.12 km, the range for the coldspot cells was 1.73 km to 8.59 km.

4. Discussion

4.1 Light pollution

The strong correlation between the number of birds in each cell between light regimes suggests that fledglings were still attracted to the brightest relative locations. Despite shielding, we still found clusters of grounded birds near individual streetlights. Given the similarities in magnitude (Reference Ch.2) and spatial distribution of fallout in the HPS and LED lighting regimes, it seems unlikely that the shielded LED lights were less attractive to WTSH fledglings. Although the overhead satellite imagery showed a reduction in radiance, as measured from space, it is unclear how the birds perceive the lights. Because WTSH fledge from ground level, below the lights, they are likely still vulnerable to their effects. In particular, the angle at which birds are flying can influence the visibility of the shielded lights, thus providing more opportunities for encountering the light as they maneuver in flight. Thus, future research modelling the visibility of artificial light for ground-nesting seabirds would help us gain a better understanding of

how WTSH are perceiving the shielded streetlights. For instance, Troy et al. (2013) modelled visible artificial light pollution on Newell's Shearwater colonies and along their flight paths in Kauai.

Compared to previous studies, the birds we observed grounded further from the colony, with 50% of birds within 3.7 km and 95% within 6.9 km of the main breeding colony (Mānana Island). However, Friswold et al. (2020) analyzed distance from the fallout location to the nearest colony rather than the primary breeding colony, documenting 96% of fallout occurring within 5 km of a colony. Rodriguez et al. (2015) found 50% of GPS tagged shearwaters stranded within 3 km of their source colony. Because we do not know the source colony of the grounded birds we documented, our analysis assumes that all birds came from Mānana Island, given that this colony accounts for 72% of the southeast windward population (See Thesis Chapter 2).

The significant positive relationship between the night-time radiance and the number of grounded WTSH supports the notion that seabirds are attracted toward brighter areas. While Rodriguez et al. (2015) found most birds stranding in areas with radiance values greater than 18 nw/cm^2/sr, 95% of birds we documented were in cells ranging from 2 to 11 nw/cm^2/sr, indicating that even low radiance levels can be attractive. Rodriguez et al. (2015) recommend reducing light use so that radiance values do not exceed 10 nw/cm^2/sr within 3 km of the colony. However, given that most cells in our study area were below this threshold, we suggest that shearwaters are still attracted to the brightest relative locations, regardless of the radiance values. Therefore, radiance levels would have to be reduced to very low levels to mitigate light pollution. Thus, modifying other lighting

features such as wavelength, color, and spectral temperature may be more effective for mitigating their attractiveness to wildlife.

4.2 Wind Conditions

Although the number of birds per cell was significantly correlated across all wind conditions, four cells deviated from the pattern, suggesting several small scale differences. Surprisingly, under NNE and other winds, cells 14 and 15 had disproportionately high fallout (Figure 7A-C). While we expected to see more fallout toward the south end of the survey route under NNE conditions, this deviation could be related to birds from the Mokulua Islands, north of the survey route, being blown toward this area by NNE winds. Since variable winds were mostly southerly, it is likely that birds from Mānana Island were blown north and dispersed along the entire survey route. The high relative abundance (birds / km) of grounded WTSH in cells 14 and 15 could be due to proximity to the colony. While we expected more fallout toward the middle and south end of the survey route under ENE winds, fallout was disproportionately high in cells 18 and 21 on the north end (Figure 7A, C), suggesting that birds from the Mokulua Islands may have been blown there from the north. These patterns suggest that more birds were coming from the Mokulua Islands than we had expected. Alternatively, birds from Mānana Island would have had to fly into the prevailing wind to reach these brightly lit areas.

Even though there were a few outlier cells, there are several explanations for why we did not detect an overall effect of wind conditions on the location of grounded WTSH. First, we averaged wind speed and wind direction over a three-day period prior to each

road survey. It is possible that variations in the wind conditions within the three day intervals were masked by using an average. Very strong wind events may disproportionately cause fallout events or wrecks (K Swindle., Pers. Comm.). Anecdotal firsthand observations of fledging NESH on Kaua‘i and fledging WTSH within our study area while navigating obstacles indicate that even small gusts of wind can cause birds to strike a light or powerline and become grounded. However, in this study we could not quantify small-scale wind conditions at the time and location of bird groundings, given that we surveyed a three-day interval and used wind data from a shore station.

Alternatively, it is possible that wind conditions have little or no effect on the spatial distribution of fallout. Perhaps the attraction toward light overwhelms any wind effects. To better understand the spatial implications of wind on fallout distributions, future studies should attempt to quantify specific wind conditions at the time of groundings.

4.3 Bus Stops and Utility Poles

Although we found no significant influence of bus stops, we have personally observed WTSH carcasses frequently on the road near bus stop pull-offs, indicating that they were likely run over by a bus. Given that bus stops are well-lit, and likely attractive to the fledgling seabirds, they are particularly dangerous locations for seabirds. Moreover, we would expect more collisions with buses due to their high profile and maneuverability. While smaller vehicles may be able to avoid downed birds by navigating around them or slowing down, buses may have a harder time avoiding grounded birds.

Similarly, we have personally observed many instances of dead and live birds near streetlights, despite utility poles showing no significant relationship to fallout distribution. We have found WTSH carcasses under streetlights that were clearly struck by vehicles, but also carcasses that more likely died from collision with utility wires or poles. We have also observed WTSH flying in circles around individual lamps, ultimately grounding due to exhaustion. Although utility poles were not significantly related to fallout, during our surveys we observed some cases where WTSH fatalities were associated with these features.

4.2 Fallout Hotspots and Coldspots

Although fallout is influenced by a variety of factors, the proximity to the colony and the radiance value are two key parameters. Surprisingly, only 4 of the 6 fallout hotspots had NTR values greater than the average of 4 nw/cm^2/sr, suggesting that high radiance alone is not the most important driver of fallout location. In fact, the cells with the highest NTR values (11) did not have high fallout, likely because they were located further from Mānana Island. However, all the cells with no fallout had average or lower than average NTR. This suggests that the combination of well lit-areas that are also fairly close to the colony is what drives fallout hotspots, while coldspots occur because they are very dark or very far from the colony.

Cell 6 was an unusual hotspot because it had a lower than average NTR but was only 1.5 km away from the colony. This stretch of the road is located across from Sea Life Park, a marine life center with several unshielded light posts. Sea Life Park also

hosts evening luaus, which may increase the presence of light on those nights. Given the close proximity to Mānana Island and the presence of bright lights in a relatively dark region, it makes sense that this cell would account for relatively high fallout. Additionally, several nesting shearwater burrows, indicative of a small or incipient breeding colony, have been located along the roadside at this location.

Cells 14 and 15 had the highest fallout densities, with 69 and 65 birds/km respectively and were likely fallout hotspots because they encompass an area of the road that borders a residential area and runs directly adjacent to the coast, with little to no vegetation or infrastructure obstructing the view from the offshore colonies (Figure 1). The NTR values were moderate, however they were only 3.63 km and 3.2 km away from the colony (Table 4). Although the streetlights in this section are 3000° K instead of 4000° K, they are still the lights with the highest rates of attraction and are above the 2700° K recommendation for wildlife (Shulte-Romer et al., 2019).

Although cells 18, 19, and 21 were located approximately 5 km away from the colony, they likely had high fallout because they all had above average NTR values (Table 4). Cells 18 and 19 are located in a densely populated residential area. Cell 21 marks the edge of this residential area and borders a large, forested region. It is also unique because it contains a McDonald's restaurant with two bright, unshielded streetlights. In a fallout study on Malta, Raine et al. (2007) also identified a fallout hotspot associated with globe lights and unshielded lights near a McDonald's. Although the NTR value in cell 21 is only 5 nw/cm ^{2}/sr, the presence of the single unshielded light may contribute to increased WTSH attraction.

Some fallout coldspots were close to the colony and others were far away, suggesting different reasons for the lack of observed fallout. On one hand, cells 26, 30, and 31 were farther away from the colony, and likely contained no fallout since the birds that stranded were attracted toward lights nearer to the colony. On the other hand, the cells closest to the colony also happen to be the darkest, thus fledglings were probably drawn north towards the brighter regions. Although we standardized birds/km for this part of the analysis, two cells (12 and 1) without any fallout only contained <0.1 km of road. Cells 7 and 8 contained hardly any infrastructure, except for a pier in cell 8 that extends over the ocean and contains several affixed lights. Although no road-killed birds were observed in this cell, many birds have stranded on the pier and been rescued during the fledging season (SLP data). In general, fallout coldspots are associated with greater distance from the colony or low radiance values.

5. Conclusion

Based on our model, the main geographic drivers of the distribution of fallout in our study area were the distance to the colony and night-time radiance. We also suspect that stand-alone bright lights in relatively dark areas may be particularly attractive to fledgling WTSH, based off the aggregations of birds found near Sea Life Park and McDonald's. Furthermore, we believe that an unobstructed view of onshore lighting from the colony results in increased fallout. We found no influence of wind conditions on the spatial distribution of fallout at the scale of the grid cells.

Since we saw no difference in WTSH fallout under the unshielded HPS streetlights and the shielded LED streetlights, we would not recommend shielding lights

as a systematic management technique for WTSH or potentially other species of procellarids that also nest at or near sea level (below the shielding level of typical street lights (approximately 25-40 feet elevation). However, we showed that shielding does reduce overhead night-time radiance, which significantly reduced fallout rates of higher-elevation breeding species such as HAPE and NESH (Reed et al., 1985; Telfer et al., 1987). and has other benefits, like improving astronomical visibility and night-time esthetics for humans. Further research should investigate the effectiveness of motion-sensors in streetlights for dimming or shutoff during the fledging season, to test if limited illumination reduces fallout. If this approach was tested in our study area, I would recommend focusing efforts on streetlights within cells 14 and 15 first since they are areas where streetlights are the most likely cause of attraction. Other lights, such as those within Sea Life Park, and at McDonald's could be turned off completely during the fledging season to reduce attraction. However, we recognize that it may not be possible to eliminate these lights, due to requirements for human safety, but shielding, dimming, and CCT modulation may all be possible. In areas where light cannot be sufficiently reduced or mitigated, we would recommend increasing rescue efforts. As O'ahu, and many regions around the world, continue to develop and expand, we encourage managers to proceed with caution when considering the use of artificial lighting near seabird colonies.

