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Determining the Effects of Artificial Light at Night on the Distributions of Western Snowy Plovers (*Charadrius nivosus nivosus*) and California Grunion (*Leuresthes tenuis*) in Southern California

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ABSTRACT

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This study covers the role of exposure to artificial light at night (ALAN) in shaping the spatial distributions of two species of conservation concern, roosting sites of the Western Snowy Plover and locations of California Grunion spawning runs, along the coast of southern California. Observational data on plover and grunions, derived from community science sources, were obtained along with remotely sensed environmental measurements along the coast of southern California. The study area comprises a 1.5 km wide coastal strip, bounded by the mean low-tide line, and stretching from 10 km north of the northern Ventura County line to 10 km south of the southern Orange County line. These data were used as inputs within three species distribution models: a generalized linear model, Maxent, and random forest. Exposure to ALAN was based on a ground-verified model of night sky illuminance. In the highest performing models, which used random forest modeling, exposure to ALAN was the most important environmental factor influencing distribution of grunion runs and second-most important factor for plover roosts. Significant declines were found in the likelihood of plovers roosting in locations where exposure to ALAN exceeded illuminance levels equivalent to that produced by approximately one half a full moon and for grunion spawning at one full moon. Disruption of behaviors related to reproduction, roosting, and spawning associated with elevated levels of ALAN are likely a result of increased predation risk in illuminated coastal areas. With evidence of ALAN providing significant ecological disturbances to these two managed species, it is therefore recommended that control of nighttime illumination be used, even at naturalistic intensities, to mitigate disturbances to critical reproductive coastal habitats and potentially other environments.

ADDITIONAL INDEX WORDS: *Artificial light at night, coastal habitats, ecological light pollution, species distribution modeling, citizen science, community science.*

INTRODUCTION

A substantial body of evidence in ecology has demonstrated a significant role for artificial light at night (ALAN) in disturbing animal behaviors (Lacoeuilhe *et al*., 2014; Longcore and Rich, 2004), with implied subsequent changes to their use of space, which have been documented for migratory routes (Cabrera-Cruz, Smolinsky, and Buler, 2018). In coastal habitats, light pollution is of particular concern (Bolton *et al*., 2017); given rapid urbanization (Sterzel *et al*., 2020), this will increasingly be the case (Hölker *et al*., 2010). Although an influence of ALAN in general is now well known, managers lack information on specific thresholds of influence for species of concern. This indicates a need to determine species-specific thresholds for behavioral disturbances due to ALAN exposure and for the subsequent development of policies to help mitigate impacts of existing conditions or future development. In part, this lack of knowledge arises from the difficulty of measuring light at night from the perspective of an organism, extrapolating those measurements across landscapes, and analyzing space use relative to those and other environmental features. Schirmer *et al*. (2019) presented an analysis for space use of urban-tolerant wildlife in Chicago, finding a threshold for reduced activity at an exposure to nighttime illuminance exceeding 6000 millilux (mlx). This is a level of illuminance equivalent to approximately 60 full moons (assuming a full moon produces illumination of 0.1 lux or 100 mlx; Kyba, Mohar, and Posch, 2017). This paper demonstrates a method to evaluate such effects on more sensitive species at a regional scale, using the sandy beach ecosystem of southern California as an example.

Focus was placed on factors associated with the spatial distribution of two managed species, California Grunion (*Leuresthes tenuis*) (Figure 1C) and threatened Western Snowy Plover (*Charadrius nivosus nivosus*) (Figure 1B), along the biodiverse and urbanized southern California coast (Myers *et al*., 2000). These species of interest were selected given their sensitivity to anthropogenic stressors (Martin and Adams, 2020), as well as evidence of sensitivity to ALAN within similar species (Burger and Gochfeld, 1991; Dwyer *et al*., 2013; Reynolds, Thomson, and Casterlin, 1977).