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Table 1. Spearman's Rank Correlation (rho and p-value) between % WTSH fallout in 31 grid cells, for each wind regime (NNE = North-northeast trade winds, >8 knots, 15-45 degrees; ENE = East-northeast trade winds, >8 knots, 46-75 degrees; Other = light variable winds, <8 knots (all directions), 76-360 degrees, 0-14 degrees).

r/p	**NNE**	**ENE**	**Other**
NNE	------	0.0003	0.0003
ENE	+0.6255	------	0.0001
Other	+0.6087	+0.6645	------

Table 2. Correlations between predictor variables, measured at 31 grid cells. NTR (Night-time Radiance), Colony Distance (to Mānana Island), Length of Road, Number of Bus Stops, and Number of Utility Poles. (*=significant at alpha=0.01, **=significant at alpha=0.001).

r / p	NTR	Colony Distance	Length of Road	Number Bus Stops	Number Utility Poles
NTR	-	0.0003**	1	0.006*	0.0012*
Colony Distance	+0.673	-	1	0.516	0.516
Length of Road	-0.0339	-0.0541	-	0.6	0.334
Number Bus Stops	+0.566	+0.298	+0.237	-	<0.0001**
Number Utility Poles	+0.629	+0.295	+0.347	+0.718	-

Table 3. Output from best fitting model (AIC=177, n=31) (* significant at alpha=0.01, ** significant at alpha=0.001).

Explanatory Variable	Estimate	S.E.	Z-score	p-value
Intercept	0.700	0.651	1.077	0.282
Length of Road	+0.004	0.001	2.774	0.006*
Colony Distance	-0.407	0.128	-3.178	0.001*
NTR	+0.355	0.094	3.770	0.0002**

Table 4. Fallout aggregation identified six fallout hotspots (cells containing 50% of relative abundance) and seven fallout coldspots (cells with zero fallout). Encounter rate (WTSH / km), NTR= Maximum night-time radiance (nw/cm^2/sr), colony distance (km from midpoint of cell to Mānana Island)

Cell #	Encounter Rate	NTR	Colony Distance
Fallout Hotspots			
Cell 14	69	5	3.63
Cell 15	65	4	3.20
Cell 21	58	5	5.12
Cell 6	43	2	1.50
Cell 18	38	6	5.02
Cell 19	33	6	4.59
Fallout Coldspots			
Cell 1	0	1	2.37
Cell 7	0	2	2.11
Cell 8	0	1	1.73
Cell 12	0	1	1.96
Cell 26	0	4	7.87
Cell 30	0	3	8.59
Cell 31	0	3	8.19

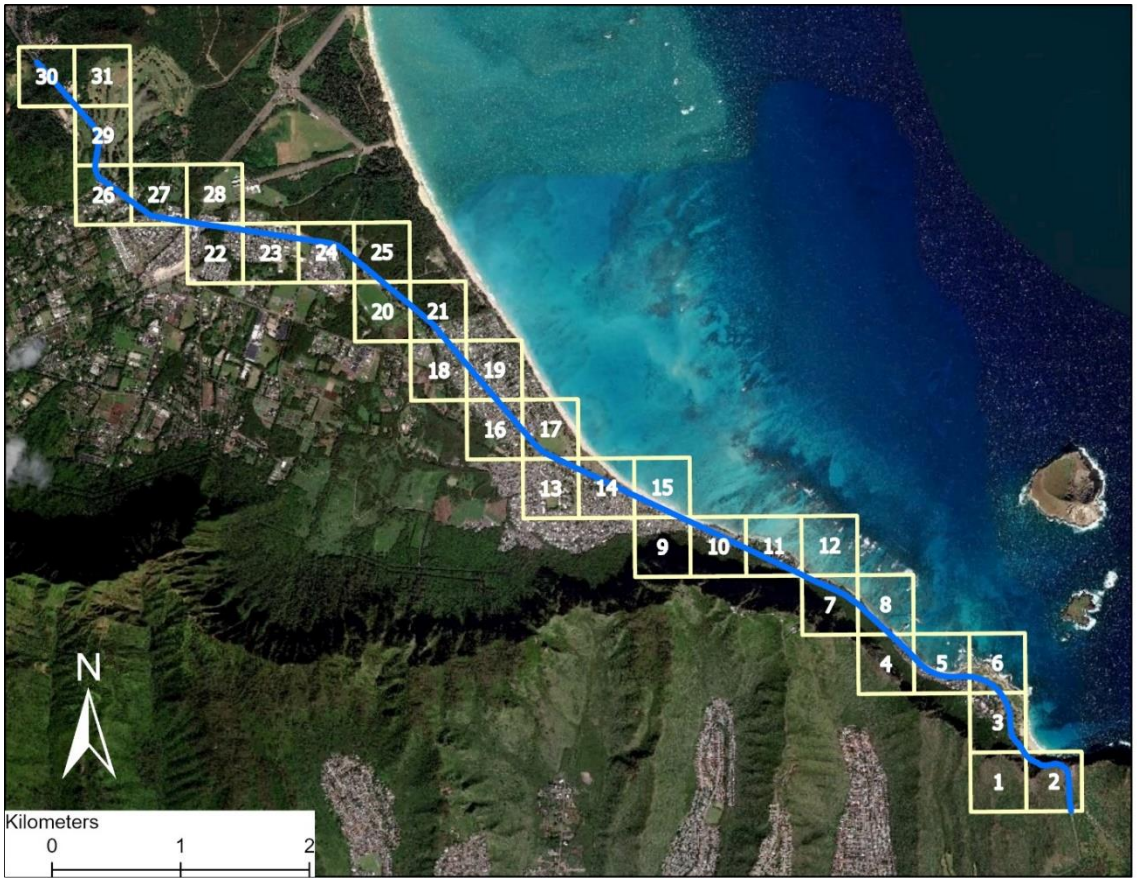

Figure 1. Fishnet grid around survey route defining 31 grid cells. The blue line is the survey route (10.17 km) along the Kalaniana'ole Highway.

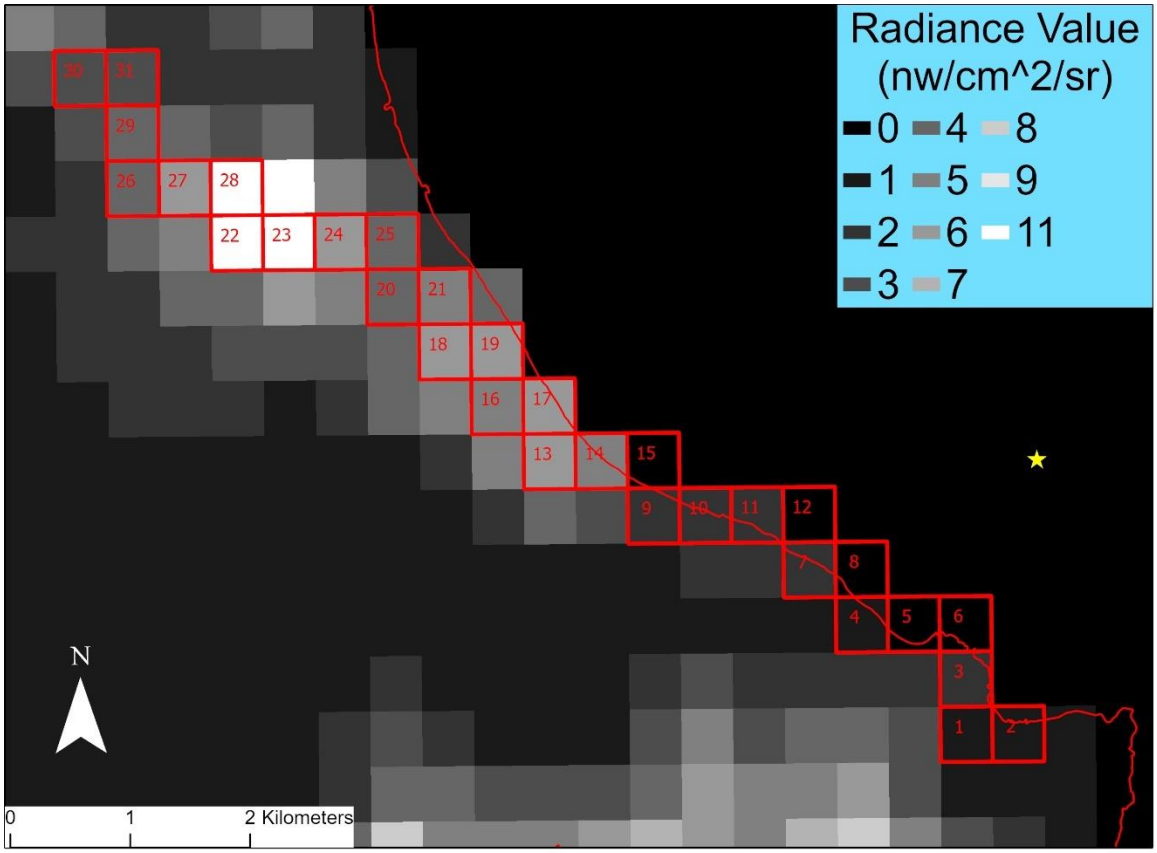

Figure 2. Maximum night-time radiance in the study area (range = 0 to 11 nw/cm^2/sr). (Imagery from the Visible Infrared Imagery Radiometer Suite (VIIRS) sensor is a composite of the maximum values from Nov-Dec 2012 – 2019). The thin red line is the coastline and the yellow star is the midpoint of Mānana Island.