Even with disturbances associated with urbanization, sandy beaches are important habitats for a range of species

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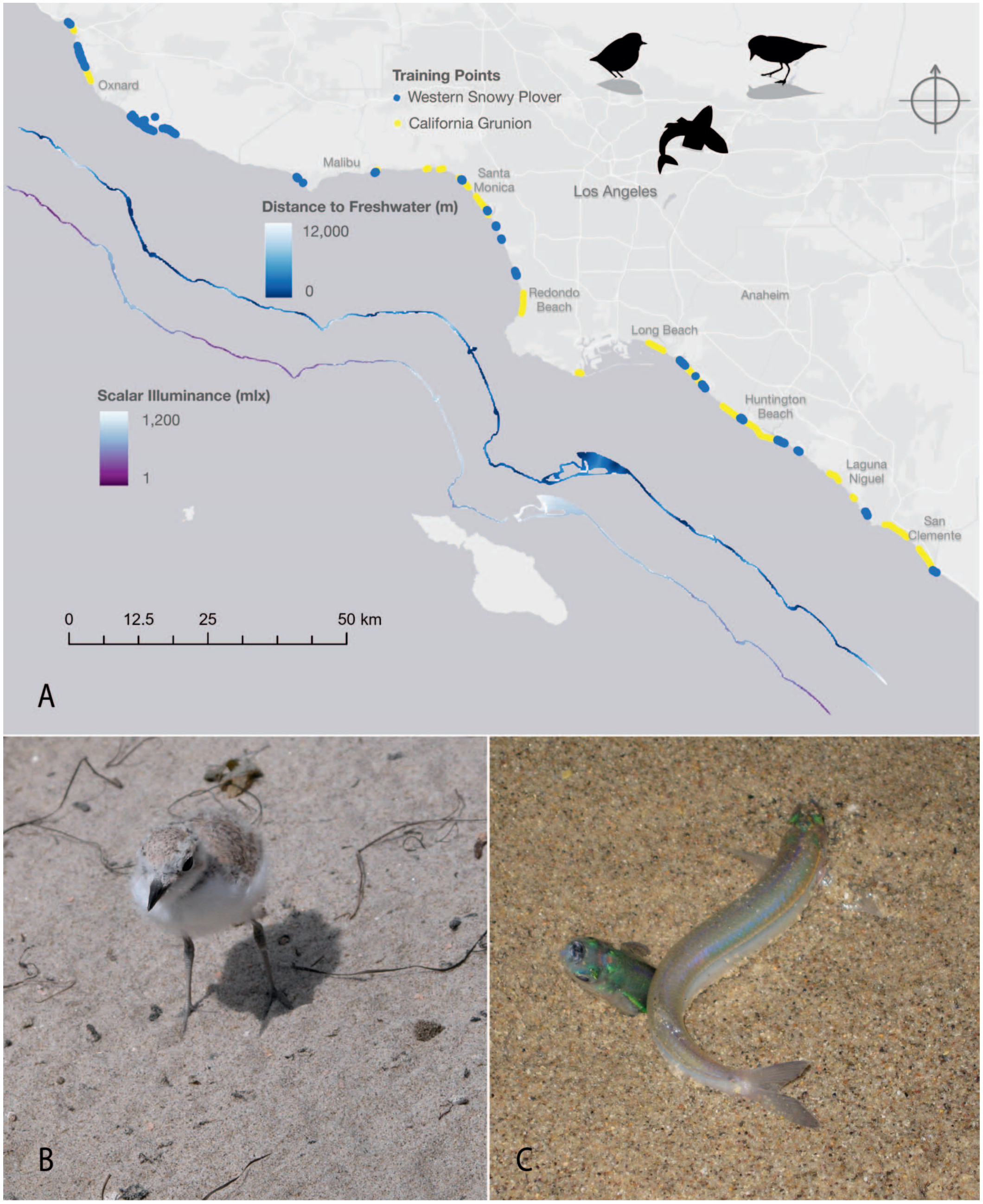

Figure 1. (A) Project area with species data. Distribution of training points for plover roosts and grunion run locations on sandy beaches in Los Angeles, Orange, and Ventura counties, California. Included are examples of environmental layers for hemispherical illuminance (mlx) and distance to freshwater (m). (B) Western Snowy Plover chick (Photo: T. Longcore). (C) Spawning California Grunion (Photo: D. Martin, Grunion.org).

(Schlacher *et al*., 2007). Sandy shores can be nighttime refuges, with some species foraging and others roosting during periods of low human activity. But beaches themselves are threatened by climate change and anthropogenic activities (Martin, 2015; Schlacher, Thompson, and Price, 2007). Levels of nighttime illumination can inhibit habitat use by native species, even at protected beaches. This is the case with both terrestrial and marine species, such as beach mice (Bird, Branch, and Miller, 2004) and sea turtles (Hu, Hu, and Huang, 2018). Both California Grunion and Western Snowy Plover rely solely on beaches for critical parts of their life cycles, including reproduction and nesting for both species and roosting and feeding for the plovers. Identification and quantification of thresholds for impacts of lighting is essential to developing conservation policies that allow for continued persistence and recovery of these species.

Additional nighttime light, whether moonlight or artificial, increases foraging efficiency of predators and reduces activity of prey (Longcore and Rich, 2004; Seligmann *et al*., 2007). This phenomenon has been shown in different habitats, including beaches (Bird, Branch, and Miller, 2004; Schlacher *et al*., 2007). For species in a roost, such as Western Snowy Plover, two responses to illumination are possible. When the species exhibits communal predator defense, greater illumination may be preferred because of enhanced group vigilance. This is reflected in the concentrations of urban American Crow roosts in illuminated areas (Gorenzel and Salmon, 1995) and the schooling of some fishes under illumination (Nightingale, Longcore, and Simenstad, 2006). Many shorebirds forage at night, including plovers (Burger and Gochfeld, 1991; Lafferty, 2001; Page *et al*., 1995), although this is likely due to a combination of defense against predation (Thibault and McNeil, 1994) and an increase in invertebrate activity along nighttime beaches (Evans, 1987). A second response to illumination is avoidance, using darkness to hide from predators. So, although many species of waterfowl, including other species of plovers, have been recorded foraging or roosting under artificial light (Thibault and McNeil, 1994), it is then hypothesized that Western Snowy Plover, given its small size and susceptibility to predation, will roost at darker sites on beaches.

California Grunion emerge onto sandy beaches at night, during the highest tides, to engage in spawning runs, despite the predation risk from various shorebirds and other predators, including humans (Martin, 2015; Martin and Raim, 2014). It can then be hypothesized that grunion will avoid more brightly illuminated locations to minimize predation risk. Mass spawning events by grunion are likely a form of predator swamping, but their location may also indicate avoidance of lights to minimize visibility to predators. The grunion runs occur within roughly four nights after either the new moon or full moon, and so they are not limited to the darkest nights. Anecdotally, however, grunion may favor the darker parts of the beaches on which they spawn (Sandrozinski, 2013; personal observation), and coastal conditions often result in overcast nights during full moons.

This study covers an analysis of associations between locations of Western Snowy Plover nighttime roosts and spawning locations of California Grunion, with ambient nighttime illumination, while accounting for other habitat features. This analysis involved development of a high-resolution map of ground-level hemispherical illuminance, that is, the illuminance of the full night sky, validated by extensive field data and incorporation of observational datasets collected by community scientists for species distributions. The results provide quantifiable thresholds that can inform policies to control light pollution and to illustrate how satellite and ground-based measurement of ALAN can be integrated to understand its effects on species distributions in the wild, with important implications for conservation of coastal biodiversity.

METHODS

The study area is a 1.5 km wide coastal strip, the outer boundary of which is defined by the mean low-tide line, running from 10 km north of Ventura County through Ventura, Los Angeles, and Orange Counties, to a point 10 km south of Orange County in California (Figure 1A). This coastline contains many highly urbanized areas and is close to residences, businesses, and the Pacific Coast Highway. The study area also contains numerous public beaches, which welcome millions of visitors a year.

Observational data were collected on areas where significant grunion runs were aggregated by the community science group Grunion Greeters (Martin *et al*., 2020). Although observations made on behalf of Grunion Greeters focus on wide beaches opportunistically, they have been repeatedly vetted as reliable between observers over the more than two decades of data acquisitions (Martin *et al*., 2020). Beach areas were considered to contain a significant run if they were recorded as having a Walker scale (Martin, Schaadt, and Lawrenz-Miller, 2021) observation of W-2 or higher during the period 2013–16. The Walker scale was developed specifically for assessing grunion spawning runs (Martin, Schaadt, and Lawrenz-Miller, 2021). It ranges from W-0, where few or no fish appear, to W-5, with thousands of fish carpeting the shoreline for over an hour. A score of W-2 or higher indicates hundreds to thousands of fish involved at the peak of the run and a high likelihood of many clutches of eggs under the sand. Within the study area (Figure 1A) an initial set of 2200 presence and 17,900 pseudo-absence points was then generated for the grunion (supplemental information).