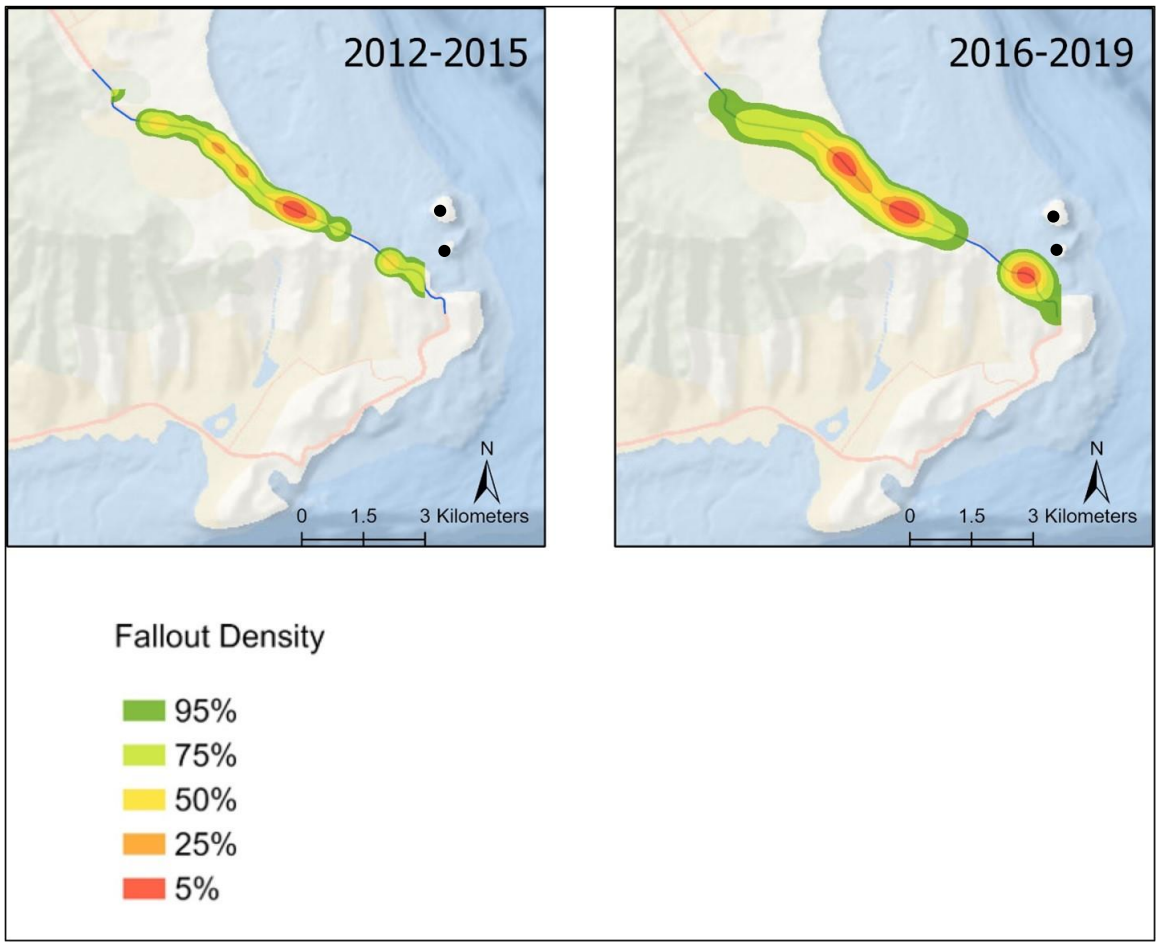

Figure 3. Kernel density maps of fallout along the survey route, during the two lighting regimes, HPS (2012-2015), and LED (2016-2019). Black dots indicate breeding colonies.

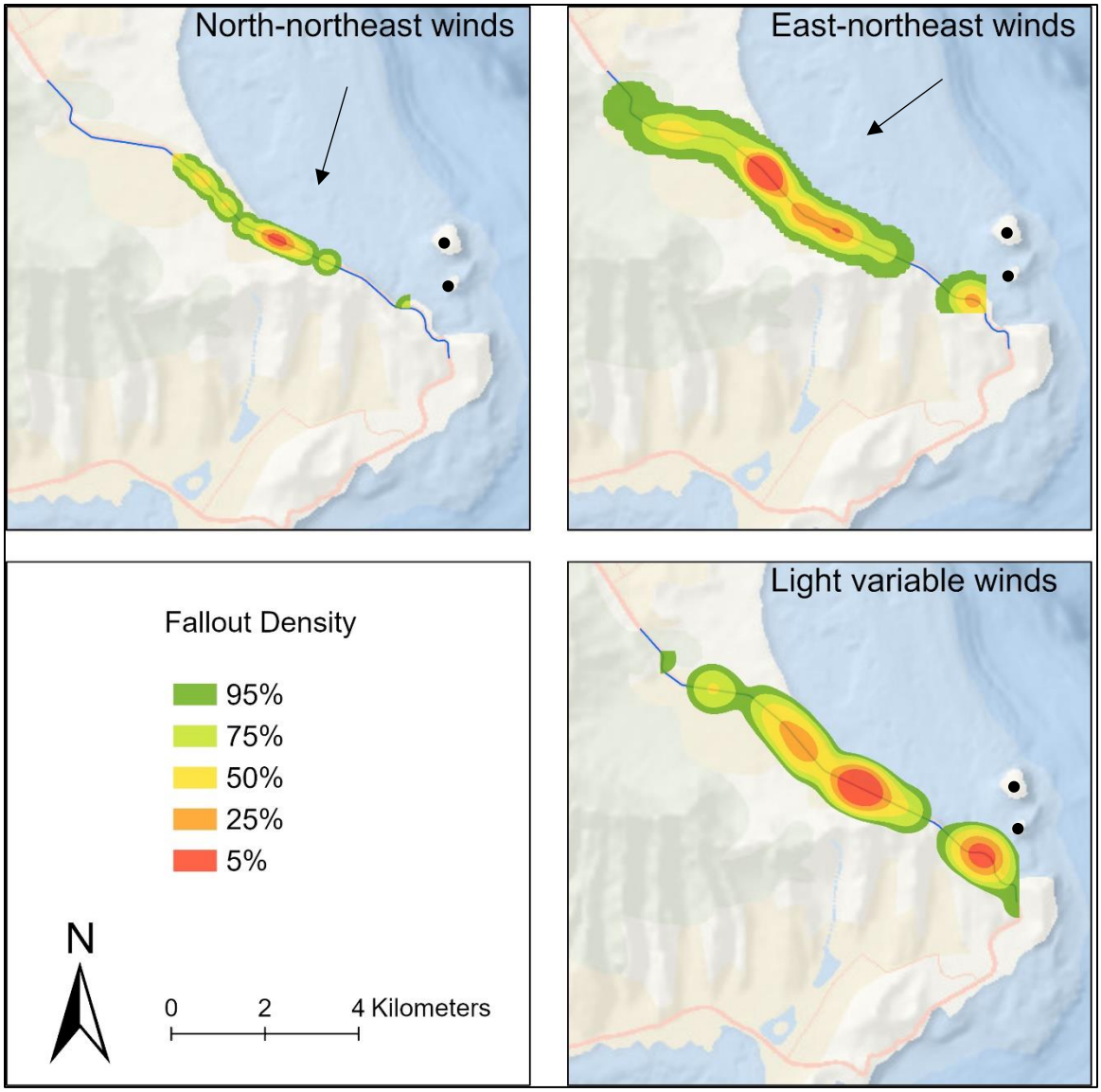

Figure 4. Kernel maps of fallout density based on wind direction. Three wind categories are north-northeast trade winds (15-45 degrees, >8 knots), east-northeast trade winds (46-75 degrees, >8 knots), and light variable (other) winds (76-360 or 0-15 degrees and <8 knots). Black dots indicate breeding colonies. Arrows indicate approximate direction of the wind.

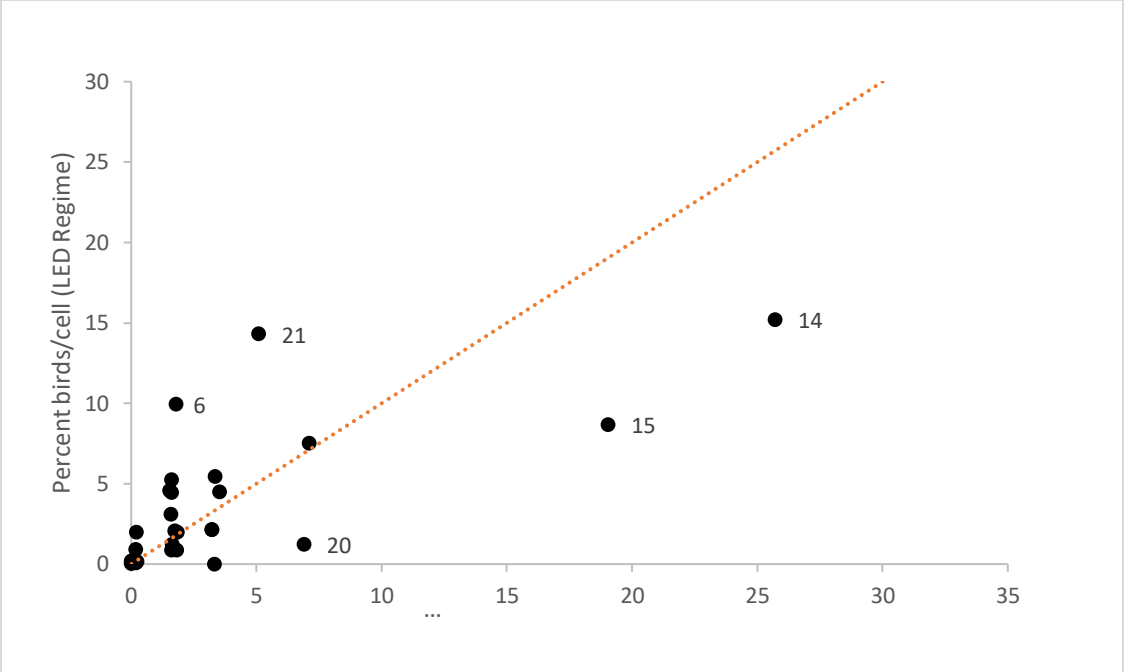

Figure 5. Correlation between the percentage of birds in each grid cell during the HPS and LED light regimes (r=0.71, df = 29, p=<0.0001), showing the 1:1 relationship (dotted line). Numbers correspond to grid cells with disproportionate fallout.