Data on plover roost areas were collected by volunteers and staff organized by the Los Angeles Audubon Society and Santa Monica Bay Audubon Society (Ryan *et al*., 2014; Ryan *et al*., 2017), Point Mugu Naval Air Station, and California State Parks. Community scientists for the Western Snowy Plovers survey the entire sandy beach coastline four times a year, and roosts are surveyed monthly. Both grunion and plover data spanned the period 2013–16. Within the study area (Figure 1A), an initial set of 6301 presence and 31,428 pseudo-absence points was then generated for the plovers (supplemental information).

Eight environmental measures were used across the study area (supplemental information): elevation, slope, distance to freshwater, distance to saltwater, nighttime illuminance, land use category adjacent to the beach, beach width, and a measure of the fraction of the sky unobscured by structures or topography along the horizon known as the sky view factor (SVF; Kidd and Chapman, 2012). These environmental measures were used because they describe both the natural landscape, such as elevation and slope, as well as long-term anthropogenic disturbances, such as nighttime illuminance and land use. Of these layers, distance to saltwater and elevation were omitted from species distribution modeling of grunion runs because they were not expected to vary; grunion emerge from saltwater to spawn in the high intertidal zone of sandy beaches. All environmental layers were then rendered at a horizontal resolution of 10 m, as this provided the highest spatial resolution while being manageable with the available computational resources. All data were projected into the State Plane Zone 5 coordinate system (EPSG:6423).

The nighttime illuminance layer was derived from modelling the illuminance across the entire hemisphere of the night sky, known as scalar illuminance (SI), as a function of zenith sky

Table 1. *Evaluation metrics for three SDMs. Comparison of evaluation metrics for three SDMs of the likelihood of observing plover roosts or significant grunion runs. Values recorded as the mean value (standard deviation on the mean value) and the possible range of values is indicated, with higher values indicating better model performance.*

Organism	Model	AUC 0–1	Pearson Correlation –1–1	Cohen's Kappa <0–1	Yule's Q –1–1	TSS <0–1
Grunion	GLM	0.78 (0.04)	0.18 (0.02)	0.27 (0.06)	0.73 (0.09)	0.27 (0.04)
	Maxent	0.90 (0.03)	0.46 (0.04)	0.46 (0.07)	0.91 (0.03)	0.39 (0.03)
	RF	0.92 (0.03)	0.55 (0.07)	0.55 (0.07)	0.93 (0.03)	0.47 (0.04)
Plover	GLM	0.69 (0.06)	0.14 (0.04)	0.26 (0.08)	0.56 (0.13)	0.18 (0.06)
	Maxent	0.93 (0.02)	0.54 (0.05)	0.62 (0.08)	0.95 (0.02)	0.43 (0.02)
	RF	0.95 (0.03)	0.73 (0.06)	0.73 (0.08)	0.96 (0.02)	0.46 (0.03)

brightness from the World Atlas of Artificial Night Sky Brightness (WAANSB; Falchi *et al*., 2016) and the SVF. This map layer describes the expected illuminance of the full night sky given the predicted brightness of its zenith as modelled by the WAANSB. This model of nighttime sky SI was parameterized using photographs taken at 515 locations under new moon conditions and stratified within categories of satellite-measured upward nighttime radiance within the study area, with SI measured using Sky Quality Camera (Euromix Ltd., Llubljana, Slovenia; Simons, Yin, and Longcore, 2020). The photos used to build this model were taken under various levels of cloud cover over multiple seasons, but it was found that neither the sampling date nor the percentage of the night sky covered with clouds made significant contribution to it (Simons, Yin, and Longcore, 2020). A log-10 transformed SI (mlx), designated as log(SI), was then used for each 10-m cell for ALAN exposure.

To provide a comparison with the influence of exposure to ALAN and other measures of anthropogenic disturbance, each beach polygon was assigned a categorical attribute based one of six categories of landscape: (1) flat, undeveloped landscapes containing no buildings within 100 m of the shoreline; (2) flat, developed landscapes containing buildings within 100 m inland of the coastline; (3) elevated, undeveloped landscapes where land rises to more than 10 m of elevation within 100 m inland of the coastline; (4) elevated, developed landscapes where land rises to more than 10 m of elevation within 100 m inland of the coastline and contains buildings within 100 m of the shoreline; (5) beaches backed by water where open water bodies are within 100 m inland of the coastline; and (6) beaches backed by water that is developed into a marina or port. These beach polygons were then rasterized.

Table 2. *Relative importance of variables in random forest SDMs. The mean and standard deviation of the relative importance, as measured by the mean decrease in their Gini indices, of variables in explaining the likelihood of observing significant grunion runs or plover roosts using a random forest model. Values recorded as the mean value (standard deviation on the mean value), with higher values indicating greater importance of the variable to the model.*

Variable	Relative Importance (Grunion)	Relative Importance (Plover)
Elevation	NA	10.44 (0.89)
Distance to freshwater	12.66 (2.02)	16.13 (1.55)
Log(SI)	16.42 (3.70)	14.76 (1.41)
Distance to saltwater	NA	9.56 (1.12)
Slope	10.66 (1.11)	7.34 (0.52)
Beach category	3.28 (0.35)	4.65 (0.71)
Beach width	15.35 (2.82)	10.51 (1.37)
SVF	13.01 (2.16)	10.55 (1.30)

To develop the species distribution models, 100 presence and 1000 pseudo-absence points were randomly sampled from the initial set of points, for both grunions and plovers, across the study area, and the environmental data associated with these points were extracted (supplemental information). Then the following species distribution models were run in order to identify influential environmental factors: general linear models (GLM) with logistic regressions between environmental variables and species presence, MaxEnt, and random forest (RF; Liaw and Wiener, 2002). Each model was run 100 times using training and testing sets split with fivefold partitioning with the *kfold* function within the R package *dismo* (Hijmans *et al*., 2017). The mean and standard deviation of a set of evaluation metrics were then calculated (supplemental information), with models based on RF outperforming either those using MaxEnt or a GLM (Table 1). The means, standard deviations, and the relative importance values of environmental variables in the random forest models were then calculated (Table 2). The relative importance values of environmental variables within each model were then calculated and visualized as heat maps of these 100 partial dependence plots (supplemental information).

RESULTS

Building on previous analysis (Simons, Yin, and Longcore, 2020), a regional-scale ALAN exposure layer was developed to estimate hemispherical light exposure (measured in mlx) as a function of the WAANSB and the proportion of the horizon visible (Figure 1A). With this and other environmental layers, species distribution models that used random forest classifiers generally outperformed either generalized linear models or Maxent models (Table 1). The area under curve for RF models exceeded 0.9 for both species, which is considered to be an excellent fit.

Focusing on the output of RF models, the nighttime exposure to ALAN was found to be the environmental variable with the greatest relative importance in explaining the likelihood of detecting grunion runs and, of second-most importance, in detecting plover roosts (Table 2). The RF models also indicated an increase in the likelihood of both species being present in association with an increase in beach width (Figures 2 and 3). The likelihood of grunion runs peaked near 100 mlx, equivalent to the illumination from a full moon (Kyba, Mohar, and Posch, 2017), and declined at