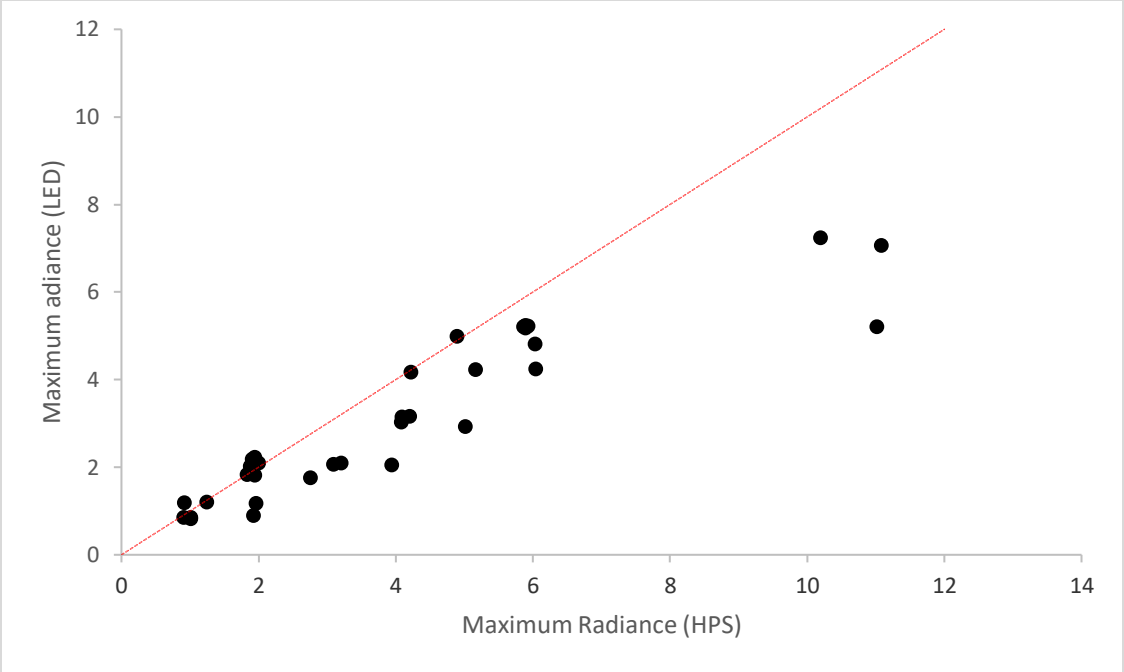

Figure 6. Correlation between the maximum radiance (nw/cm2/sr) value in each cell under HPS and LED lighting ($r = 0.96$, $df = 29$, $p < 0.0001$), showing the 1:1 relationship (dotted line).

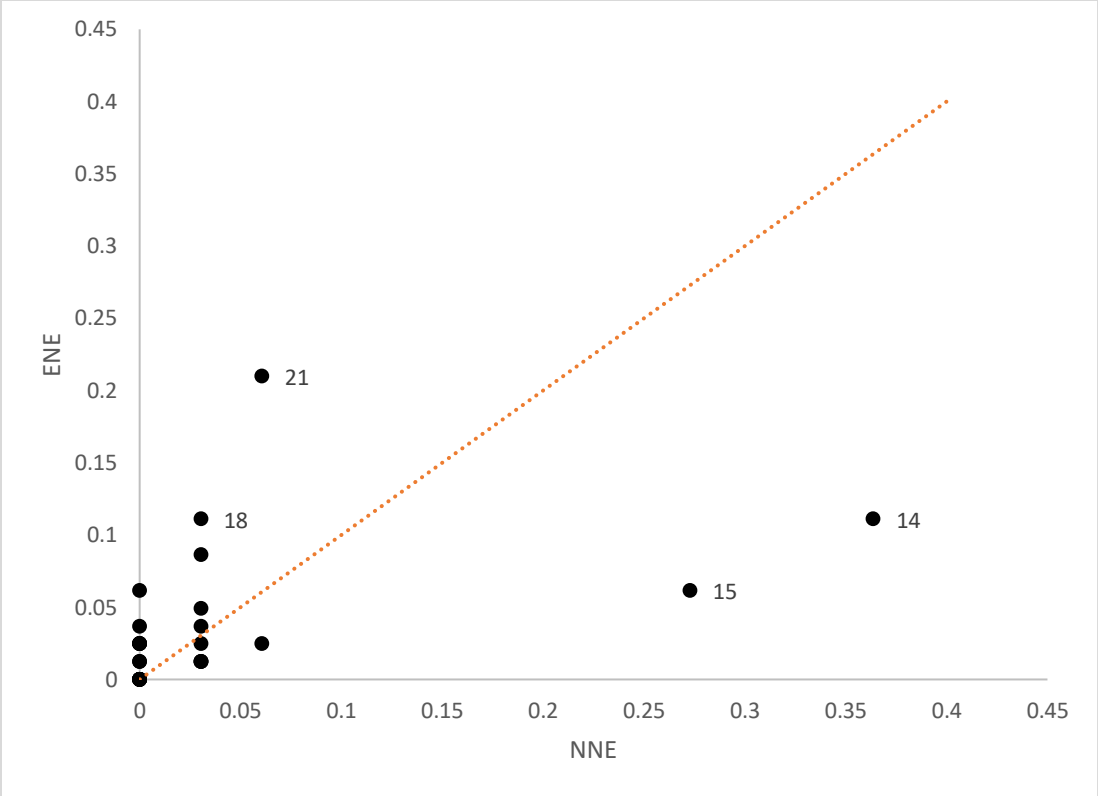

Figure 7A. Scatterplot of fallout encounter rate (WTSH / km of road) in each grid cell between NNE and ENE wind conditions, showing the 1:1 relationship (dotted line). Numbers identify those grid cells with disproportionate fallout.

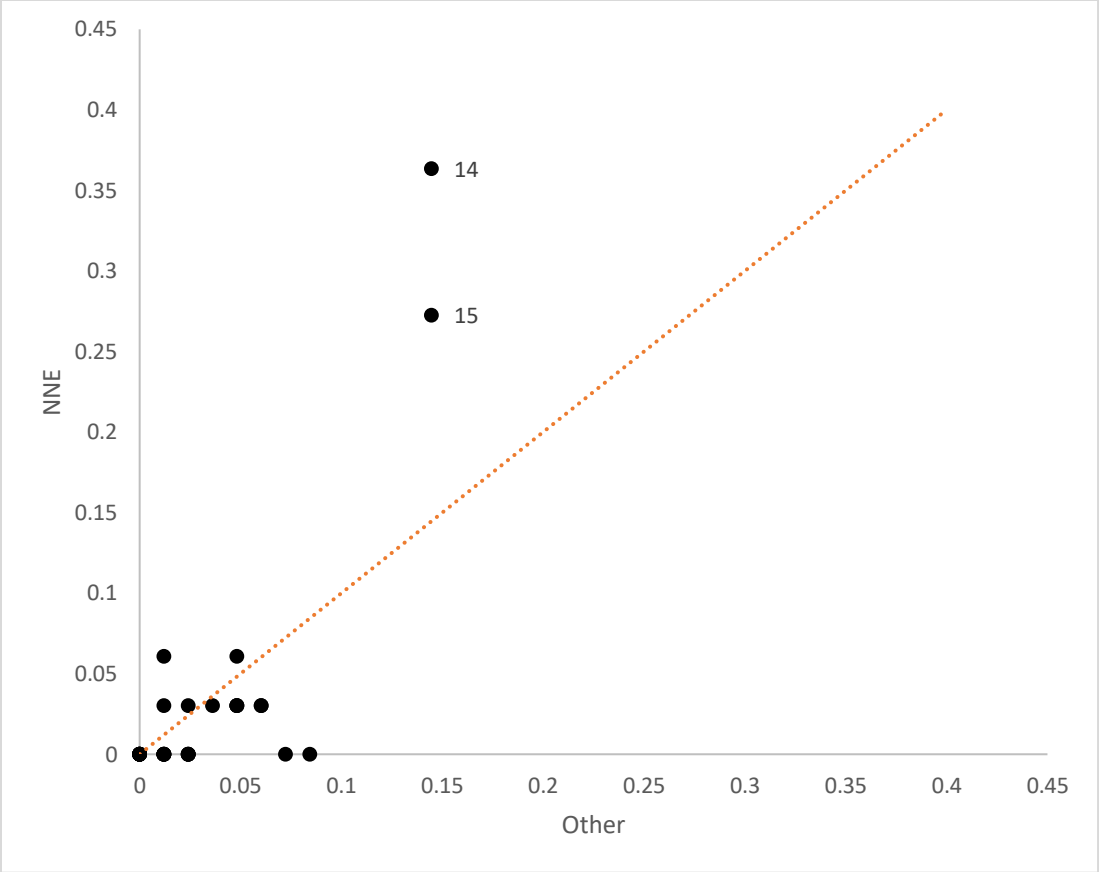

Figure 7B. Scatterplot of fallout encounter rate (WTSH / km) in each grid cell between other winds and NNE winds, showing the 1:1 relationship (dotted line). Numbers identify those grid cells with disproportionate fallout.