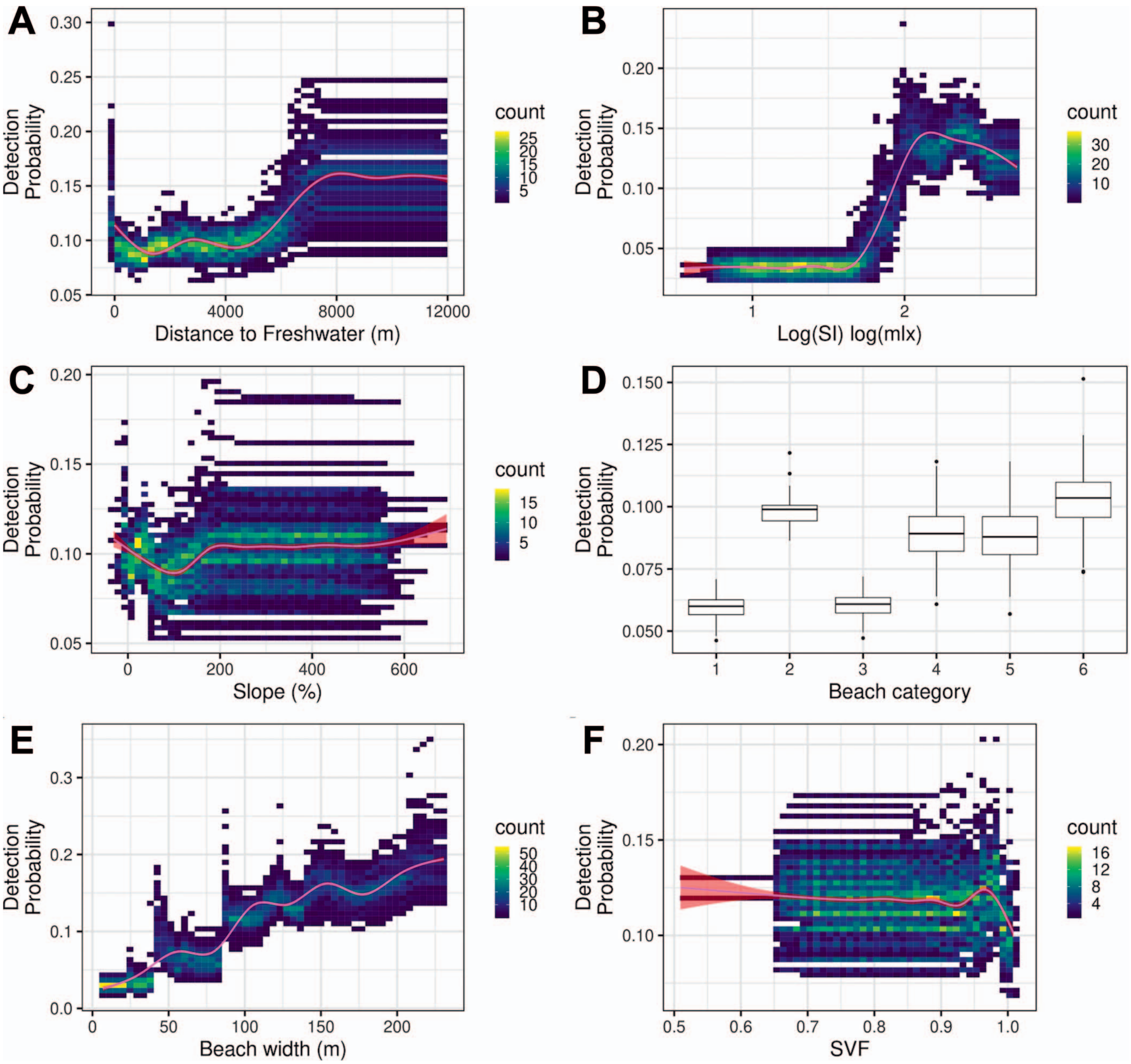

Figure 2. Partial dependence plots for grunion runs for environmental variables. Density of 100 partial dependence plots for random forest models of the likelihood of significant grunion runs for distance to freshwater (m), log-transformed scalar (hemispherical) illuminance (log[SI]; mlx), slope (%), beach category (1: flat, undeveloped land, 2: flat, developed land, 3: elevated, undeveloped land, 4: elevated, developed land, 5: water, undeveloped, 6: water: developed), beach width (m), and SVF. The pink line represents a nonparametric loess curve with associated 95% confidence interval.

>100 mlx (Figure 2). Consistent with this observed peak, grunion runs were found to be more common in categories of beaches backed by illuminated bodies of water rather than those backed by undeveloped areas.

For plovers, the likelihood of a roosting site declined significantly at illumination greater than 50 mlx, falling to 50% of their peak probability of presence above 100 mlx (Figure 3). Models also indicated increased roost prevalence near freshwater and with wider beaches (Figure 3).

DISCUSSION

Although it was unsurprising to find that ALAN exposure was a significant factor associated with the location of grunion runs and plover roosts, the importance of this factor was high compared with other environmental factors. The thresholds for impacts for both species (50–100 mlx SI) is similar to natural illumination levels (*e.g.*, from the full moon with a clear sky; 100–300 mlx) and contrasted with the higher levels of light

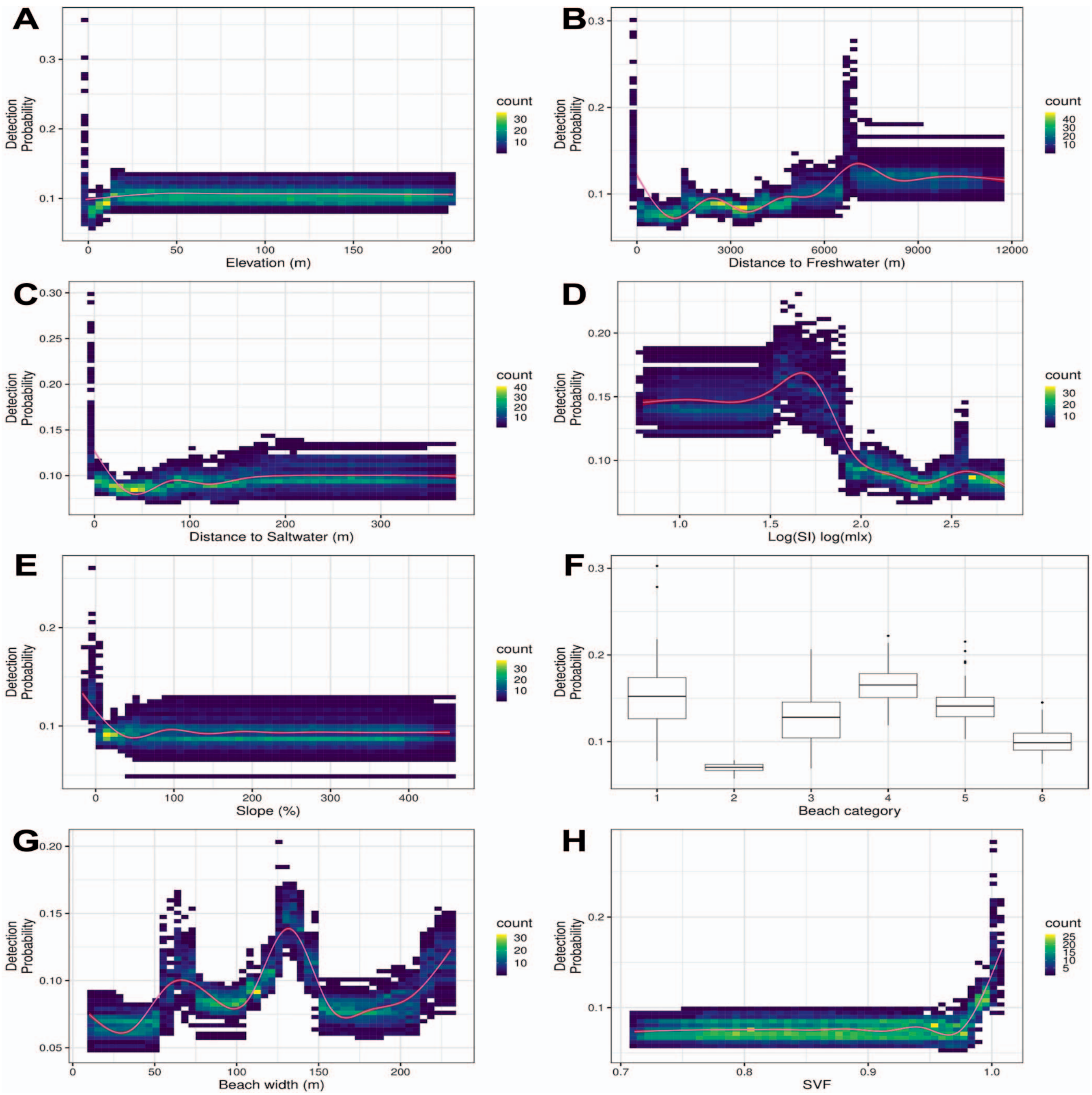

Figure 3. Partial dependence plots for plover roosts. Density of 100 partial dependence plots for random forest models of the likelihood of significant grunion runs for elevation, distance to freshwater (m), distance to saltwater (m), log-transformed scalar (hemispherical) illuminance (log[SI]; mlx), slope (%), beach category (1: flat, undeveloped land, 2: flat, developed land, 3: elevated, undeveloped land, 4: elevated, developed land, 5: water, undeveloped, 6: water: developed), beach width (m), and SVF. Density of 100 partial dependence plots for random forest models of the likelihood of plover roosting. The pink line represents a nonparametric loess curve with associated 95% confidence interval.

found to influence urban-tolerant species in previous studies (6000 mlx; Schirmer *et al*., 2019).