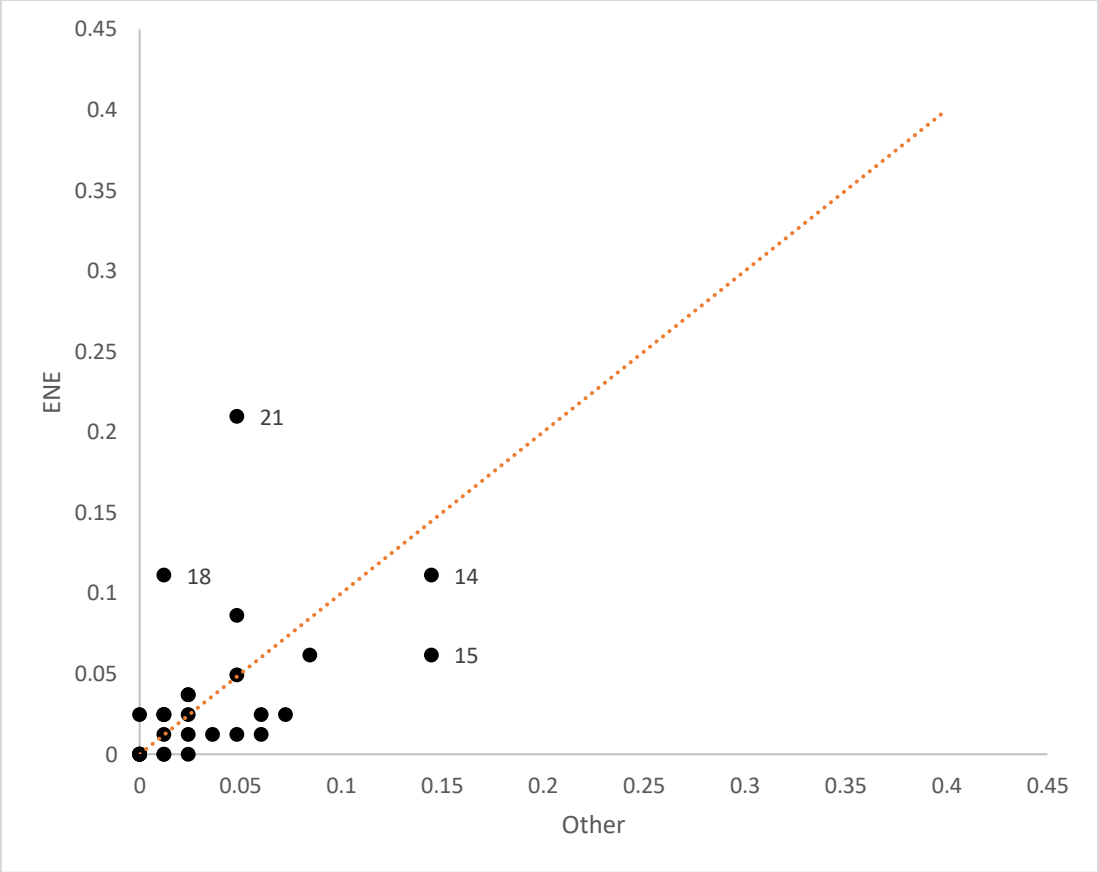

Figure 7C. Scatterplot of fallout encounter rate (WTSH / km) in each grid cell between other winds and ENE winds, showing the 1:1 relationship (dotted line). Numbers identify those grid cells with disproportionate fallout.

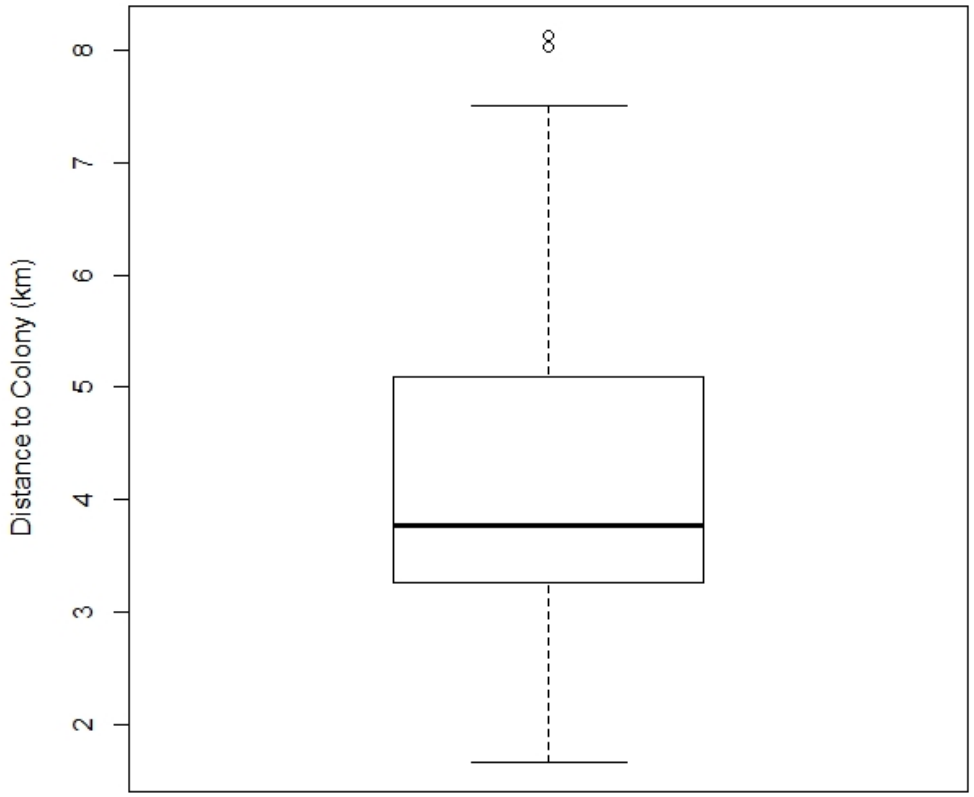

Figure 8. Boxplot showing the distribution of the distance from each WTSH carcass to the midpoint of Mānana Island (km) (n=150).

Supplementary Materials

Table S1. AIC model combinations for GLM analysis (NTR = night-time radiance, Road = length of road per cell, BusStops = number of bus stops per cell, Poles = number of utility poles per cell, ColonyDis = distance from cell midpoint to Mānana Island midpoint, total=15 models).

Birds per cell ~
NTR + Road
BusStops + Road
Poles + Road
ColonyDis + Road
NTR +BusStops + Road
NTR + Poles + Road
NTR + ColonyDis + Road
BusStops + ColonyDis + Road
BusStops + Poles + Road
Poles + ColonyDis + Road
NTR + BusStops + Poles + Road
NTR + BusStops + ColonyDis + Road
NTR + Poles + ColonyDis + Road
BusStops + Poles + ColonyDis + Road
NTR + BusStops + Poles + ColonyDis + Road

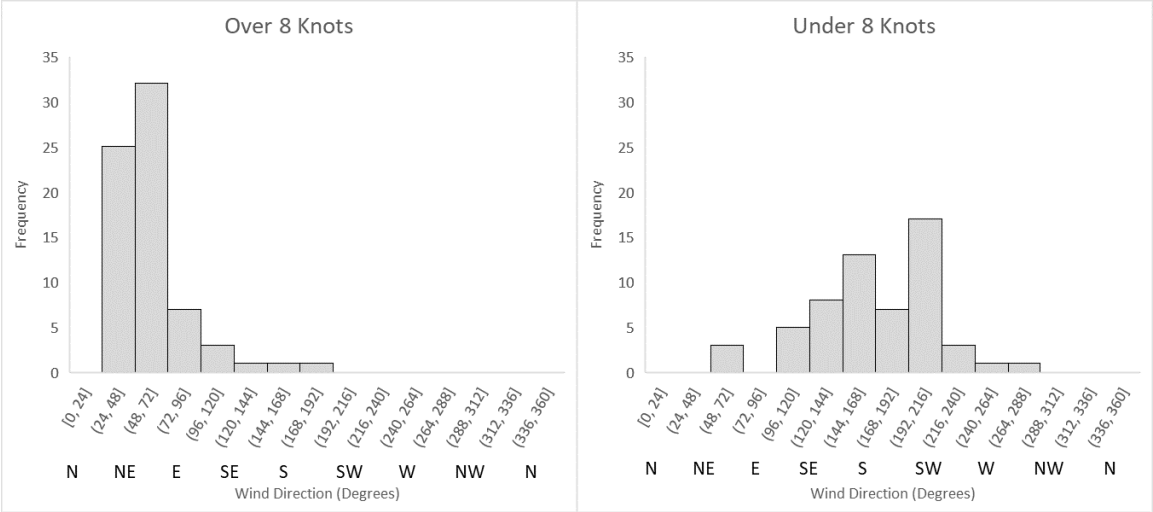

Figure S1. Histogram shows the distribution of wind direction on survey days was skewed toward northeast winds when wind was greater than 8 knots, but platykurtic when wind speeds were under 8 knots (>8 knots: n=70; <8 knots, n=58).

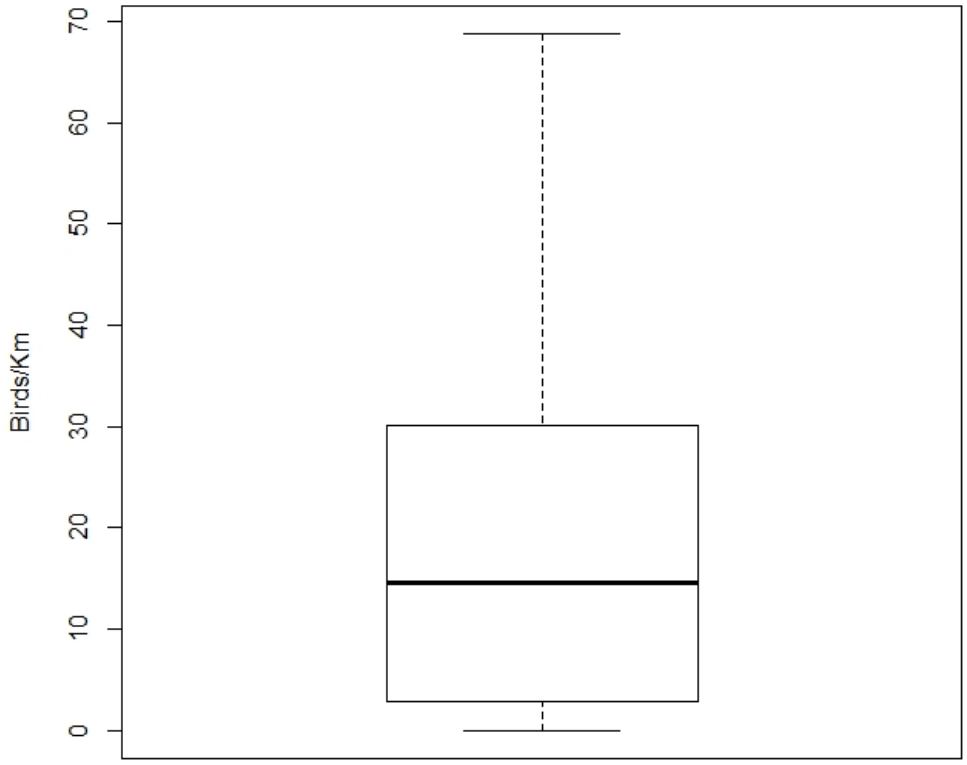

Figure S2. Boxplot showing the encounter rate (birds/km) within each cell (n=31).

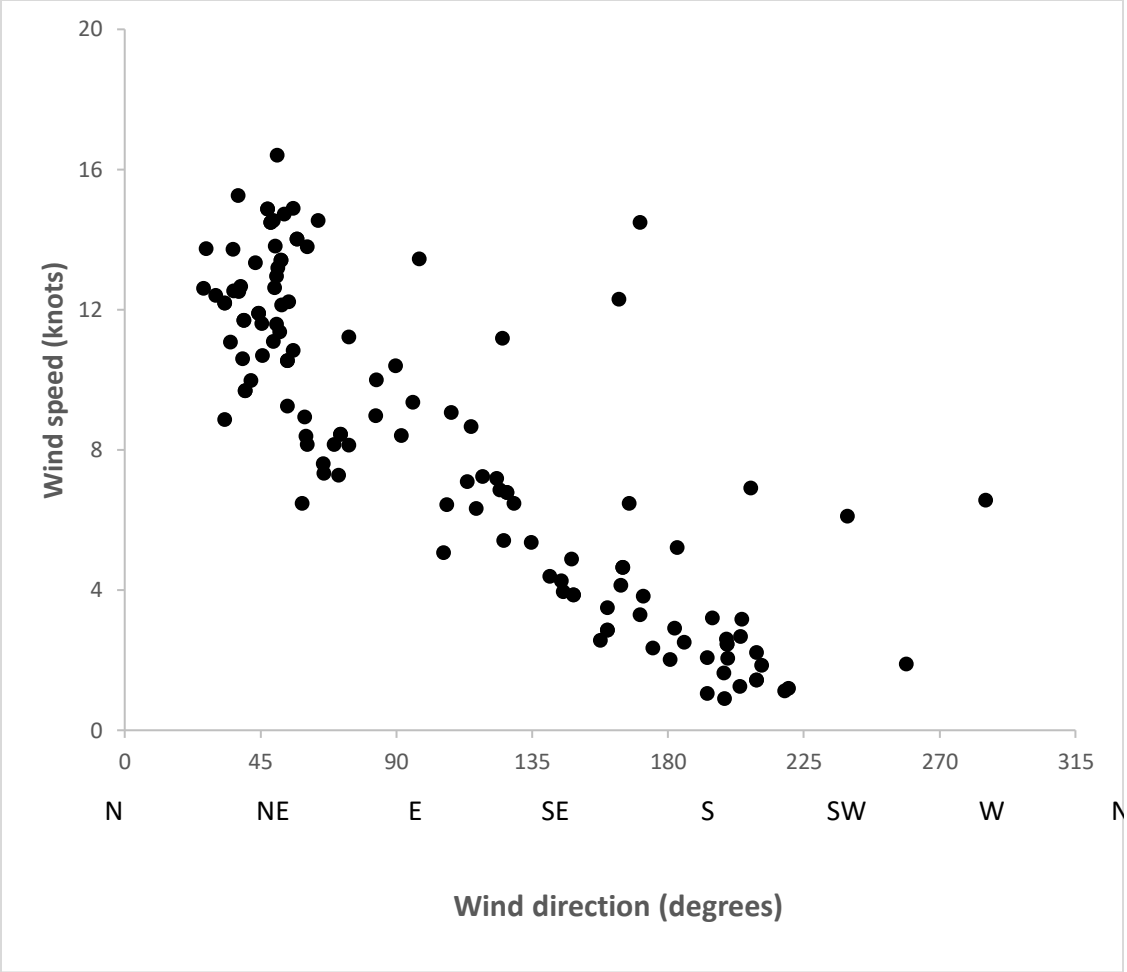

Figure S3. Scatterplot of wind direction versus wind speed including data from each survey from 2012-2019, ($r=-0.83$, $df = 134$, $p<0.001$,).

Chapter 4

Conclusions and Future Directions

Summary

The goal of my MSMS thesis research was to study patterns in Wedge-tailed Shearwater fallout over an 8-year period, when a change in highway lighting occurred. First and foremost, my interest is in conserving what is currently a healthy population of Wedge-tailed Shearwaters on Oʻahu. Moreover, I hope that my research can benefit seabirds beyond WTSH on Oʻahu, by offering a new understanding of the temporal and spatial drivers of fallout. Fallout affects several species of endangered seabirds like the Newell's Shearwater (*Puffinus newelli*) and the Hawaiian Petrel (*Pterodroma sandwichensis*) on the neighboring island of Kauaʻi and other seabirds throughout the world (Rodriguez et al., 2017a). Since WTSH are abundant and have been consistently stranding on land every year, the trends in fallout are more obvious than in species with smaller populations. WTSH Fallout on Oʻahu has been studied since the early 1990s (Work and Rameyer, 1999), but my thesis research provides new knowledge about the environmental drivers of fallout, fallout hotspots, and the effects of a change in lighting.

Chapter 2

Our study was the first to conduct consistent, systematic road surveys to document the timing and magnitude of WTSH fallout on Oʻahu. While our study area was monitored in the past, we created a protocol to survey at 3-day intervals, using the same dates each year for consistency (Friswold et al., 2020; Hyrenbach et al., In Progress). This protocol was an effective way to standardize for survey effort, to ensure that changes in observed fallout were not a result of increased search effort. Our

monitoring protocol could be adopted in future fallout studies on Oʻahu and in other parts of the world where road surveys are done to document fallout.

Our study revealed that switching the streetlights on Oʻahu from unshielded high pressure sodium (HPS) lights to shielded light-emitting diode (LED) lights did not change the timing or magnitude of WTSH fallout. While laboratory and field experiments can dive deeper into the "whys" of seabird attraction to different types of lighting, this study is a real-world example of what happened when streetlights were modified. Although we saw no difference in fallout between two light regimes, it is difficult to say why. Perhaps a combination of decreased initial attraction due to shielding and increased attraction once near the lights due to shorter-wavelength emissions evened out to show no overall difference. Alternatively, it is possible that the fledglings did not perceive a difference between the light regimes, regardless of the changes in shielding and wavelength.

While this may be the case for seabirds that nest at ground level, the effects may have been different for species nesting higher up in mountains, like Newell's Shearwaters. Shielding lights on Kauaʻi was likely successful in reducing Newell's Shearwater fallout because they are starting above the lights (Reed et al., 1985). Thus, it is important to remember that our conclusions about the change in lighting do not necessarily apply to all seabird species. As urban development continues in coastal areas where seabirds reside, it is inevitable that many regions will soon transition to more energy-efficient lighting. Seabird researchers should take advantage of these opportunities to study if/how fallout patterns change.

The second important takeaway from this study was the synergistic effect of the moon and wind speed on fallout. While many previous studies have shown that fallout increases near a new moon, only a few studies have looked at the effects of the wind (Rodríguez et al., 2014; Syposz et al., 2018). My study was the first to model an interaction between the moon and wind, finding that low moon illumination and high wind speeds resulted in increased fallout. I believe that the moon is responsible for determining whether seabirds will be attracted toward light on land, but wind speed is responsible for dictating how many birds will fledge on a given night. We can use these findings to prepare rescue efforts, ensuring that extra emphasis is placed on nights with little moonlight and strong winds.

This chapter helped expand knowledge of the environmental drivers of WTSH fallout on O‘ahu and showed a lack of effect in fallout magnitude due to the lighting change. My third chapter was a spatial analysis to gain a better sense of physical features characterizing fallout locations and to determine if the lighting change influenced the distribution of fallout.

Chapter 3

Using the survey data from Chapter 2, I conducted a spatial analysis on fallout to assess fallout hotspots. I analyzed the spatial distribution of fallout by creating and overlaying a fishnet grid onto the study area and looking at features within each grid cell including the road length, distance to the colony, radiance value, number of utility poles, and number of bus stops. The cells that had the most birds were the cells with more road

length, higher radiance values, and shorter distance to the colony. We also checked for spatial differences across lighting regimes, and across three wind regimes, but found no significant differences. I observed three clusters of cells that were fallout hotspots and have proposed explanations for why each cluster consistently yielded high fallout.

The first cluster was attributed to proximity to the breeding colony. These cells were located directly across from Mānana Island, making it easy for many fledglings to accidentally end up on land. I suspect that strong, onshore winds blew many of the unexperienced fliers onto land, where they ended up stranding. Another prominent characteristic of this location is the presence of Sea Life Park (SLP), the marine life center and seabird rehabilitation center. Bright lights within the facility may be another drawing source of light, which is likely visible from the colony. Although the streetlights along this section of the road are sparse, the lights in SLP are likely causing high fallout in this area. Notably, and in contrast, nearby cells with no fallout, also had very low radiance. Additionally, there is historical evidence of low level nesting (5 – 10 nests) within several meters of the survey route, across from SLP.

The second cluster, while further from the colony than the first, was still in relatively close proximity to the colony. The distinguishing characteristic of this area was the clear line of sight from the colony to the road, without tall structures or vegetation blocking the light from the road or nearby residences. I think that the unobstructed view of the streetlights from the colony drew the birds toward land as they left their colonies.

The third cluster was further away from the colony but featured several unique characteristics. First, there is a major landscape change near this location, where the dominant land cover type shifts from dense residential area to dense deciduous forest.

Right at the border of this landscape change is a McDonald's restaurant with several brighter than average, unshielded light posts. I suspect that this bright location stood out against the neighboring dark forest, drawing in many confused birds. Furthermore, this colony is directly downwind from the Mokulua Islands, where we suspect many of these birds originated from.

In this chapter we used satellite imagery from NASA's Suomi NPP Satellite (https://eogdata.mines.edu/download_dnb_composites.html) to look at changes in light pollution (i.e., night-time radiance) after the transition to shielded LED streetlights. Interestingly, most of O'ahu showed decreases in radiance after the switch to LED streetlights. When looking at images side-by-side, the most obvious difference is the reduction in light pollution along the highways that run through the middle of the island (Figure 1). To make the changes more apparent, I mapped the change in radiance per cell to show areas that decreased radiance in blue and increased in red (Figure 2). Except for a few red locations in the highly developed regions, most of the island showed a decrease in radiance, suggesting that overall light pollution has decreased since the installation of the shielded LED streetlights. Although we saw a significant decrease in radiance in our study area, the spatial trends in fallout remained the same. One possible explanation for this result is that the distribution of brightness remained the same, so the birds were still attracted toward the brightest grid cells location. Another possible explanation is that the shielding did not reduce visibility to WTSH since they fledge from coastal location near or at sea level and are likely below the lights when fledging. The first takeaway from my research is that radiance and distance to the breeding colony were the two most important drivers of the distribution of fallout. The second is that the change in lighting did not

affect the spatial distribution of fallout but it did decrease overall light pollution, which likely has benefits beyond WTSH.