For each species, model results were consistent with previous research on environmental determinants of habitat use, while adding additional information about ALAN exposure. For example, models of grunion runs also found the distance to freshwater and beach slope to be important factors, with flat beaches close to freshwater sources more conducive to spawning (Martin *et al*., 2020). Similarly, the importance of distance to freshwater and beach width in the model of plover roosting sites is supported by prior observations of plover behavior and associated models of habitat suitability (Brindock and Colwell, 2011; MacDonald, Longcore, and Dark, 2010).

The responses to ALAN that were found for each species are also consistent with their ecology. The decline in grunion run likelihood above 100 mlx of ALAN likely stems from predator avoidance. Although larval grunion are attracted to light (Reynolds, Thomson, and Casterlin, 1977), adults in spawning aggregations avoid lights underwater (KLMM, personal observation). Grunion runs are stronger after new moons than after full moons (see figure 2 in Martin and Raim [2014]), suggesting photophobia or predator avoidance under the brightest conditions. The concentration of plover roosts in darker portions of beaches as a means to avoid disturbance and nocturnal predation is consistent with previous studies of nocturnal foraging (Mouritsen, 1992) and predator avoidance (Santos *et al*., 2010). One might expect plovers to use brighter locations where approaching predators would be visible, but the data suggest that on an open beach, darkness is a refuge for this species. As with daytime behavior, plovers tend to remain in place when predators approach and rely on their cryptic coloration to evade detection.

This study, however, has limitations. First, the study is correlational. Given the sensitivity of the species involved it is not feasible to experimentally increase lighting levels at the scale needed to draw inferences nor is it feasible within the context of an experiment to decrease lighting levels at scale. Second, light has been described in mlx, a thousandth of a lux, which is a unit that is calculated based on the response of the human eye. This has been done in part as a limitation of the tools available to quantify low-light conditions in a cost-effective manner. Tools are not yet available that measure spectrally resolved irradiance at nighttime intensities, and so reliance has been placed on human-centered mlx as a proxy measure that does not account for the different visual systems of birds and fish, although future research may yield further insights in this regard.

Notwithstanding limitations of current methodological tools, this study presents an advance that is important to conservation. Studies are needed that validate the presumed impacts of ALAN on species distributions in field conditions and that can be connected to quantifiable thresholds to develop policy. This study analyzes a uniquely large study area and demonstrates the importance of controlling light pollution that falls within the range of what has been termed naturalistic light at night (nLAN; Walbeek *et al*., 2021), comprising light equivalent to that cumulatively produced by the moon, stars, and other natural light (*e.g*., zodiacal light, airglow). Even nLAN, including light similar to that produced by a half moon under a clear sky, can exceed the threshold beyond which habitat suitability declines for these two sensitive beach-dependent species. This information is essential for beach managers and environmental regulators to control the sources of direct glare that illuminate sensitive coastal habitats, especially during planning and environmental analysis. This knowledge can also be used to encourage nearby cities, including the coastal megalopolis of southern California, to put in place policies that reduce coastal light pollution, starting at the beach and moving inland.

CONCLUSIONS

The coast of southern California is exposed to levels of ALAN far in excess of natural nighttime conditions, and this exposure is highly variable even on spatial scales on the order of hundreds of meters (Simons, Yin, and Longcore, 2020). As a consequence, and in conjunction with other environmental factors, ALAN is likely contributing to habitat fragmentation for a wide variety of species (Challéat *et al*., 2021). It has therefore been found that exposure to ALAN to be a significant stressor for these beach-dependent species, challenging the ecosystem integrity of coasts and potentially many other ecosystems, and placing an obligation on conservation planners to integrate quantitative performance thresholds into plans and policies to protect sensitive species in these contexts.

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