Carcass Removal and Underestimation

During our road surveys, we used mark-recapture protocol to assess WTSH carcass removal as a source of underestimation. For the first 6 years, carcasses were selected via coin toss to be marked. Carcasses were marked with a colored string and metal tag with a number-letter code for identification. Carcasses were revisited once every morning for up to 9 days after being marked. During 2018-2019 the protocol was augmented by marking every bird and revisiting birds twice daily, around 8:00 AM and 8:00 PM to gauge removal at a finer scale. We used this data to create two survival curves: the first including data from 2012-2019 and showing carcass removal at daily intervals and the second including data from 2018-2019 showing removal at 12 hour intervals.

In order to use the data from 2018-2019 with the previous 6 years of data, we did a coin toss to determine which carcasses to include in the full analysis, and only included daily intervals. For the full 8-year analysis, we saw the highest rates of removal during the first day, and it gradually leveled out over a 10 day period (Figure 3). We then did a fine-scale analysis of the final two years including all marked birds at 12-hour intervals. The fine-scale curve showed a similar trend, with the most removal happening in the first 12 hours, and a gradual decrease in removal rates over time (Figure 4). This is likely because a freshly killed bird may be easy removed by scavengers or people, but as the

carcass is repeatedly run over by vehicles, it becomes flattened and stuck to the road, and is undesirable for both animals and humans to pick up.

I would encourage future analysis of the data I collected to investigate other factors contributing to carcass removal such as carcass position on road, night-time radiance, and landscape development intensity (Brown and Vivas, 2005). Understanding carcass loss could help correct the minimum mortality estimates based on road surveys.

Personal Observations

There are several personal observations I made during my research that sparked questions and speculations about seabird fallout. It is my hope that my observations can provide insight and spark curiosity for other researchers studying seabirds.

The fledging season is an exciting, nerve-wracking time for WTSH conservation. Although my road surveys largely documented road-killed WTSH, I found and delivered several live stranded shearwaters to Sea Life Park for rehabilitation. In doing so, I paid careful attention to the behaviors of the birds I encountered. The following paragraphs contain noteworthy observations regarding road-killed and living WTSH that were victims of fallout.

When documenting road-killed birds, I made several observations that may be useful to know. While we assume that most carcasses we observed on the road were victims of vehicle strikes because of the carcass condition and location on the road, I have observed birds that I suspect died of other causes. For example, I observed an intact carcass in the grass alongside the road, directly underneath a streetlight with many utility wires

attached. Upon examination, the bird had a broken wing but no open wounds or other apparent injury. I question if this bird was attracted toward the streetlight and broke its wing by colliding with wires or the pole itself. Beyond the road, I suspect that fledgling WTSH are colliding with other structures associated with bright lights, likely leading to death.

Over the course of our study, many of the marked WTSH carcasses were removed from the road. We assumed that some WTSH carcasses were being removed by scavengers, but I witnessed it occurring on several occasions. For instance, one evening when doing a resight survey of marked carcasses, I observed a feral cat dragging a WTSH carcass off the road. I also observed a pet dog move a WTSH carcass into bushes alongside the road. In addition to scavenging, we suspected that humans may remove carcasses from the road. One of our marked intact carcasses was brought to Sea Life Park rehabilitation center. I suspect that most carcass removal is from scavengers, but other means including removal by humans, or displacement by vehicles, wind and rain likely play a role.

Two years in a row, a friend of mine reported a stranded shearwater in her driveway. Interestingly, there is a single streetlight outside the home and the surrounding area is very dark. What I found surprising is that this home is located further inland, 1.4 km from the coast, and 2.6 km from the nearest colony. The home sits at the backside of a small mountain, and I suspect that birds flying from the nearby colonies go over the mountain and come down on the other side when encountering this single bright light. I question if the shielded LED streetlight was still bright enough to attract a shearwater flying overhead.

Regarding the specific attraction of WTSH to streetlights, I have witnessed multiple dead and alive birds directly underneath streetlights, suggesting that they were attracted to the streetlight. During an evening survey, I found a grounded bird sitting in the glow directly underneath a streetlight. The bird was calm and did not react when I approached it, likely because it was exhausted and confused. On the contrary, several birds I have encountered during the daytime were less calm and resisted being handled by a human. I suspect that some birds that strand at night attempt to find hiding locations and are often discovered the following day. For example, several birds have been found on campus at the Oceanic Institute, across from Mānana Island and attached to Sea Life Park. One bird was found tucked behind a water fountain and another was hiding behind a small ladder in an outdoor laboratory. I suspect that birds affected by fallout are stunned and confused immediately after grounding, making them less capable of avoiding traffic and predators. However, birds that do manage to find shelter may be disoriented and unable to return to the wild unless assisted by a human.

Future Directions for Documenting Seabird Fallout

Although my 8-year study on WTSH fallout is finished, there is always more we can learn by documenting fallout. Future road surveys following our protocol can be used to validate the model I generated in Chapter 2. Furthermore, modern GIS technology has made it incredibly simple for users to document spatial data from mobile devices. Through the ArcGIS application, Quick Capture, I designed a program to easily record road survey data, simplifying the process for future surveys.

I am also collaborating with partners on Oʻahu to create a program through the ArcGIS Survey 123 application for documenting fallout. This application will be used by the different organizations on Oʻahu (DOFAW, HMAR, HPU, USFWS) to document fallout and expand the spatial data to other parts of the island. There is potential to expand this effort to citizen science, allowing community members to document fallout. Expanding knowledge on the spatial extent of fallout will allow us to target rescue efforts in those areas, ultimately reducing mortality from light attraction.

As urban development changes the natural landscape, it is important to take advantage of these changes to study wildlife responses and mitigate negative effects. Fortunately, we conducted surveys prior to the change in lighting so we could do a "before and after" comparison. Although we cannot always predict changes in development, consistent monitoring of wildlife in urbanized areas can provide a baseline understanding for future comparisons. Regarding seabird attraction to streetlights, I would recommend monitoring annual fallout to establish a baseline for comparison in the event that streetlights are transitioned to new lighting. As municipalities seek to reduce utility costs, it is likely that many regions will undergo a transition to more cost-effective lighting solutions in the future, providing additional opportunities to study the impacts of lighting on seabirds.

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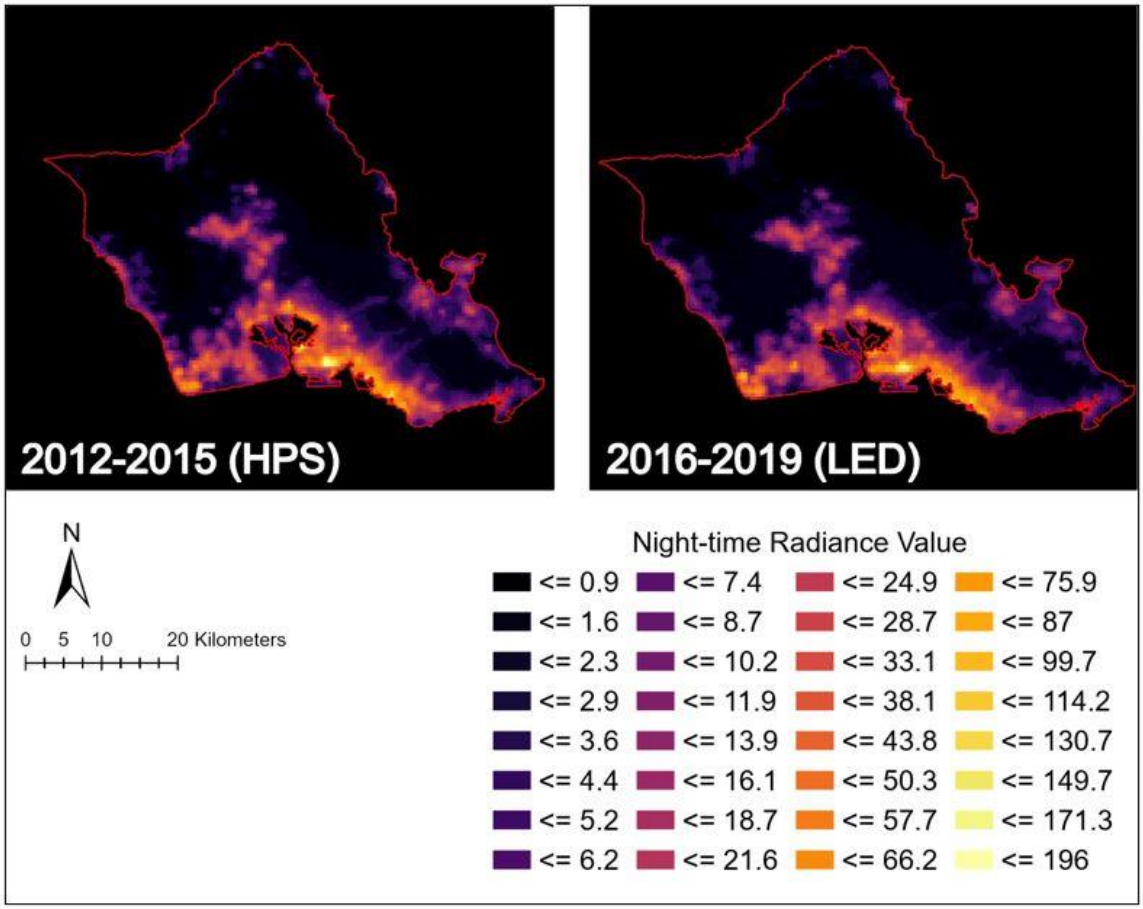

Figure 1. Average night-time radiance during the 2012-2015 HPS regime and the 2016-2019 LED regime (nw/cm^2/sr).

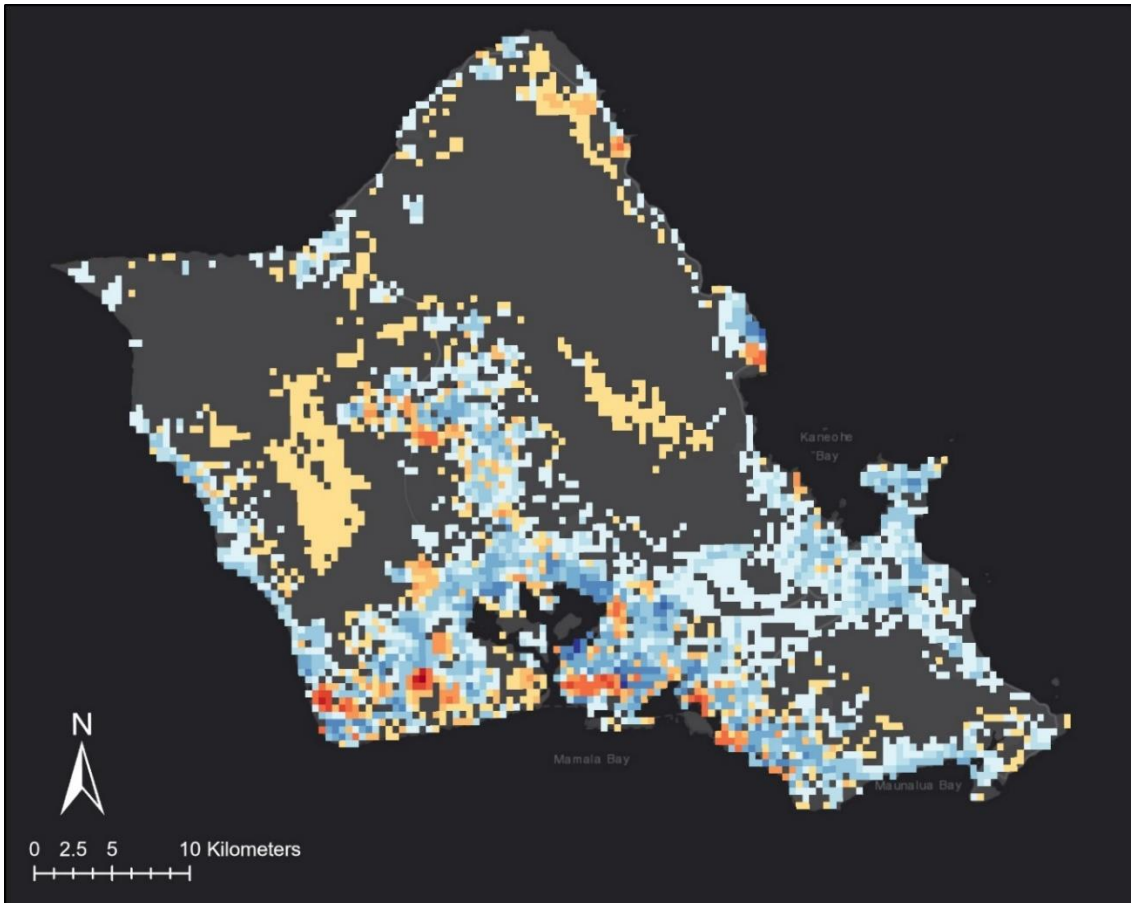

Figure 2. The difference in night-time radiance values after O‘ahu switched from unshielded HPS to shielded LED streetlights. Blue indicates areas where radiance decreased, red indicates where radiance increased. Gray (value = 0.0) indicates no change in radiance.

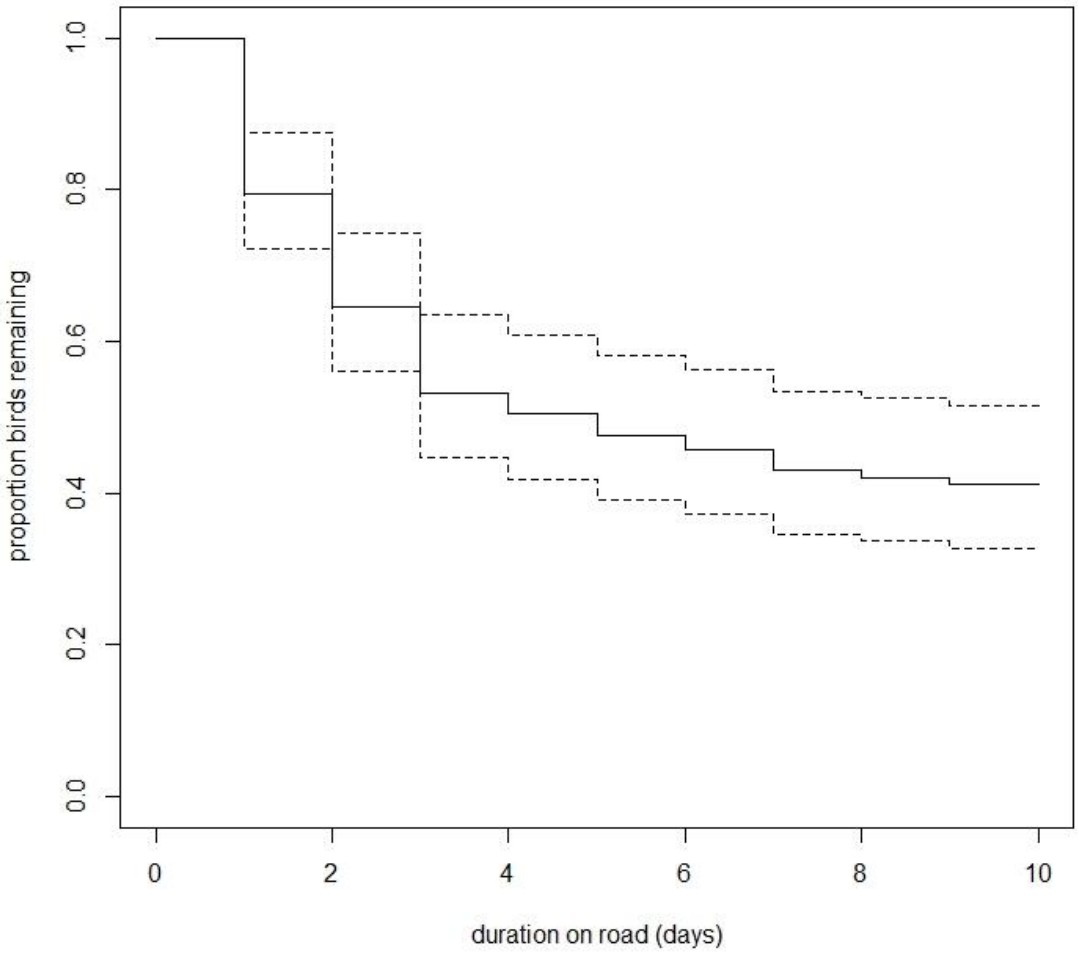

Figure 3. Survival curve showing the proportion of all marked carcasses remaining on the road at daily intervals (2012-2019), (n=107).

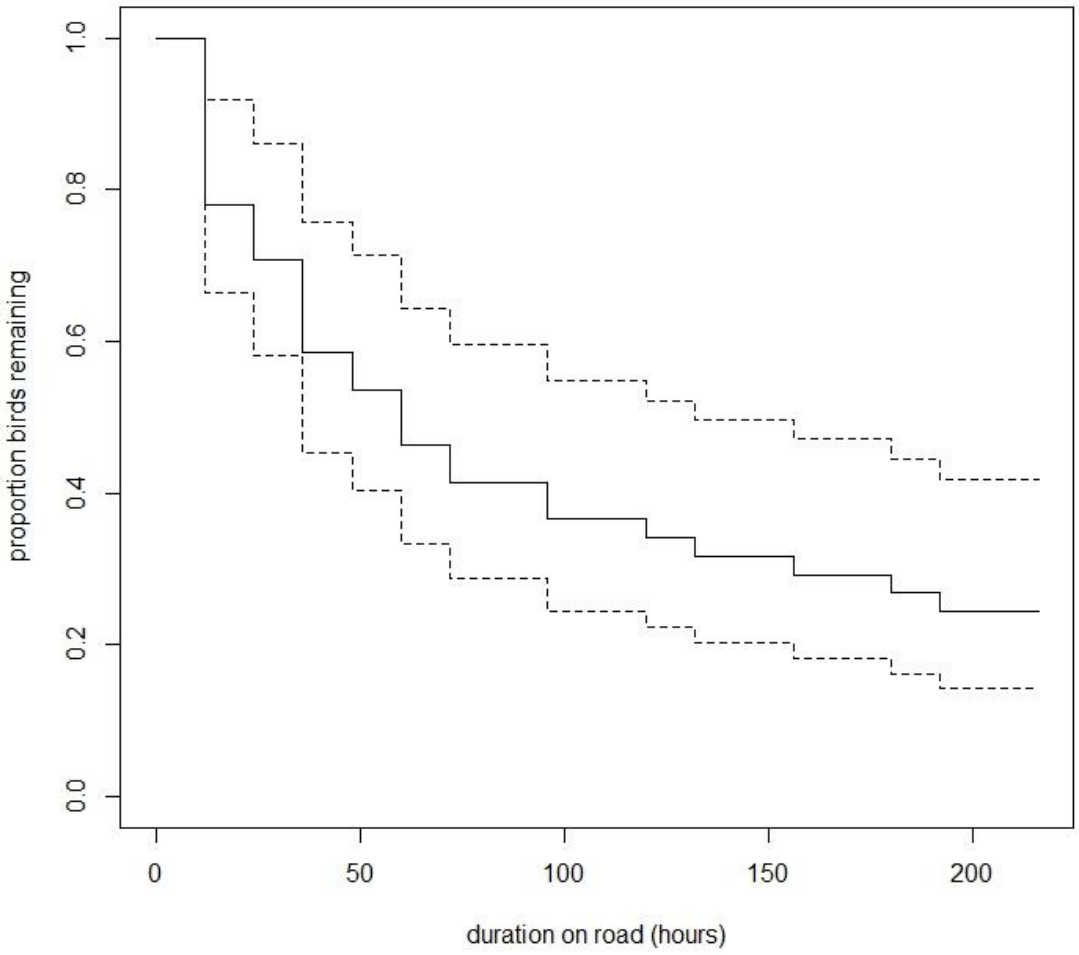

Figure 4. Survival curve showing the proportion of marked carcasses remaining on the road over at 12 hour intervals (2018-2019), (n=41).